A changing view of eye dominance

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Thesis summary

Eye dominance can be broadly defined as the preference for one eye over the other and several distinct types of eye dominance have been identified since the existence of eye dominance was first recorded in the 16th century. Since then, eye dominance has generally been assumed to be a fixed quantity, but recent work has shown that one form of eye dominance can change with gaze direction. This finding was directly investigated in this thesis, as was the ability for other forms of eye dominance to switch between the eyes. It was found that eye dominance switching does take place and there is evidence for a hierarchy of cues which trigger changes in two types of dominance. Differences in retinal image size appear to be the cue that is most heavily favoured when determining which eye is treated as dominant. Other cues include eye position signals and differences in luminance between the eyes, the latter suggesting that eye dominance switching is not controlled solely by changes in gaze direction. The relation between eye dominance and the centre of visual direction, the egocentre, was also considered. It was found that the egocentre is unlikely to change location in a manner similar to eye dominance. The conclusion of this work sets dominance switching within the context of a mechanism designed to maximise the amount of data available for use by the visual system.

Chapter 1

Eye dominance and the past: introducing eye dominance

Despite the symmetry of the body, there is an inherent preference for the parts of one side of the body over the other. This most commonly manifests itself as a preference for one of the limbs over the other, with handedness being especially important in everyday life. In addition to limb preference, there is also a preference for the visual input of one eye over the other. The preferred eye is known as the dominant eye. The concept of eye dominance was first referred to in 1593 in Porta's De Refractione (Porac & Coren, 1976). Almost all of the studies of eye dominance that followed Porta's work have assumed that eye dominance is fixed. However, this view has been challenged by Khan & Crawford (2001) who propose a radical alternative. They present evidence that eye dominance changes as a function of gaze direction. Their claim will be investigated in this thesis.

To date, eye dominance has been studied in over 570 articles (Mapp, Ono & Barbeito, 2003) and has been related to measures and concepts ranging from reaction time (Minucci & Connors, 1964) and size distortion (Coren & Porac, 1976) to accuracy of line bisection (Mefferd & Wieland, 1969), marksmanship (Crider, 1943) and even 'soldierliness' (Banister, 1935). Critically, in all of the above studies, the eye treated as dominant is assumed to be consistent within tasks. This makes eye dominance similar in concept to hand dominance because, in general, the hand used for a particular task does not change on a whim. However, while handedness might not change within a task, it is not unusual for handedness to change depending on the task (Oldfield, 1971) and this is also true for eye dominance (Walls, 1951).

It is the apparent consistency within tasks that makes the findings of Khan & Crawford (2001) so important. They found that eye dominance could change within a task. Their task and data are shown in Figure 1.1.

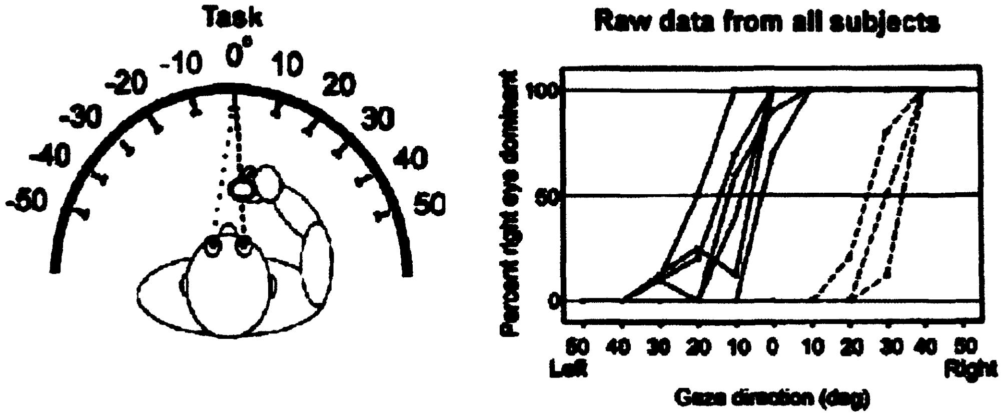

Figure 1.1: The task and data from Khan & Crawford (2001)
The left panel shows the task used by Khan & Crawford and the right panel shows Khan & Crawford's data. Here, gaze direction is plotted along the horizontal with the percentage of right eye dominance along the vertical. The percentage of right eye dominance is a representation of the number of times the ring is brought back to the right eye, rather than the left. The solid lines are data from observers who are right eye dominant at straight ahead. The dotted lines represent observers who are left eye dominant at straight ahead.

As the left hand panel of the figure shows, the task involved observers sitting in front of a horizontal row of rings spaced at 10° intervals in a 100° arc extending symmetrically either side of them. Observers were instructed to reach out, grasp a ring and bring it back to their face, while maintaining a line of sight through the ring. This ensured that the ring would be brought back to one of the observer's eyes. The results, in the right hand panel, show that rings located to the left of an observer were brought up to the left eye and rings to the right of the observer were brought up to the right eye, irrespective of which eye was dominant at straight ahead. This suggests that observers were sighting with their left eye when selecting rings on their left and with their right eye when selecting rings on their right, strong evidence that sighting dominance is dependent on gaze direction.

Khan and Crawford hypothesised that the reason eye dominance switches between the eyes with gaze direction is to optimise the field of view for visually guided tasks. This is an intriguing and important hypothesis, not least because it has not been considered in the four centuries since eye dominance was first discussed. Neither is Khan & Crawford's result the only example of eye dominance switching with target direction. The studies that have directly followed from Khan & Crawford's result (Banks, Ghose & Hillis, 2004; Khan & Crawford, 2003; Quartley & Firth, 2004) have reported data compatible with the dominance switching hypothesis.

The findings of the three main papers on dominance switching (Banks et al., 2004; Khan & Crawford, 2001; Khan & Crawford, 2003) formed the basis for the forthcoming chapters. Chapter 2 followed directly from Khan & Crawford (2001) and determined whether their result generalises to a different eye dominance task. The task used in this chapter involved reducing the luminance in one eye. This, in turn, produced a discrepancy in reaction times between the eyes and changed the binocular reaction time. Binocular reaction time should give an indication of which eye is being treated as dominant. Reaction time was measured at various eccentricities as a direct test of Khan & Crawford's dominance switching hypothesis.

Chapter 3 investigated the cues that drive dominance switching. This issue was first addressed in one of the follow-up studies to Khan & Crawford's work, Banks, Ghose & Hillis (2004). Banks et al examined the role of the extra-retinal eye-position signal and the retinal relative image size cue (Banks, Backus & Banks, 2002). They identified image size as the primary cue responsible for dominance switching. Following a series of experiments manipulating properties of the retinal images, Chapter 3 considered whether image size is the sole cue for dominance switching.

The final chapter investigated the link between changing eye dominance and the reference point used to make judgements relative to the self. Several studies have linked the location of the dominant eye and the centre of visual direction, the egocentre (Barbeito, 1981; Porac & Coren, 1986). If the locations of the egocentre and the dominant eye are linked and, furthermore, the dominant eye does not have a fixed location, the egocentre could also vary in location. Although there is much debate as to whether the location of the egocentre is fixed or variable (Banks, van Ee & Backus, 1997; Mansfield & Legge, 1996; Mansfield & Legge, 1997), the studies of Khan & Crawford (2001; 2003) are unable to directly address the location of the egocentre. Khan & Crawford's task was adapted into one suitable for determining the location of the egocentre and existing evidence for and against a variable egocentre location was discussed in the chapter.

Before presenting any experimental findings, it is necessary to review the previous work on dominance. The review will also cover other areas of research that have been either linked to eye dominance or that have been considered in the experimental chapters.

A history of prominent eye dominance research

As stated above, the first recorded reference to eye dominance was made by Porta in 1593. Porta also developed a test for dominance, although this test is usually known as the Rosenbach test (Miles, 1929) or the Porta-Rosenbach test (Miles, 1930). For this test, an observer holds a pencil (or similar object) and lines it up with a mark on a wall. When performing this task, the observer tends to align the pencil and mark with the line of sight of one eye. Whichever eye is used for alignment is the dominant eye.

Despite the development of this simple test, eye dominance as a subject was largely ignored until the early part of the 20th Century and the development of further tests of eye dominance. One of the best-known dominance tests is that devised by Miles (1929). For this test, an observer holds a truncated cardboard cone up to their face and sights a target through the smaller opening in the cone. Similarly to the Porta test, they align the opening of the cone and the target with the line of sight of one eye – the dominant eye. The benefit of this task is that observers are unaware that they are sighting with only one eye. The reliability of this test is also very high (Miles, 1930).

Following from the Miles test, a battery of seven sighting tests was developed by Crider (1944). The battery of tests included Miles' test as described above, a test in which observers sight through a ring (this test formed the basis of Khan & Crawford's 2001 study) and another test in which observers sight through a hole in a piece of card. Crider intended these tests to be used as a standardised measure of eye dominance and the specific tests mentioned above are still in use to this day (Ehrenstein, Arnold-Schulz-Gahmen & Jaschinski, 2005; Handa, Mukuno, Uozato, Niida, Shoji & Shimizu, 2004).

Although dominance could be measured accurately, researchers were still unsure as to the significance of the dominant eye. Sheard (1926) reported one possibility. He found that, when fixating on an object, the dominant eye maintained the line of sight and the non-dominant eye converged in order to produce a single image. This fact is remarked upon and supported in several later papers and also formed the basis for an eighth test of dominance in Crider's battery of eye dominance tests (Crider, 1944). For this test, Crider defines the dominant eye as that which maintains fixation and does not diverge as a fixated object is brought to within three inches of the face (i.e. closer than the near point of convergence).

Relating the dominant eye to everyday activities was also an avenue of early eye dominance research. The study conducted by Banister (1935) exemplifies this trend by examining the effects of the dominant eye on marksmanship (also studied by Crider, 1943). He found that, when shooting from the right shoulder, those who were right eye dominant were considerably more accurate than those with left eye dominance.

The middle of the 20th century saw a shift away from developing specific tests for dominance, although Walls (1951) produced a list of 25 specific eye dominance criteria, and more towards linking eye dominance to other visual phenomena. Of particular interest here are those studies that, in retrospect, can be seen to have offered tantalising evidence of variable eye dominance (Charnwood, 1949; Francis & Harwood, 1952).

The study conducted by Charnwood (1949) required observers to align themselves with two hanging beads. Observers generally placed themselves so that the beads were aligned with their midline. However, when a blurring lens or neutral density filter was placed before one eye, they clearly adjusted themselves in favour of the uncovered eye. This would suggest that the line of sight is moving towards that eye. Therefore it could be considered that the dominant eye is shifting towards the eye with the brightest image, i.e. the image that can provide the most visual data. This finding was also supported by Francis & Harwood (1952) who used almost exactly the same setup and judgement as Charnwood (1949) although, rather than using a simple filter, they placed a variable density filter before one eye. As the density of the filter increased, observers adjusted themselves with increasing weight on the uncovered eye. Again, this provides further evidence of dominance changing to favour the eye with the brighter image.

Along with the findings of Charnwood and Francis & Harwood, evidence also began to mount for the existence of more than one type of eye dominance. Walls (1951) described two different types of dominance. One, which he called motor dominance, is the form that is tested during all of the eye dominance tests outlined above. The other is the eye that tends to dominate in situations involving binocular rivalry. Cohen (1952) suggests that this form of dominance be called sensory dominance.

Despite the apparent existence of several forms, one type of dominance continued to feature heavily in studies, namely motor dominance, now known as sighting dominance. Minucci & Connors (1964) tested the time taken to react to flashed stimuli under three viewing conditions: binocular, sighting eye only and non-sighting eye only. They found reaction times were fastest for binocular viewing, but also that the sighting eye produced a slightly shorter reaction time than the non-sighting eye. Another study investigated how sighting dominance influenced the bisection of lines (Mefferd & Wieland, 1969) by measuring sighting dominance and asking subjects to bisect horizontal lines into two equal sections. They found that those who sighted with their right eye tended to overestimate the length of the left side of lines during bisection. Similarly, those sighting with their left eye overestimated the length of the right side of the line.

However, sensory dominance was not completely passed over in favour of studying sighting dominance. Toch (1960) attempted to discover if sensory eye dominance could be altered. He used stereograms, consisting of two dissimilar images, which were designed so that one image strongly dominated the other. For example, one stereogram used the face of an ape and the face of President Eisenhower. In a preliminary test designed to check the dominance of the stereogram pictures, 21 of 28 observers exclusively perceived the image of the ape rather than that of Eisenhower. During the main experiment, the stereograms were viewed for one minute each, with the dominant image always being presented to the left eye. Sensory eye dominance was measured following this training procedure by presenting observers with another stereogram. This stereogram presented oblique lines on a red background to one eye and oblique lines, which ran in the opposite direction, on a green background to the other eye. The green image was always presented to the left eye during the measuring procedure and observers were asked to report how long each colour was visible in the percept. The results suggested that sensory dominance had changed to favour the left eye more than the right, with the green image perceived more often than the red, although the change was not significant. Despite the lack of a significant change in dominance, this does give some evidence that sensory dominance can be affected by training.

Finally, Hayashi & Bryden (1967) investigated the effect of eye dominance on visual field preference. They used a tachistoscope to present test stimuli (consisting of a single, capital letter) for a duration in the range of 15 – 35 msec. The stimuli were also presented in either the left or right visual field at two different locations, these being either near or far from a fixation point. Observers were asked to identify the letters presented to them and, while sighting dominance (measured using the Miles test) did not have any impact on letter recognition ability, differences in acuity between the eyes did have an effect. Those with a higher acuity in the right eye tended to have a greater accuracy for letters in the right side of the field and those with higher left eye acuity tended to have a greater accuracy in the left side of the visual field. This hints at the existence of another form of dominance, namely that due to a difference in spatial resolution between the eyes or acuity dominance.

Gronwall & Sampson (1971) attempted to identify how many different types of dominance exist. They found correlations between various tests of dominance, but were unable to categorise eye dominance to their satisfaction. However, Coren & Kaplan (1973) successfully separated eye dominance into three different groups - sighting dominance, sensory dominance and acuity dominance (defined as above). The relations between these types of dominance will be discussed in greater detail in the next section.

Following from this study, Coren also contributed to numerous other studies of dominance (Coren, 1974; Coren & Porac, 1976; Porac & Coren, 1975; Porac & Coren, 1982), as well as a comprehensive review of the early literature (Porac & Coren, 1976). The earliest study shows that dominance can be measured in preverbal infants using a variant of one of Crider's battery of tests (Crider, 1944). A light is brought towards the infant's face until one eye stops converging or diverges. This is the non-dominant eye. Coren also tested groups of school-age children and adults and found that responses were more consistent as age increased, although the percentage of right eye dominant observers in all groups stayed roughly constant. This suggests that eye dominance does not change significantly with age.

Coren & Porac (1976) and Porac & Coren (1982) report two novel consequences of sighting dominance. Coren & Porac (1976) presented observers, who had equal acuity in both eyes, with circular targets. These targets were presented using apparatus that separated the monocular images, similar to the effect of the prism goggles used in Porac & Coren (1975). Two thirds of the observers thought the target presented to their sighting eye was larger than the other, even though there was no actual difference in size between the monocular targets. Since there was no difference in acuity between the eyes, Coren & Porac conclude that this must be a psychological effect. It is also important to note that this result could be linked with that of Mefferd & Wieland (1969) who found that line-length was overestimated on the side opposite to the sighting eye, although the results appear to oppose each other.

Porac & Coren also present evidence relating the sighting dominant eye to the fading of an afterimage (Porac & Coren, 1982). Observers were presented with a stabilised, retinal image and the time taken for the image to fade was recorded. All presentations were monocular and the results clearly showed that the image took longer to fade in the sighting eye than in the non-sighting eye. The simplest physiological explanation for this phenomenon, as suggested by Porac & Coren, is that there is a weighted distribution of cells responsive to the eyes and that the sighting eye is more heavily weighted. They also suggest that this may be the reason for the difference in reaction times between the eyes, such as that noted by Minucci & Connors (1964).

In addition to their work on sighting dominance, Porac & Coren also addressed issues relating to sensory dominance. Porac & Coren (1975) followed from Toch's earlier work in testing whether training could change the effects of sensory dominance. They used a training technique designed to alter anomalous suppressive processes, such as those linked to amblyopia. The experiment separated the monocular images with a pair of prism goggles, so no fusion was possible. Half of the observers then conducted an eye-hand coordination task which involved sorting rods into designated slots. The other half read aloud from a page of text. Following this training period, sensory eye dominance was then measured. After training, sensory eye dominance had been altered to slightly favour the non-dominant eye, although the difference in pre- and post-test rivalry dominance was not significant. The finding that training can affect dominance is important because it builds on the previous findings of Toch (1960). The only difference between the two studies is that Porac & Coren (1975) used a much longer training time than Toch, indicating that considerable effort might be needed to overcome the effects of dominance arising from rivalrous viewing conditions.

While the studies of Toch (1960) and Porac & Coren (1975) hint that sensory dominance may not be a fixed quantity, a more concrete example of this comes from a study conducted by Leat & Woodhouse (1984). They briefly presented rivalrous stimuli at various locations in both sides of the visual field and asked observers to report which eye's view was dominating their binocular percept. They found that sensory dominance could easily change depending on where these briefly flashed stimuli were presented in the visual field. However, there was no consistent effect of field location. Some observers showed right eye dominance with stimuli presented in the right visual field, while others showed right eye dominance with stimuli presented in the left visual field. This effect almost entirely disappeared when the stimuli were continuously presented and there was no effect of visual field location on eye dominance. Unfortunately, Leat & Woodhouse could not provide a reason why sensory dominance should change based on visual field location, but do show that extensive training may not be required to alter the effects of dominance.

The egocentre and the dominant eye

Following the much earlier work of Charnwood (1949) and Francis & Harwood (1952), several studies addressed the issue of whether their evidence of an apparently moving dominant eye was evidence of a shifting centre of visual direction. This became possible following several studies that were conducted to locate the centre of visual direction, herein referred to as the egocentre (Barbeito & Ono, 1979; Mitson, Ono & Barbeito, 1976). The most appropriate method for locating the egocentre will be discussed in more detail in Chapter 4.

Barbeito (1981) determined both the location of the egocentre and the sighting dominant eye in his observers. He found that the egocentre tended to be located slightly off the midline, towards the sighting eye. This led him to conclude that the sighting eye is little more than a residual effect of a non-centrally located egocentre. This result is also supported by Porac & Coren (1986) who presented observers with a point of light and asked them to adjust it until they perceived it as being located straight ahead. They found that those who sighted with their left eye tended to have a leftward bias in straight ahead, while those who sighted with their right eye had a rightward bias. This suggests that the reference point for their judgement is displaced towards the sighting eye, agreeing with the findings of Barbeito (1981).

Barbeito also contributed to a study that attempted to determine if the egocentre is located in the sighting eye (Ono & Barbeito, 1982). Using the hole-in-card test, as described by Crider (1944), Ono & Barbeito presented a range of results. When the hole in the card was aligned with the sighting eye when viewing a distant target, the target appeared to be located on a visual axis collinear with an egocentre located directly between the eyes. They also reported that when observers were asked to bring the card up from their left to perform the sighting task, they tended to use their left eye to sight through the hole. Similarly, when the card was brought up from their right, observers tended to sight through their right eye. These results show that the egocentre is not located in the sighting eye and also suggest that sighting dominance can vary depending on the specific viewing conditions. Other studies that have investigated the apparent movement of the egocentre will be discussed in the last section of this chapter.

The findings of Charnwood (1949) and Francis & Harwood (1952) were tested directly by Mansfield & Legge (1996). Observers viewed two Gabor patches, presented stereoscopically, which were vertically separated. The upper Gabor had differing contrast levels in each eye, while the lower Gabor maintained an equal contrast ratio in the eyes. When asked to vertically align the patches by moving the lower Gabor, observers tended to favour the eye with the higher contrast. For example, if the upper Gabor had a higher contrast in the right eye, observers would tend to align the lower Gabor to the right of the upper Gabor. This suggests that eye dominance is being shifted towards the eye with the higher contrast, echoing the findings of Charnwood and Francis & Harwood.

The 21st century view of eye dominance

Definitive evidence for a moving sighting eye was provided by Khan & Crawford (2001), which has already been dealt with above. Therefore, attention will now be paid to those studies that followed Khan & Crawford's important result. Khan & Crawford themselves provided supporting evidence for their 2001 study with a follow-up in 2003 (Khan & Crawford, 2003). A diagram of the task used and their main results are shown in Figure 1.2.

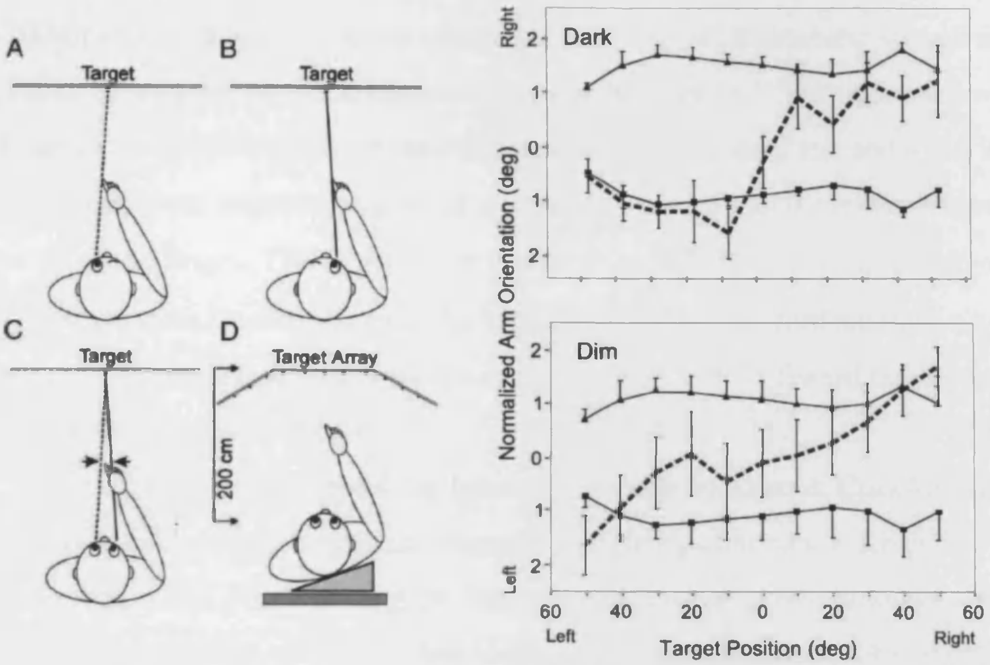

Figure 1.2: The task and data from Khan & Crawford (2003)
The left panel shows the task used by Khan & Crawford. Observers completed left eye monocular data (A), right eye monocular data (B) and binocular data (C) collection. D shows the target array used and also shows the wedge-shaped board designed to aid observers with the pointing task. The right panel shows Khan & Crawford's data. The dotted line represents the binocular data and the solid lines represent monocular data. Left eye data are shown with square points, right eye data with triangular points. The target position is shown on the horizontal and the normalised arm orientation shown on the vertical. All orientation data were normalised relative to the averaged pointing positions.

The task used for this study, which did not involve observers reaching out and grasping rings, is shown in the left hand panel of Figure 1.2. Here, observers were required to point at illuminated targets which were presented at 10° intervals in a 100° arc around the participant, during both darkness and dim lighting conditions. The judgement was based on the assumption that the tip of the finger should coincide with the line of sight of one eye in order for it to be perceived as pointing directly at the target (following from cyclopean eye theory, as summarised by Ono, 1991) and so this new judgement still acts as a test of sighting dominance. The results showed that observers did not align their fingertip precisely with the line of sight of one eye, but that they produced a continual shift between the eyes. They aligned with a point close to the left eye for leftward targets, a point between the eyes for straight ahead targets and with a point close to the right eye for rightward targets, as shown in the right hand panel of Figure 1.2. This result is compatible with those of Charnwood (1949) and Francis & Harwood (1952) in that the results indicate that the viewpoint is moving between the eyes.

Further support for Khan & Crawford's results is also provided by Quartley & Firth (2004) who used three different eye dominance tests with eccentric stimuli and found the effect of gaze direction reported by Khan & Crawford. The tests used were taken from Crider (1944) and were the Miles test, the hole-in-card test and a test in which observers were required to point at a target and report which eye was aligned with the tip of the finger. The targets were placed in an 80° arc in front of observers, with a 10° separation between targets. As with the Khan & Crawford studies, Quartley & Firth found that observers favoured the left eye for leftward targets and the right eye for rightward targets.

Quartley & Firth also report the speculation made by Khan & Crawford (2001) as to what is responsible for triggering changes in sighting dominance. Khan & Crawford identify two possible triggers. One is the difference in retinal image sizes that occurs with eccentric viewing; when viewing an eccentric object, the eye closer to the object will have the larger image. In this case, the eye with the larger image should be treated as sighting dominant. The other possible trigger, and the one favoured by Khan & Crawford, is eye position cues to horizontal version. In this case, when the ocular feedback shows that the eyes are pointing to the side, the eye on the corresponding side of the median plane will be treated as sighting dominant. Although they favour gaze direction as a trigger, their study is unable to provide sufficient evidence that only eye position signals are responsible for dominance switching.

Following from the Khan and Crawford studies, Banks, Ghose & Hillis (2004) devised an experiment designed to determine which of the two possible triggers for dominance switching was being used by the visual system. They independently manipulated retinal image size and horizontal eye position using a custom stereoscope (see Backus, Banks, van Ee & Crowell (1999) for a description of the apparatus used) and also used a purely perceptual task, rather than one involving reaching and grasping (Khan & Crawford, 2001) or pointing (Khan & Crawford, 2003). Figure 1.3 shows their stimuli and results.

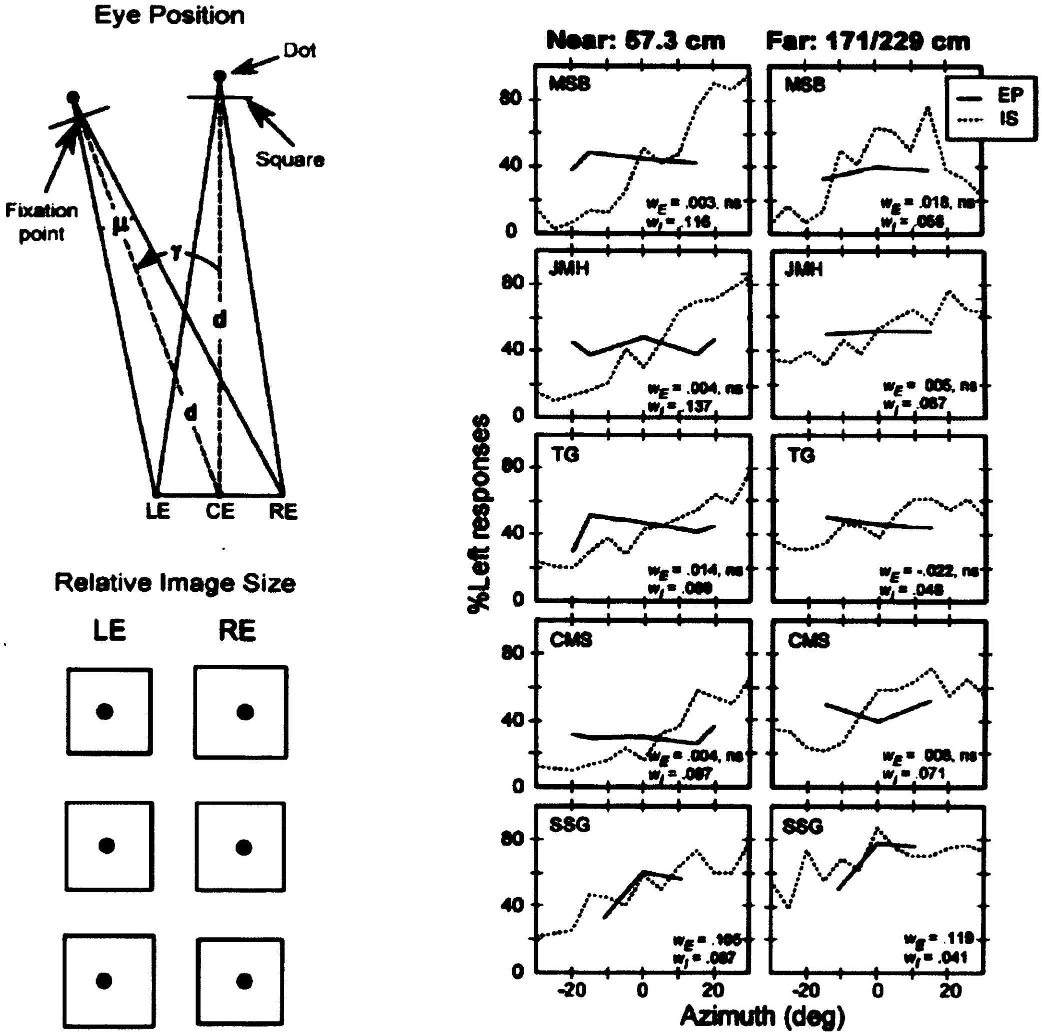

Figure 1.3: The apparatus and data from Banks, Ghose & Hillis (2004)
The left panel shows a plan view of the eye position manipulation in the upper half and the image size stimuli in the lower half. For the plan view, d is the fixation distance, μ the vergence measure and γ the version. The left, right and cyclopean eyes are denoted by LE, RE and CE respectively. The stimuli show the corresponding change in image size for 20° to the right (top row), straight ahead (middle row) and 20° to the left (bottom row). Diverge the eyes to fuse the stimuli.
The data show the percentage of 'leftward' responses against the azimuth (leftward azimuth is positive), for two different fixation distances. The dotted lines show azimuth designated by image size, while the solid lines show azimuth designated by eye position signals. The numbers inside each plot denoted the weights on eye position (w_E) and image size (w_I) in the linear combination $L(E,I) = w_E E + w_I I + k$, where E, I and k represent eye position, image size and a constant bias respectively.

The upper left panel of the figure shows how the stimuli were presented in depth, with a frame centred on a dot projected behind the plane of the frame. This means that the left eye views the dot towards the left of the frame and the right eye views the dot towards the right of the frame, as shown in the lower left panel of Figure 1.3. Observers were asked to indicate where they perceived the dot to be located relative to the frame. As Figure 1.3 shows, if the left eye dominated the percept, the dot would appear towards the left side of the frame. Similarly, a dominant right eye causes the dot to appear towards the right of the frame. The right hand panel of Figure 1.3 shows that when azimuth is designated by image size cues, the number of 'leftward' responses consistently increases as the image cues suggest an azimuth changing from rightward to leftward. Therefore, observers did change dominance between the eyes due to changes in retinal image size, i.e. a larger left eye image corresponded to left eye dominance. Changes in horizontal eye position had little effect on dominance. This would seem to suggest that image size is solely responsible for changes in dominance. However, it is debatable which form of dominance this result is linked to. The task used by Banks, Ghose & Hillis (2004) used dichoptic stimuli which were fused into a single image. According to Ogle (1962) and Sheedy & Fry (1979), the perceived direction of the binocular image should be closer to one of the monocular images than the other. The eye viewing this preferred monocular image is considered as dominant. This form of dominance may not exactly match up to any of the three types of dominance, but it still involves a preference for one eye over the other and hence the findings of Banks et al. (2004) should still be described in terms of eye dominance.

Another study which showed evidence of the visual system adapting to favour the eye which provided the most visual data was one conducted by Meegan, Stelmach & Tam (2001). They presented observers with stereoscopic images where one of the images was degraded, either by blurring or pixilation (chosen to simulate the results of image compression). When asked to match the blurriness or pixilation of the test image, there was a clear difference between which monocular image the match image was closest to. When one image was blurred, observers adjusted the match image to closely resemble the clearer monocular image. However, when one image was degraded into blocks, the match image was closest to the blocky image. This led Meegan et al. to conclude that observers tended to prefer the eye that gave the most visual information since a blurred image removes high spatial frequency information and degrading an image into blocks increases the number of contours and, therefore, increases the amount of contour information. This would seem to agree with the findings of dominance switching studies that indicated dominance was changed to the eye that could provide the most data to the visual system.

Given the importance of Khan & Crawford's claims, it is perhaps surprising that only the Quartley & Firth (2004) and Banks et al. (2004) studies have directly addressed the issue of dominance switching. The latest studies concerning eye dominance are embroiled in the debate about how the various types of dominance relate to one another, with several studies tackling the relations between the various types of dominance and how dominance relates to other visual phenomena (Ehrenstein et al., 2005; Handa et al., 2004; Pointer, 2007).

Ehrenstein, Arnold-Schulz-Gahmen & Jaschinski (2005) used standard optometric tests to measure visual characteristics such as visual acuity, eye dominance and stereoscopic prevalence (a directional bias towards one eye in fused images – see below). They found a correlation between sighting dominance and stereo prevalence, but no correlation between sighting dominance and acuity dominance or other related measures such as accommodation.

The lack of correlation between the sighting eye and the eye with better acuity has previously been reported by Coren & Kaplan (1973) and recently reported in a literature review by Pointer (2007). The finding that stereo prevalence correlates with eye dominance has also been supported by Kommerell, Schmitt, Kromeier & Bach (2003). They define stereo prevalence as occurring in the region of visual space known as Panum's fusional area. This is defined as the region around fixation where double images do not occur (Mitchell, 1966). Stereo prevalence can occur when two stereo objects are presented vertically with the upper image behind fixation and the lower image in front of fixation. If the images do not appear to be vertically aligned, then one eye is has prevalence over the other. Hence, in order for the images to appear vertically aligned, the lower image must be displaced towards one eye. This eye is defined as the prevalent eye. Kommerell et al. used a variant of this stimulus to measure eye prevalence. They also measured sighting dominance with the Miles test. They found that the prevalent eye matched the dominant eye in three quarters of observers tested.

The link between sighting and sensory dominance was addressed by Handa, Mukuno, Uozato, Niida, Shoji & Shimizu (2004). They determined sighting dominance with the hole-in-card test and sensory dominance by presenting observers with rivalrous stimuli and determining the length of time one stimulus dominated the percept. They found a strong correlation between the sighting eye and the sensory dominant eye.

In addition to these studies, Valle-Inclán, Blanco, Soto & Leirós (2008) developed a novel method of determining eye dominance. They presented observers with streams of letters, with a different stream presented to each eye. Observers were asked to report the appearance of a target letter or number within the stream. The target would be randomly placed within the tail of one stream and to a randomly chosen eye. The results showed that observers only perceived one letter for each position in the stream. When the target was presented to one particular eye, it would be correctly identified but, if it was presented to the other eye, it was generally missed. The eye that detected all targets presented to that eye is classed as dominant. This test refines the tests for sensory dominance and the results are also highly correlated with sighting dominance, further evidence for a high correlation between sighting and sensory dominance.

Further considerations of eye dominance

A concept that must be considered when carrying out any investigation of eye dominance is the existence of several forms of eye dominance. These forms of dominance were primarily identified by Coren & Kaplan (1973) who collected eye dominance data from thirteen different dominance tests and carried out a factor analysis on the results. They found evidence for three different types of dominance - sighting dominance, sensory dominance and acuity dominance.

Sighting dominance has by far the most tests associated with it (Crider, 1944; Miles, 1929; Miles, 1930). These tests involve either choosing an eye for monocular viewing or unconsciously aligning objects with one eye. Sighting dominance also occurs during convergence where only one eye tends to consistently foveate an object approaching the face (Coren & Kaplan, 1973). Therefore, sighting dominance is the form of dominance most likely to be encountered during day-to-day viewing, especially for activities that require monocular viewing such as using microscopes, rifle shooting or even accurately converging on an approaching object in order to intercept or avoid it. Because of the wide familiarity with sighting dominance situations, it is understandable that it is often taken to be the ‘definitive’ type of eye dominance (Mapp et al., 2003; Porac & Coren, 1976). It is also the form of dominance that is most easily measurable. An experimenter needs only ask an observer to peer through a pinhole to determine sighting dominance (Crider, 1944).

In contrast to sighting dominance, sensory dominance is specific to situations involving binocular rivalry (Coren & Kaplan, 1973). Under these conditions, the monocular views are highly discrepant. With continued viewing, the monocular views will alternate in the percept, with one view being present for a longer time than the other. The eye that produces the longer-lasting monocular image is considered to be dominant. Therefore, sensory dominance can be determined by comparing the length of time each monocular view lasts in the binocular percept (Cohen, 1952; Coren & Kaplan, 1973). Therefore, tests for sensory dominance require stimuli designed to promote binocular rivalry, or some other external manipulation, such as reducing the luminance in one eye (this manipulation is central to the experiments in the next chapter). It is also clear that sensory dominance is not encountered on a daily basis, as can be argued for sighting dominance, but only manifests in specific situations, such as those caused by the prolonged reduction of clear vision in one eye or when objects are placed closer to the face than the near point of convergence. This suggests that sensory dominance is not simply another facet of sighting dominance, but a distinctly different type of dominance.

The third type of eye dominance, acuity dominance, also seems to be markedly different from the other forms of dominance. As the name implies, acuity dominance refers to differences in visual acuity between the eyes. In this situation, the eye with the higher acuity is considered to be dominant and can be measured using standard acuity tests. Coren & Kaplan (1973) showed that this form of dominance is invoked in tests involving situations in which stimuli are degraded in some way, such as being difficult to resolve or very briefly flashed. The concept of acuity dominance can also be extended to conditions in which clarity of vision in one eye is markedly reduced compared with the other, such as amblyopia (Porac & Coren, 1975), or situations in which one eye is more short-sighted (myopic), or long-sighted (hyperopic), than the other. Therefore, acuity dominance is rooted in the physiology of the eyes, since acuity is determined by the efficiency of connections between the eye and the brain (Bruce et al., 1996) and myopia and hyperopia determined by the physical dimensions of the eyeball (Blake & Sekuler, 2006). Therefore, acuity dominance can affect everyday tasks, particularly those requiring close-up work, but becomes truly important when there is a marked difference in acuity between the eyes, such as occurs due to ocular diseases such as macular degeneration or due to the presence of cataracts.

The physiological basis for acuity dominance marks it out as different from the other forms of eye dominance, since both sighting and sensory dominance tend to manifest in situations due to some external manipulation or behaviour requirement and may both be able to alter between the eyes. For example, Khan & Crawford (2001) reported that sighting dominance changes as a function of gaze direction and the results of Meegan et al. (2001) indicate that sensory dominance could change depending on the manipulation performed on one of the two monocular images. Clearly, it would be nearly impossible for the connections between the brain and the eye to be re-wired in response to external manipulations. It would be a similarly impossible feat to change the dimensions of the eyeball based on external factors. Therefore, it is logical to assume that acuity dominance must be a fixed quantity and could not change at the behest of some external force.

However, the distinction between the three types of dominance may not be as clear-cut as it appears. For example, consider acuity and sensory dominance. Both types of dominance involve situations in which the monocular images do not match, either because one cannot be resolved as clearly as the other or because they are markedly different. If presentation time is short, the difference in acuity between the eyes is responsible for deciding dominance. However, over prolonged exposure periods, whichever monocular view dominates the percept decides dominance. Therefore, acuity and sensory dominance could be related somewhat. For example, if the vision in one eye is blurred so as to reduce acuity, this should induce a form of eye dominance into the visual system. If the difference in acuity between the eyes is small, then the eye with the higher acuity should be treated as dominant, by the definition of acuity dominance. However, if the difference in acuity is large enough to render the monocular views highly discrepant, then, by the definition of sensory dominance, whichever view dominates the percept for the longer time represents the dominant eye. This may, or may not, be the eye with the higher visual acuity. This suggests that acuity and sensory dominance, while not being directly correlated, exist at either end of a single spectrum. Acuity dominance represents the natural, physiological differences in vision between the eyes that determine dominance. If some external manipulation is made to alter the differences in vision between the eyes, then the mechanism for determining the dominant eye is 'pushed' towards the sensory dominance end of the spectrum. One possibility could be to think of renaming acuity and sensory dominance as intrinsic and extrinsic dominance respectively in order to emphasise that they are elements of the same scale, with one able to 'bleed' into the other based on external circumstances.

The above discussion of acuity and sensory dominance may make out that sighting dominance is completely independent of the other forms of eye dominance. However, consider stereo prevalence (Kommerell et al. 2003) in which the directions in a fused image are biased towards aligning with one eye. This situation has elements of sighting dominance (alignment with one eye) and sensory dominance (preference for one monocular image over the other) and, as such, stereo prevalence could be described as the illegitimate offspring of these two forms of dominance. This shows that, while sighting dominance may not lie on the same spectrum as acuity and sighting dominance, the three types of dominance are not as distinct from one another as Coren & Kaplan (1973) suggest.

Reviewing related issues

As the above literature review shows, investigators have approached the issue of eye dominance in a variety of ways. Although this thesis is primarily concerned with how eye dominance changes within a task, several other concepts related to eye dominance have relevance in the forthcoming chapters. These concepts will be considered here in more detail.

Chapter 2 and, later, Chapter 4 focuses on the effects of stimuli which are physically located to the side of the head. As pointed out by Khan & Crawford (2001) and Banks, Ghose & Hillis (2004), an eccentrically placed stimulus provides two cues to its location. One is the 'felt' eye position given by feedback from the ocular muscles. The other is retinal image size differences, with the eye closest to the stimulus having the larger retinal image. As outlined in the previous section, Banks et al. (2004) concluded that it was the difference in retinal image sizes that provided a cue to changing eye dominance. However, a stimulus with unequal image sizes in the eyes can appear slanted to observers (Kaneko & Howard, 1996; Ogle, 1938; Pierce & Howard, 1997; van Ee & Erkelens, 1998). The question arises as to whether this perception of slant in the Banks et al. stimulus could trigger changes in eye dominance. The experiments in Chapter 3 are intended to determine the full effect slant has on response bias.

Charnwood (1949), Francis & Harwood (1952) and Mansfield & Legge (1996) also provided evidence of variable eye dominance. These studies found that observers tended to align two stimuli with a line of sight close to the eye that had the brighter, or clearer, view. Given that there are elements of both sighting (alignment of stimuli) and sensory dominance (preference for one of two discrepant images), these studies could be used to provide further support for the argument that eye dominance changes based on the amount of data available to each eye. However, they are more relevant to another area of research that has been concerned with the link between the dominant eye and the centre of visual direction, or egocentre.

The egocentre is the origin used when estimating the visual direction of one or more objects (Ono, 1991). The relation between eye dominance and the egocentre is hotly debated. Some studies (Barbeito, 1981; Porac & Coren, 1986) maintain that the relation between the two is nothing more than the egocentre being slightly displaced towards the sighting dominant eye. Other studies suggest that the egocentre lies in the sighting eye (Sheard, 1926; Walls, 1951). Furthermore, some of the studies already discussed above (primarily Charnwood (1949), Francis & Harwood (1952) and Mansfield & Legge (1996)) have argued that their results are evidence for a variable egocentre location. The theories that relate to either the egocentre being coincident with the sighting eye or that the egocentre does not have a fixed location have come in for the most criticism (Banks et al., 1997; Mapp & Ono, 1999; Mapp et al., 2003), mainly because of how the tasks used in these studies relate to the egocentre.

The issue with the theories outlined directly above boils down to the difference between what are termed relative and absolute tasks. A relative task is one that involves relating the positions of distinct objects with each other, such as aligning a distant house and a tree. An absolute task, however, involves relating the positions of distinct objects with the self. For example, imagine a situation similar to that used by Charnwood (1949) where an observer is presented with two beads separated in depth. If the observer is asked to align the beads with each other, the beads should coincide with the line for sight of one eye (the sighting dominant eye – compare this to some of the tests for dominance described by Crider, 1944). On the other hand, if the observer is asked to align the beads so that the line between them appears to be pointing directly at them, then they should align the points directly with the egocentre, not with the line of sight of one eye. Therefore, only absolute tasks can be used to indicate the location of the egocentre since the egocentre is defined as the centre of the self. Using a relative judgement to make inferences about the location of the egocentre will lead to erroneous conclusions, such as assuming the egocentre lies in the dominant eye.

The evidence of a change in egocentre position has been produced by studies which use relative judgements and tasks, not absolute ones (Charnwood, 1949; Francis & Harwood, 1952; Mansfield & Legge, 1996). In particular, Mansfield & Legge's study was taken to task by Banks et al. (1997) for confusing the two tasks and the conclusions that can be drawn from them. Mansfield and Legge's response to this criticism (Mansfield & Legge, 1997) admits that their data do not show evidence of a moving egocentre, but rather a change in what they call the effective viewpoint. This is the point of view from which relative judgements are made. Considering earlier work, the results of the studies conducted by Charnwood (1949) and Francis & Harwood (1952) also support this theory of a change in effective viewpoint. Other studies have also shown evidence of a change in effective viewpoint (Erkelens, Muijs & van Ee, 1995; Erkelens & van de Grind, 1994). These studies presented binocular stereograms to observers. These stereograms contained two lines, which could be presented binocularly or monocularly if required, and observers were asked to align these lines with each other. Both studies showed that, if one line was presented monocularly and the other binocularly, the lines were adjusted to coincide with the line of sight of the eye which viewed the monocular line. Although this type of judgement cannot be used to make inferences about the location of the egocentre, despite claims made in these studies, it does provide further evidence of effective viewpoint changing depending on viewing conditions. Furthermore, it shows that effective viewpoint changes to favour the eye which can provide the most data.

Although the notion of an effective viewpoint is an alluring one, the view that the egocentre is variable in position still lingers, as pointed out by Mapp et al. (2003). The behaviour of the egocentre under certain viewing conditions needs to be fully established in order to tackle the theory of a variable egocentre location. Chapter 4 addresses the issue of how the egocentre behaves under eccentric viewing conditions.

As this discussion has shown, eye dominance is a widely studied topic and the findings that it is not a fixed quantity clearly need further investigation. In each of the following chapters, the results of the three main sighting dominance studies will be investigated. The results should determine if all types of dominance are variable, or if it is only a subset of these which can be affected within a specific task.

Chapter 2

Eye dominance and reaction time: changing sensory dominance

The experiments outlined in this chapter make use of the effect of luminance on reaction time to investigate whether the claim made by Khan & Crawford (2001) that sighting dominance changes as a function of eccentricity can be generalised to other forms of eye dominance. As has been discussed in the previous chapter, acuity dominance should not change with eccentricity and, therefore, the following experiments will investigate if sensory dominance is affected by eccentric viewing. Sensory dominance arises in situations in which highly discrepant images are presented to the eyes and one eye comes to dominate the binocular percept. In the following experiments, the discrepant images will be created by reducing the luminance in one eye and measuring the time taken to react to the motion of a stimulus. If sensory dominance can be affected by gaze direction, as reported for sighting dominance by Khan & Crawford (2001), then changes in gaze direction, when combined with differing luminance levels between the eyes, should change the pattern of reaction times accordingly.

A reaction time task allows for a straightforward measure of the effect of sensory dominance. Asking observers to estimate how long a particular image dominates their binocular percept is a measure of sensory dominance, but is open to an element of bias on the part of observers. In contrast, a reaction time task involves judgements that are much more instantaneous and, therefore, less susceptible to any bias. However, some consideration must be given to what type of reaction time task is used. The two possible types of reaction time task are reaction to a flashed stimulus and reaction to motion onset. Only reaction to motion onset is appropriate for an investigation of sensory dominance since, as discussed in the previous chapter, sensory dominance is a factor in situations involving binocular rivalry. Therefore, observers should be able to view the stimulus for enough time in order to allow sensory dominance to develop due to the binocular rivalry in the stimulus, caused by the difference in luminance between the eyes. Clearly, a task that involves reaction to a flashed stimulus will not allow enough time for sensory dominance to fully develop (and, since the presentation of the stimulus is brief, more likely to be governed by acuity dominance rather than sensory). Therefore, a reaction to motion onset is appropriate since the motion can be delayed while binocular rivalry, and therefore sensory dominance, fully develops.

Before considering the effects of sensory dominance and gaze direction, it is necessary to consider the effect of reducing luminance on reaction time. First, consider the situation in which the luminance is equal in both eyes. In this situation, monocular reaction times tend to be longer than, or equal to, binocular reaction times (Minucci & Connors, 1964; Ueno, 1977; although an exception was noted by Teichner & Krebs, 1972). In particular, Ueno (1977) found that monocular reaction times (with flashed stimuli) were slower than binocular reaction times for varying levels of luminance. This is because, when monocular images are combined, the increase in information reduces the binocular reaction time.

Now consider a situation in which one eye's image is reduced in luminance. This will increase the monocular reaction time associated with that eye since reaction time is inversely proportional to luminance (Becker, Vontheim, Volpe & Schiefer, 2005; Burr & Corsale, 2001; Schiefer, Strasburger, Becker, Vontheim, Schiller, Dietrich & Hart, 2001). It then follows that the binocular reaction time will increase in proportion with the monocular reaction times, due to the summation of monocular information. If it is assumed that both eyes are treated equally during summation, then it should not matter which eye is reduced in luminance since the effect on binocular reaction time will be the same in both cases. Hence, this is an equilibrium point and indicates neither eye is given more weight than the other. However, as soon as one eye is weighted more than the other, the binocular reaction time will move away from equilibrium and will increase or decrease, according to whether the more heavily weighted eye is reduced in luminance or not.

As defined above, sensory eye dominance causes the image in one eye to dominate the binocular percept more than the image in the other eye. Therefore, when one eye is reduced in luminance, sensory dominance can upset the equilibrium between the eyes and affect binocular reaction times. How sensory dominance should affect reaction times is shown in Figure 2.1.

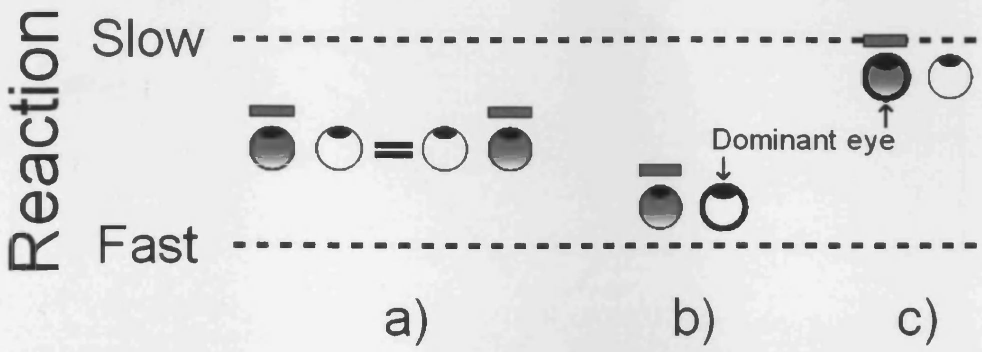

Figure 2.1: The relation between sensory dominance and reaction time.
The figure accompanies the example given in the text. The equilibrium point where both eyes are weighted equally is shown at a). Here, reaction is constant no matter which eye is reduced in luminance. For parts b) and c), the dominant eye is shown with a thicker outline. In b), the high luminance eye is dominant and the binocular reaction time is shorter than equilibrium. A similar reasoning applies to b) where the low luminance eye is dominant.

2.1a shows the point of equilibrium, described above, where both eyes are treated equally. Clearly, in this situation, it does not matter which eye has reduced luminance. Now consider 2.1b. Here, the eye which is treated as sensorially dominant has a higher luminance than the other eye. Since the dominant eye contributes the most information to the visual system, it has the greatest effect on binocular reaction time. Hence, the reaction time is shorter than the equilibrium case. Conversely, 2.1c shows the case where the sensory dominant eye has been reduced in luminance. Therefore, since a reduction in luminance increases reaction time, the time to react is longer than the equilibrium case.

As the above figure shows, when one eye is reduced in luminance, sensory dominance directly affects reaction time in a measurable way. This now allows the generality of the dominance switching theory, proposed by Khan & Crawford (2001), to be tested. This will be done by reducing one eye in luminance and measuring the time taken to react to the onset of motion in stimuli which are presented at an eccentric gaze angle. If sensory dominance changes, as Khan & Crawford claim sighting dominance does, then it should present the pattern of results shown in Figure 2.2.

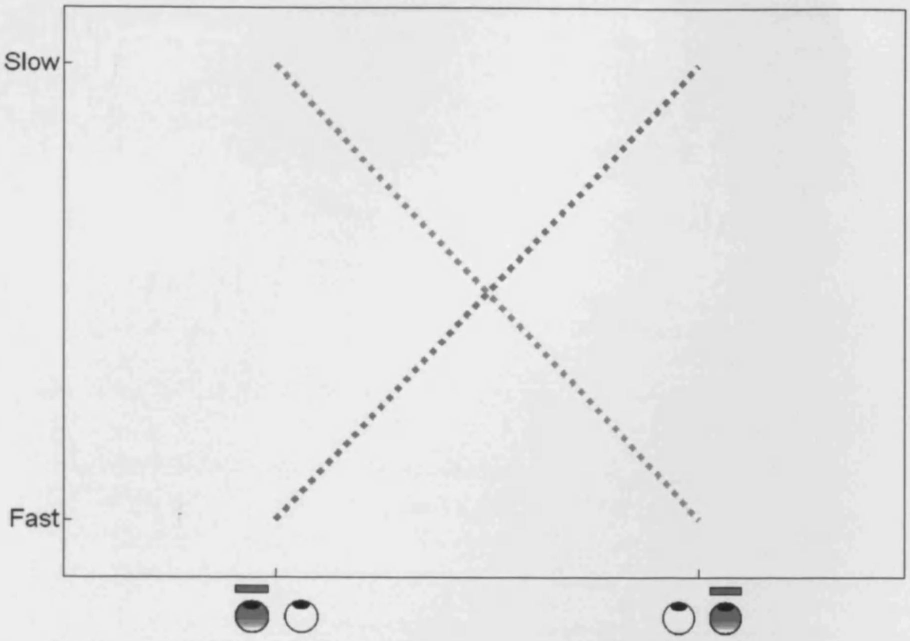

Figure 2.2: Sensory dominance changing with gaze direction
The green curve shows the predicted data when gaze is directed to the left. Similarly, the red curve shows the predicted data for rightward gaze. The luminance conditions are shown along the horizontal axis, with reaction speed along the vertical.

When gaze is directed to the left, as shown by the green curve in Figure 2.2, the left eye is assumed to be sensory dominant. So when the left eye is reduced in luminance the reaction time is longer than when the right eye is reduced in luminance, as explained in Figure 2.1. Similar reasoning shows that when gaze is directed to the right, shown in red in Figure 2.2, reaction times will be shorter when the left eye is reduced in luminance. Therefore, if sensory dominance changes with gaze direction, it should produce the curves shown in Figure 2.2, i.e. an interaction between luminance and gaze direction should be evident.

Method

Observers

Six observers originally participated in the study. All were postgraduates in the School of Psychology, Cardiff University and had normal, or corrected to normal, vision. One observer was the author, the rest were naïve as to the purpose of the experiment. All had prior experience as psychophysical observers.

Stimuli and apparatus

The stimulus used was a laser dot projected onto a semi-circular screen directly ahead of observers at a distance of 0.8m. The laser dot subtended a visual angle of 4.3x8.6 arcmin. The laser emitter was situated above and behind the participant and emitted a 670nm beam with an average power of 3mW (class 3B) through a polarising lens, placed close to the point of origin of the laser beam. The emitter was controlled by a computer program.

To change luminance between the two eyes, observers wore a modified spectacle frame with a polarising lens placed over the appropriate eye, while the other eye was left uncovered. This lens reduced the luminance to around 27% of the normal luminance. The magnitude of this reduction in luminance was measured with a photometer. The head was kept stationary with a chin and forehead support. All reaction time trials were performed in a darkened room with the laser point as the only source of illumination.

At the start of each condition block, observers were asked to fixate a stationary laser spot presented at the relevant eccentricity for that condition. Once the spot was fixated, the observer initialised the first trial with a button press. The fixation spot was extinguished and the test spot appeared after an interval of 1s. The test spot remained stationary to allow sensory dominance to fully develop, as outlined above, before moving vertically either up or down. Observers were required to indicate with a button press the direction of motion as soon as they perceived the dot to be moving. Once the response was made, the spot was extinguished for 1s before the next trial began.

Procedure

Stimuli were presented at ±25° eccentricity to the head (a negative eccentricity denotes leftward gaze). Observers were required to react to the onset of vertical stimulus motion. Five stimulus speeds were used to ensure, firstly, that any effect of speed on reaction time did not interact with the effects of gaze or luminance and, secondly, that none of the speeds produced a ceiling effect. The speeds used ranged from 3.2°/s to 16°/s in 3.2°/s intervals. The stimulus motion was in the upwards or downwards directions, split evenly for each condition block, but in a random order. The motion began after a random interval of 1s ± up to 200ms for each trial.

The luminance conditions used were Low/High in which the left eye was reduced in luminance and High/Low in which the right eye was reduced in luminance. Gaze direction was combined with the luminance conditions to yield four experimental conditions. For binocular data collection, observers performed 100 trials for each condition block, with 20 trials for each stimulus movement speed, and carried out each condition block once per experimental session. Three sessions were completed for each observer, for a total of 300 trials per condition with 60 trials to each data point.

Monocular data were also collected, primarily to ensure reaction time did change as a function of luminance. Observers repeated the conditions used in the binocular trials, with either their left or right eye covered, for a total of eight possible conditions. As with the binocular trials, observers performed 100 trials for each condition block, over three sessions, for a total of 300 trials per condition with 60 trials to a data point.

Results

Before analysing the data, outlying reaction times below 100ms or above 600ms were removed, in line with previous research (Becker et al., 2005; Schwarz, 2006). In addition to these removals, any incorrect responses were also removed prior to data analysis.

Figure 2.3 shows that reaction time changes as a function of luminance. The monocular data are shown for the six observers, collated according to stimulus speed and viewing condition for each observer, with the median reaction time for each observer and condition being collated. The medians were taken to prevent any large skew in the reaction time data from affecting the results.

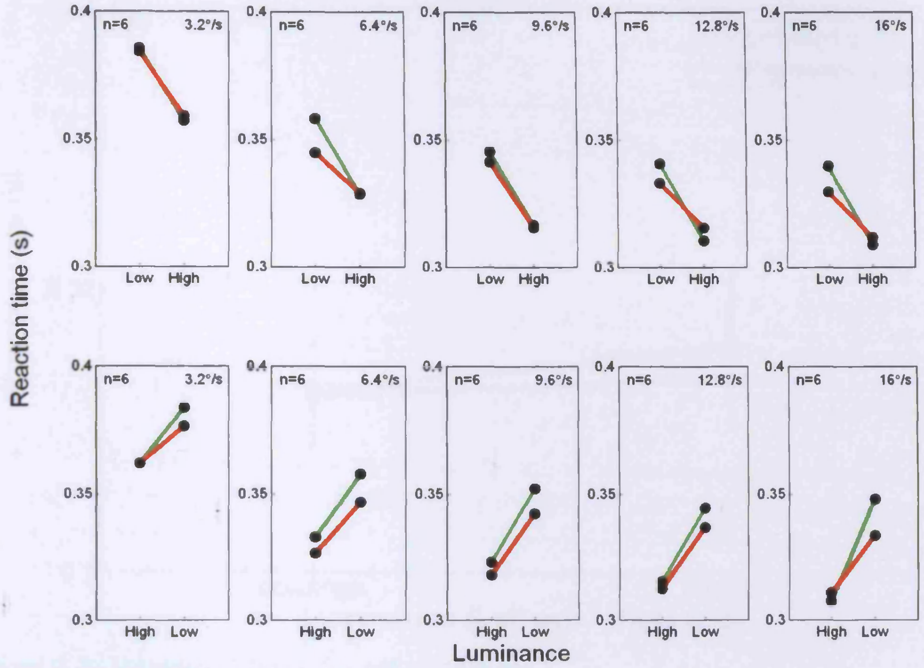

Figure 2.3: The effect of changes in stimulus speed on reaction time.
The upper row of plots present the left eye data, with the right eye data presented in the lower row. The luminance conditions are plotted on the horizontal (with L/H representing the Low/High condition and H/L representing the High/Low condition) and median reaction times on the vertical. All data are averaged across observers, with the green line denoting leftward gaze and the red line denoting rightward gaze. The relevant stimulus speeds are shown in the upper right hand corner of each plot.

These data show that reaction times change as both a function of stimulus speed and luminance, showing that reaction time is affected by luminance, as expected, and that no ceiling effect occurred with any of the presented speeds. A 5x2x2 within-subjects ANOVA on the left eye data showed a significant effect of speed ($F(4,20) = 108.82$, $p < 0.01$) and luminance ($F(1,5) = 103.21$, $p < 0.01$) but no interaction ($F(4,20) = 0.35$, $p = 0.84$). The same was true for the right eye data: the effect of speed was significant ($F(4,20) = 106.46$, $p < 0.01$) as was luminance ($F(1,5) = 73.30$, $p < 0.01$) with no interaction ($F(4,20) = 2.44$, $p = 0.08$). Since there are no interactions relating to stimulus speed, reaction times were collapsed over speed in the following analysis. Figure 2.4 shows these data for the binocular conditions.

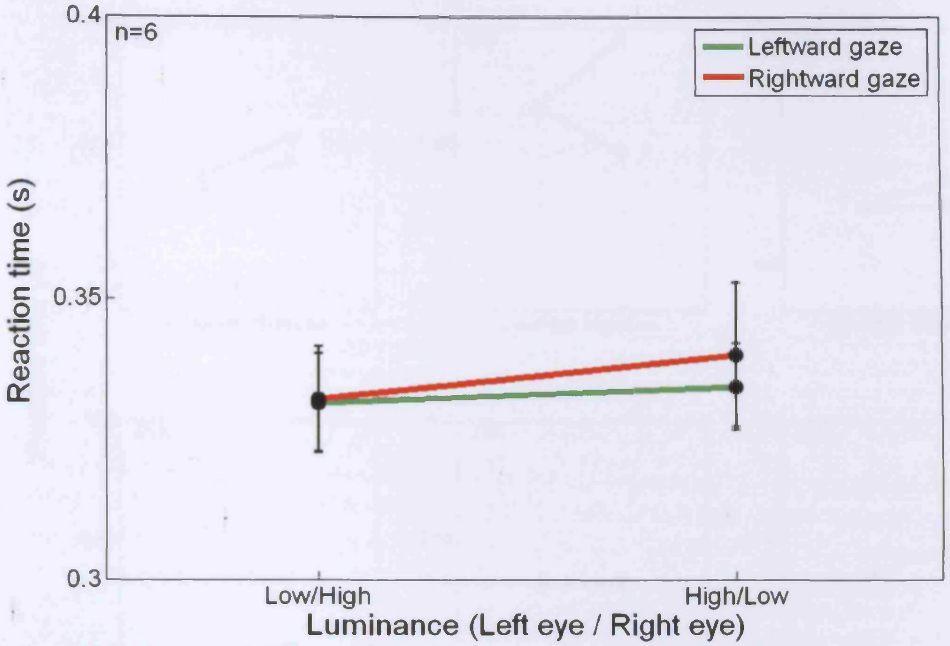

Figure 2.4: Reaction times for all observers
The reaction times, averaged as discussed in the text, are plotted here for all observers. The luminance conditions are shown on the horizontal axis, with reaction times along the vertical. All error bars denote standard errors.

If eye dominance depends on gaze, then an interaction between luminance and gaze direction, as depicted in Figure 2.2, would be expected. The data in Figure 2.4 strongly suggest that this is not the case. A 2x2 within subjects ANOVA revealed no interaction ($F < 1$). Furthermore, there is no significant effect of gaze direction ($F < 1$), but a significant effect of luminance ($F(1,5) = 7.51$, $p < 0.05$). The shape of the curves suggests a preference for one eye over the other in both gaze conditions. If both eyes were favoured equally, the curves should be horizontal. As it is, they are tilted such that there is a shorter reaction time when the right eye has a high luminance, but a slow reaction time when the right eye has low luminance. Therefore, this suggests that the right eye is strongly favoured in both gaze conditions. This could indicate that observers are simply favouring the right eye irrespective of experimental manipulation. However, the large ranges of the error bars for the binocular data suggest a large variation between observers. Figure 2.5 shows the individual binocular data.

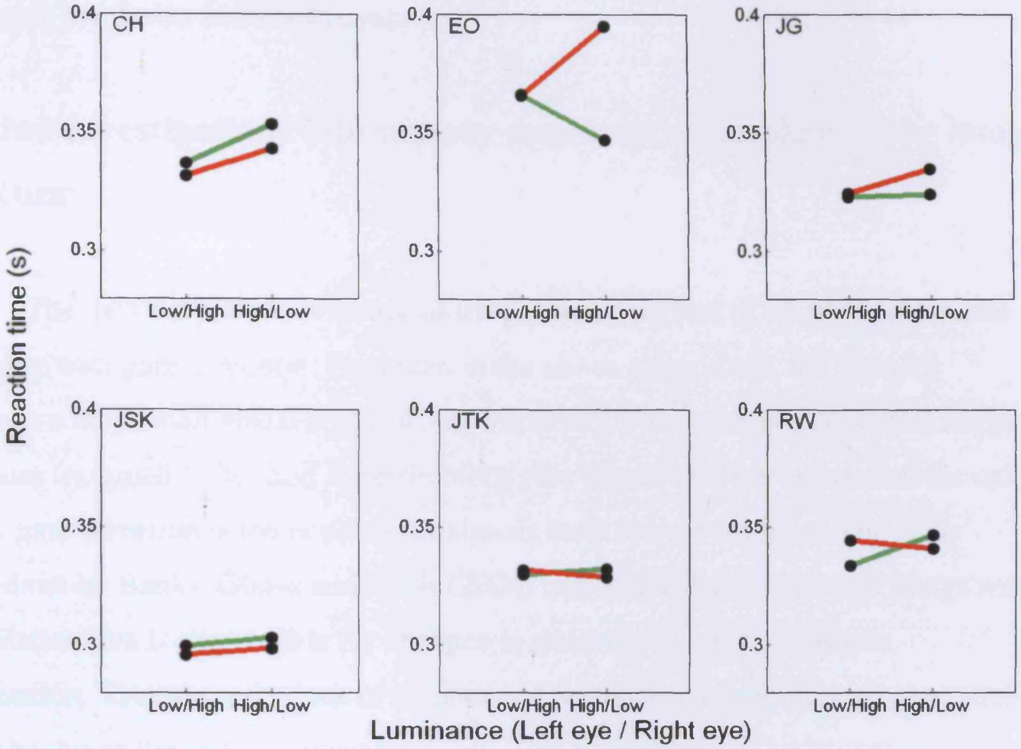

Figure 2.5: Individual reaction time data
The binocular reaction times are plotted here for each observer. As with Figure 2.4, the green and red lines denote leftward and rightward gaze respectively. The luminance conditions are shown on the horizontal axis, with reaction times along the vertical.

As the figure shows, there is large variation in reaction times between observers. Only observer CH seems to show a definite preference for the right eye, while observer JG shows a pattern almost identical to the averaged data in Figure 2.4. Observers JTK and RW show evidence of a crossed interaction, but one that is opposite to that shown in Figure 2.2. This could suggest that they have a reversed switching mechanism, but could also simply be a slight variation away from a horizontal relation, such as that shown by observer JSK. Observer EO shows a strong effect of gaze direction, so it is likely this observer compensates for the data of observers JTK and RW in the averaged plot.

Looking at the individual data shows a large variation, with only one observer showing a strong effect of gaze direction. Assuming observers JTK and RW are simply showing variations on the pattern shown by JSK would suggest that sensory dominance does not easily change with gaze direction. Furthermore, the patterns shown by observers JSK, JTK and RW would suggest either that sensory dominance is most likely switching to the higher luminance eye or that these observers are averaging the inputs from both eyes.

Further investigations into sensory dominance – implementing image size cues

The data show little evidence of the predicted pattern of sensory dominance changing with gaze direction. However, in the above experiment, the stimulus subtends a very small visual angle (4.3x8.6 arcmin). This renders any overall image size cues too small to be used for estimating gaze direction. This means that the only cue to gaze direction is the oculomotor signals from the eye muscles. The study carried out by Banks, Ghose and Hillis (2004) concluded that it is overall image size information that is responsible for changes in dominance, not eye position information. Therefore, the lack of evidence of dominance changing with gaze angle could be due to the lack of image size cues. This was addressed by increasing the size of the stimulus to provide useable image size information.

Method

The apparatus and experimental conditions used in this experiment were similar to the first experiment, save for the following changes:

Observers

All six of the observers who contributed data to the first experiment took part.

Stimuli and apparatus

The stimulus used was an open circle of 17.3 arcmin diameter. Due to the technical constraints of the laser apparatus, this circle was drawn at 100 revolutions per second. This velocity was not sufficient to draw the circle with a solid line. Instead, the circle appeared as a ring of dots rotating anticlockwise around the circle at a rate of 160 revs/sec. These dots continued to rotate around the circle as the stimulus moved vertically, as in the previous experiment.

Procedure

This setup used only two vertical stimulus speeds. These were 6.4 and 12.8°/s. The luminance conditions were not changed, but the reduction in speeds meant that observers performed 40 trials for each condition block with 20 trials for each vertical movement speed. Three sessions were completed for each observer, for a total of 120 trials per condition with 60 trials to each data point.

Results

As with the previous set of data, all outlying reaction times below 100ms or above 600ms and any incorrect responses were removed prior to data analysis.

Figure 2.6 shows the monocular data, collated according to speed and viewing condition.

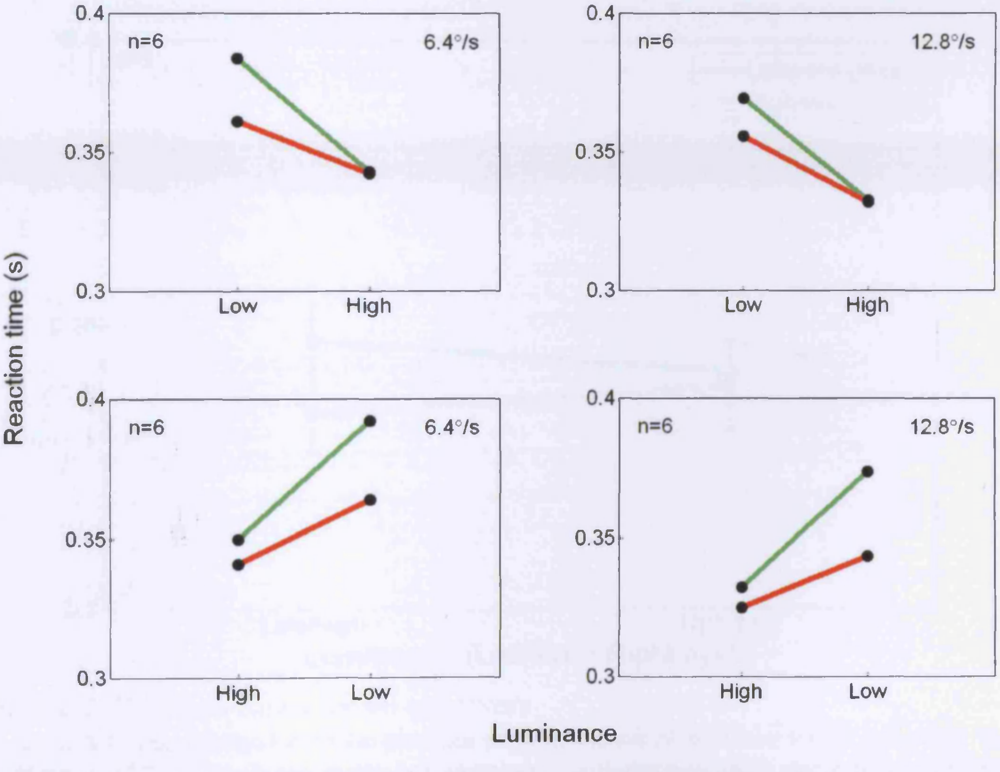

Figure 2.6: The effect of changes in stimulus speed on reaction time.
The upper row of plots present the left eye data, with the right eye data presented in the lower row. The luminance conditions are plotted on the horizontal and mean reaction times on the vertical. All data are averaged across observers, with the green line denoting leftward gaze and the red line denoting rightward gaze. The relevant stimulus speeds are shown in the upper right hand corner of each plot.

As with the data for the first experiment, reaction times change as a function of stimulus speed and luminance. A 2x2x2 within-subjects ANOVA shows a significant effect of gaze for both the left eye data (F(1,5) = 16.71, p = 0.01) and right eye data (F(1,5) = 11.57, p = 0.02) and interactions between gaze and luminance for both the left eye (F(1,5) = 10.78, p < 0.05) and right eye data (F(1,5) = 25.49, p < 0.01). An effect of gaze in the monocular data is unexpected, but is likely due to observers having consistently longer reaction times for the leftward gaze condition.

More importantly, the analysis on the left eye data shows significant effects due to speed (F(1,5) = 9.14, p < 0.05) and luminance (F(1,5) = 375.61, p < 0.01), but no interaction between them (F(1,5) = 0.01, p = 0.92). Similarly, the right eye data show significant effects of speed (F(1,5) = 33.37, p < 0.01) and luminance (F(1,5) = 22.90, p < 0.01), but no interaction (F(1,5) = 0.48, p = 0.52). Therefore, the reaction times are collapsed across speed in the main analysis below.

Figure 2.7 shows the averaged data for the binocular conditions.

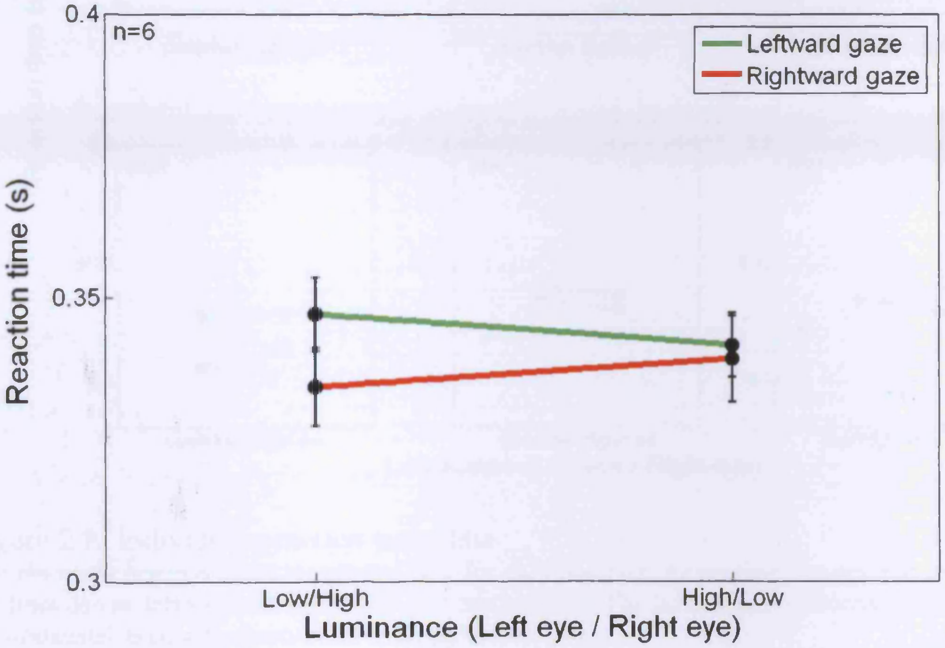

Figure 2.7: Reaction times for all observers
The reaction times, averaged as in the previous experiment, are plotted here for all observers. The luminance conditions are shown on the horizontal axis, with reaction times along the vertical. Error bars denote standard errors.

In this case, the data do not match those shown in Figure 2.4 and, more importantly, the plotted data do slope in the directions predicted in Figure 2.2, but there is no cross-over between the gaze conditions. A 2x2 within-subjects ANOVA does show a significant interaction (F(1,4) = 9.06, p < 0.05) between gaze and luminance, with post-hoc within-subject, t-tests indicating that this interaction is due to an effect of gaze for the Low-High luminance condition (t(5) = 3.54, $p < 0.05$), although this effect does not survive Bonferroni correction.

The interaction is evidence that gaze direction can affect sensory dominance providing image size cues are present, but the fact that a more conservative Bonferroni estimate does not yield a significant post-hoc test suggests that other factors could be affecting reaction time. As with the first experiment, the individual data may shed light on why the effect of image size is not as large as predicted and these data are shown in Figure 2.8.

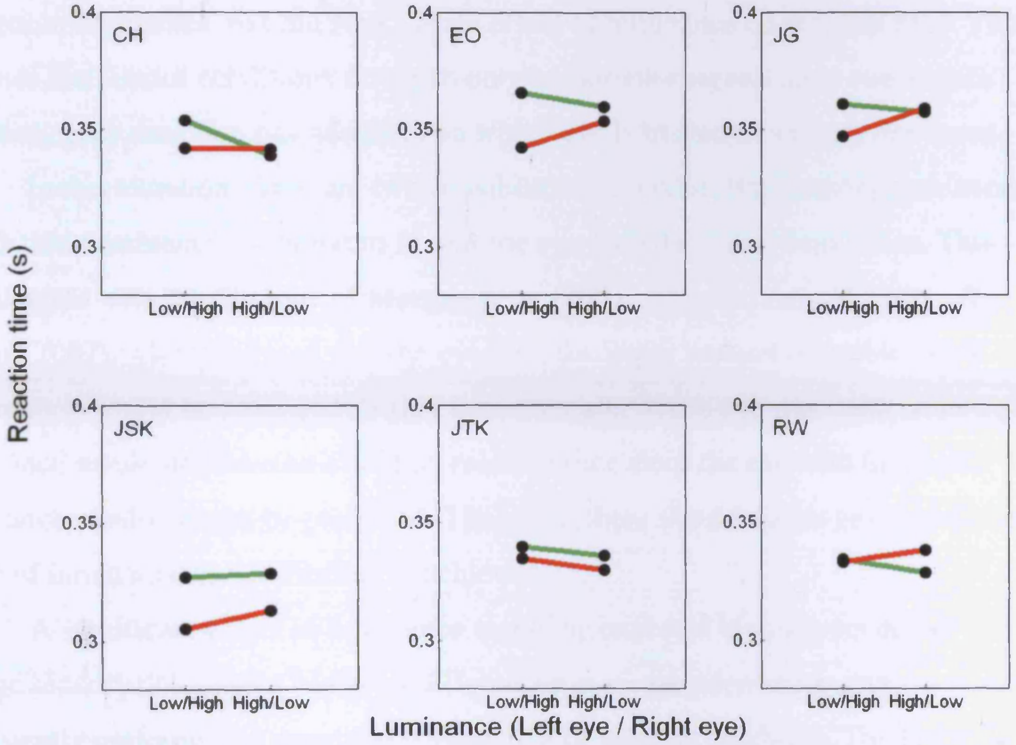

Figure 2.8: Individual reaction time data
The binocular reaction times are plotted here for each observer. As previous figures, the green and red lines denote leftward and rightward gaze respectively. The luminance conditions are shown on the horizontal axis, with reaction times along the vertical.

The individual data do show some variation, but not to the extent shown in the first experiment. There is good agreement between the data for EO and JG, with CH and RW showing very similar patterns to these observers also. However, observers JSK and JTK give essentially horizontal curves. Additionally, CH provides a horizontal curve for the rightward gaze condition. These horizontal data curves suggest the manipulations in luminance are not affecting the reaction times. This could be due to these observers consistently preferring the input from the eye with the higher luminance or that observers are averaging luminance between the eyes and hence the 'overall' luminance is the same in both conditions. The implications of both of these possibilities are considered below.

Discussion

These reaction time experiments were conducted to determine whether sensory eye dominance is affected by changes in gaze direction. The first experiment, which used a small stimulus, did not find an interaction between gaze direction and changes in luminance, but did find a main effect of luminance on reaction time. This suggests that, under conditions in which only oculomotor signals are a cue to gaze direction, gaze direction has no effect on which eye is treated as sensory dominant.

In this situation, there are two possibilities for controlling sensory dominance. One is that dominance is altered to favour the eye with the higher luminance. This would agree with the findings of Meegan et al. (2001), and also Arnold, Grove & Wallis (2007), who suggested that the eye with the larger amount of usable visual information would be preferred. If this were the case, which eye was reduced in luminance would not have an effect on reaction time since the eye with the higher luminance would always be preferred. Therefore, there should not be any significant effect of luminance as equilibrium is achieved.

A significant effect of luminance would be expected if observers do not change sensory dominance based on differences in visual information, but consistently preferred the same eye irrespective of viewing condition. The binocular data for the first experiment do show a main effect of luminance and, in addition, suggest observers tend to favour the right eye. This suggests that, far from changing sensory dominance, observers prefer the right eye in both luminance conditions.

The stimulus used in the second experiment was larger, in order to make image size cues more salient. The data from this experiment show the predicted interaction between luminance and gaze direction (albeit due to an effect of gaze for the Low/High luminance condition). This would suggest sensory dominance does vary as a function of gaze direction, but only if sufficient image size information is provided by the stimulus.

However, the results of the second experiment could be confounded by the constraints of the apparatus used for data collection. Due to the mechanics of stimulus projection, this circle was constructed as a ring of dots which slowly rotated anticlockwise. This inherent movement in the stimulus could act as a cue to motion since the rotation of the circle would pause momentarily at the point when the stimulus began to move vertically. It can be argued that this is only a cue that motion is about to begin, not to the direction of the motion, and, since incorrect responses are removed from data analysis, it should not have any effect on the data. But even for correct responses, this minor pause will prepare observers for motion and likely impact upon their time to react to the stimulus. Thus, this cue to motion onset is likely to only have a quantitative effect on the results.

The data from both experiments do show that, when image size information is introduced, sensory dominance can change with gaze direction. The individual data for the second experiment might also suggest that differences in luminance between the eyes could be causing a change in dominance. This would fit with a dominance switching mechanism based on maximising the amount of visual information available to the eyes and would also fit with the findings of Meegan, Stelmach & Tam (2001). However, an equally valid possibility is that the luminance of the eyes is averaged before binocular judgements are made, i.e. the equilibrium case outlined in Figure 2.1. This would suggest that visual judgements are independent of differences in luminance between the eyes and it is only the overall luminance that affects reaction time. Unfortunately, both possibilities would lead to equal reaction times for each luminance condition. However, if eye dominance is altered to maximise visual information, then it is highly likely that changes in luminance could trigger this mechanism. Given the proposed existence of this mechanism, it is logical to assume that luminance does change eye dominance, but can be ‘overruled’ by image size cues.

Chapter 3

Eye dominance and image size: assessing the effect of perceived slant

The previous chapter addressed the issue of whether sensory eye dominance changes in response to the oculomotor and image size signals associated with a change in gaze angle. There was evidence that image size information was used as the primary cue to gaze angle, in order to change eye dominance. Image size cues arise because the object being viewed is closer to one eye than the other. For example, if an object is straight ahead, both eyes are equidistant from the object and, therefore, the retinal images of the object are the same size. If the object is placed to the left of the head, it is closer to the left eye and the image in the left eye is correspondingly larger in size than the image in the right eye; when the object is to the right of the head, the right eye is closer and thus has the larger retinal image.

The possible role of relative image size was briefly discussed by Khan & Crawford (2001), but was fully considered by Banks, Ghose & Hillis (2004). Banks et al. independently manipulated eye position and relative image size in order to determine the contribution of each cue to dominance switching. For example, in their experiments, gaze could be directed to the left but combined with a larger retinal image presented to the right eye. They found that changes in relative image size consistently predicted a change in dominance, as measured by changes in perceived location of a central target with respect to a wireframe surround. The eye position cue had little effect. This result suggests that dominance switching is reliant upon the relative size of the visual images of an object, rather than the extra-retinal eye-position signal.

The first experiment, reported below, sought to replicate the findings of the Banks et al. study. During this replication, observers reported that manipulating image size produced noticeable changes in the perceived slant of the stimuli used. This raises the possibility that perceived slant, rather than relative image size, may be the cue controlling dominance switching. After the initial replication, the magnitude of perceived slant produced by the image size manipulation was quantified, and then attempts to dissociate slant and image size were made. The study is concluded by using mathematical modelling to estimate the contribution of image size and slant from the collected data.

The task used by Banks et al. (2004) was adapted for the replication. Banks et al. assessed eye dominance by asking observers to report the horizontal location of a dot within a square frame. The retinal image size of the frame could be manipulated between the two eyes. The replication uses a similar technique, in which a range of dot positions with respect to the frame was presented to observers, who were asked to make simple 'left' or 'right' judgements. This design allowed psychometric functions to be fitted to the data, in order for the point of psychometric equality (PSE) to be evaluated. The PSE can be defined as the dot position that appears centred in the frame to an observer. From this point on, the PSE will also be referred to as the 'perceived centre'.

The relationship between the perceived centre and eye dominance is a consequence of the stereoscopic presentation of the stimulus. The stereo presentation placed the dot behind the plane of the frame, giving the dot an uncrossed disparity. Thus, in the left eye view, the dot appeared closer to the left side of the frame. Similarly, the dot appeared closer to the right side of the frame in the right eye view. Therefore, when one eye dominates the percept due to eye dominance, the dot should appear closer to one side of the frame than the other. Banks et al. hypothesised that changes in image size should trigger changes in perceived centre as a function of changing eye dominance. Hence, when the size of the left eye's image is larger than the right, the left eye will dominate the percept, causing the dot to appear closer to the left side of the frame. Therefore, the perceived centre will be somewhere in the right-hand side of the frame.

Method

Observers

Five observers took part in the experiment. All were experienced psychophysical observers recruited from within the School of Psychology, Cardiff University. With regard to the predicted outcome of the study, one was the author, another was aware of the experimental aims whereas the remaining three were naïve. All had normal, or corrected to normal, vision.

Stimuli and apparatus

The stimuli were presented on a computer monitor (360mm width, ViewSonic P95f CRT), covered with a red filter, and viewed using a pair of CrystalEyes (Stereographics, CA, USA) stereo shutter glasses. Stereo fusion was achieved by synchronising the presentation of the left and right eye images with the opening of the relevant lens of the shutter glasses. The left and right eye images were temporally interleaved, so the left and right eye images alternated, with each eye viewing 50 frames per second, constrained by the 100Hz refresh rate of the monitor. The monitor was 1m in front of the subject and a chin rest was used to ensure the observer's head remained stable throughout the experiment. The room was darkened and only the stimuli presented on the monitor were visible.

The stimulus used was a square frame surrounding a square dot. The frame was of side length 50mm, subtending 171.9x171.9 arcmin in the eye, with the dot subtending 3.4x3.4 arcmin. The dot was placed 25mm behind the plane of the frame (which was drawn in the plane of the screen, i.e. at 1m), giving the dot an uncrossed disparity. This matches the relative frame and dot placements used in the Banks et al. experiment. The stimuli themselves were presented for an unlimited time; hence the duration time of the stimulus depended only on the speed of an observer's response. This is a small deviation from the Banks et al. study, which used a one second presentation time for stimuli.

For each presentation, observers were presented with the stimulus and asked to judge whether the dot appeared closer to the left or right side of the frame. Responses were indicated with a mouse click. The screen then went blank for 2 seconds and the next stimulus was presented.

Procedure

Three image size ratios were used in the experiment. These were calculated using the formula given by Banks et al.:

$$SR = \frac{\sqrt{d^2 + i \cdot d \cdot \sin(\gamma) + i^2/4}}{\sqrt{d^2 - i \cdot d \cdot \sin(\gamma) + i^2/4}},$$

where SR is the size ratio of image in each eye, d is the distance from the observer to the screen, i the interpupillary distance (assumed to be 65mm for calculation purposes) and γ the angular object position measured from straight ahead.

The ratios use the convention of left eye image size/right eye image size and were 1.03 (3% larger in left eye, corresponding to 30° to left at a distance of 1m), 1 (same size in both eyes, corresponding to straight ahead) and 0.97 (3% larger in right eye, corresponding to 30° to right at a distance of 1m). All ratios were correct for objects viewed at a distance of 1m. The dot displacements presented were ±6.88, ±3.44, ±1.72 and ±0.86 arcmin from centre, plus the central point itself, for a total of nine dot positions.

All observers participated in all conditions and completed three sessions of data collection. Each session consisted of 540 stimulus presentations, 180 for each size ratio. Each dot position was displayed 20 times per ratio condition.

For four of the observers, each session was split into 12 blocks of 45 trials, with each block having only one frame ratio and 5 presentations of each dot position. The order in which the blocks were completed was randomised between observers, but not between sessions for each observer.

The fifth observer completed data collection at a later date then the others, and was not given blocks of a single frame ratio, but rather 10 blocks of 54 presentations. Each block consisted of 18 presentations of each size ratio, presented in a random order. Therefore each dot position was presented twice per size ratio per block.

Analysis and results

For each observer, the results were collated according to the image size ratio presented. The percentage of rightward responses was calculated and plotted against the range of dot positions shown. A psychometric function curve was fitted to these plots by probit analysis (Finney, 1971). An example of this curve fitting is shown in Figure 3.1.

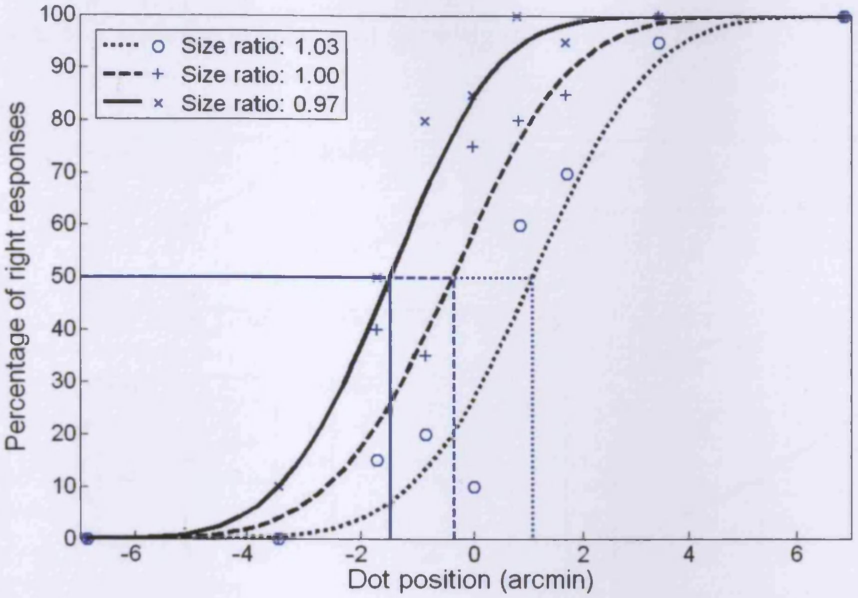

Figure 3.1: Example of curve fitting
These data were collected from one subject during the experimental procedure. The presented dot position is shown on the horizontal, the percentage of rightward responses given on the vertical. The points are the actual data collected; the lines fitted using probit analysis. The vertical lines show the location of the 50% point, with a negative value indicating a position to the left.

The curve fitting relates the perceived centre (represented here as the point with 50% right responses) to the physical position of the dot. Therefore, in all of the following data, the vertical axes will represent the position of the dot where it is perceived as central. A positive value for perceived centre indicates the dot is located in the right-hand side of the frame. As explained above, left eye dominant observers would have a perceived centre in the right-hand side of the frame and, therefore, a positive value for perceived centre indicates left eye dominance.

Although collected across three sessions, it should be noted that the locations of the perceived centres were calculated on all the collected data for each subject to give a single value, rather than averaging three centre locations across sessions. This was done for ease of curve fitting.

In order to present the data, the perceived centres for each observer were normalised relative to the location of the perceived centre for the equal image size condition by subtracting the location of the perceived centre for the equal image size condition from all perceived centre locations. This removes the effect of any natural bias towards one eye. This normalisation was only carried out on the individual data. The data averaged across observers were not normalised and all statistical calculations were carried out on these non-normalised data.

The perceived centres calculated for the replication of Banks et al. are plotted in Figure 3.2, with the largest plot showing the averaged data.

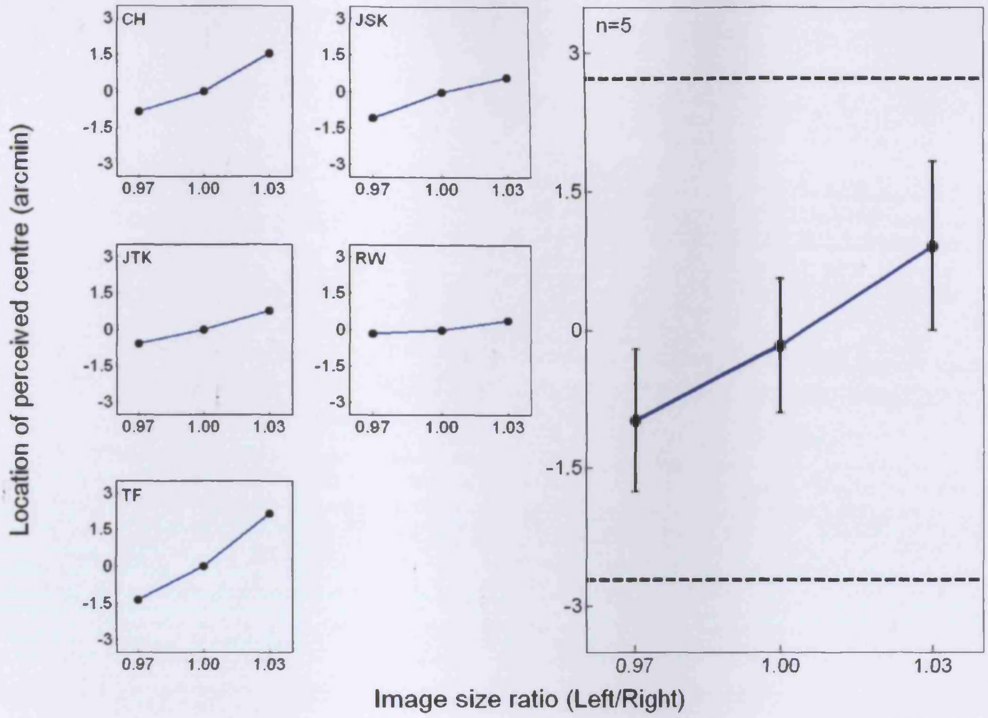

Figure 3.2: The effect of relative image size on ocular dominance
The smaller plots show the individual results for each observer. The larger plot shows the group means. Relative image size is shown on the horizontal axis and the perceived location of the centre on the vertical. Positive centre locations indicate left eye dominance and negative locations indicate right eye dominance. The dotted lines on the group graph show the maximum expected shift in perceived centre. As stated above, for each observer and condition, one PSE was calculated from all three sessions of data collectively. Hence, error bars are only applicable to the averaged plot where they denote standard errors between observers.

If eye dominance changes as a function of image size, a larger right eye image should correspond to a negative perceived centre location and a larger left eye image should correspond to a positive perceived centre location. The data clearly show a switch in perceived centre from negative to positive as the larger image is presented first in the right eye and then in the left. This indicates a switch in dominance from right to left, confirmed by a one way ANOVA, ($F(2,8) = 13.44$, $p<0.01$). As is to be expected, some individual variation occurred between the subjects, but all show the shift in perceived location associated with a change in dominance.

Discussion

These results are a successful replication of the effect found by Banks et al., who concluded that eye dominance was dependent on the relative image size of objects viewed. However, during the experiment it was noticed that the frame appeared slanted; an observation that is compatible with previous reports that an overall difference in image size has been found to invoke a perception of slant (Kaneko & Howard, 1996; Pierce & Howard, 1997; van Ee & Erkelens, 1998). Since the conclusion of Banks et al. suggests dominance switching is reliant on the properties of a visual image, it is possible that perceived slant could be the trigger for a switch in dominance, rather than overall image size.

An example of how slant could affect directional judgements that has a close link to the Banks et al. methodology is given by Fogt & Mowell (1999). In this study, the effect of slant on perceived direction was explicitly tested. Observers monocularly viewed a horizontal array of five LEDs. The array was rotated around a vertical axis passing through the centre LED of the array. Observers were required to fixate and point at the centre LED of the array. Fogt & Mowell found that if the slanted array was closer to the right side of observers, pointing responses tended to shift towards the left of centre. Similarly, if the slanted array was closer to the left of observers, pointing responses were shifted towards the right. The magnitude of shift also increased with increasing slant. However, it is important to note that the effect of slant was relatively slight and that observers tended to use eye position information to make the pointing judgements.

The study conducted by Fogt & Mowell does provide some suggestion as to how slant could affect the judgement made in the Banks et al. (2004) study and in the above replication. In the Banks et al. paradigm, observers were presented with a dot within a frame and asked to judge the location of the dot relative to the frame. If the size of the left eye image of the frame was increased, the frame should appear slanted about a vertical axis with the right edge of the frame appearing closer to the observer. According to the findings of Fogt & Mowell (1999), this should introduce a leftward shift into the responses causing the dot to appear closer to the left-hand side of the frame and, consequently, moving the perceived centre into the right-hand side of the frame. This would produce the same pattern data as was found in the above replication. Therefore, it is possible that the results attributed by Banks et al. as being due to the dominant eye moving to the eye with the larger image size are simply due to the perceived slant in the stimulus.

Before the effect of slant on the perceived centre was investigated, it was first necessary to establish that slant was consistently perceived in the experimental stimulus. In order to do this, the observers who participated in the replication experiment were asked to judge the amount of slant they perceived in the stimulus frame with a slant matching task.

Method

Observers

All observers who participated in the replication experiment also provided slant matching data.

Stimuli and apparatus

The same apparatus, square frame stimulus and image size manipulations were used as in the replication experiment. Each trial consisted of two stimulus presentation intervals. In the first interval, a test frame was presented to observers. In the second interval, a frame that could be rotated to match the perceived slant was used. The dot used in the replication experiment was not presented at any point during this experiment. The test frame underwent image size manipulations, as used in the previous experiment. The matching frame was a square that was rendered under perspective projection. The frame could be rotated, using the computer mouse, about the vertical axis in both clockwise and anticlockwise directions up to a maximum of 45°. Both frames had the same dimensions as the frame used in the replication experiment.

Observers were first presented with the test frame, which was accompanied by an audio tone to differentiate it from the matching frame. The test frame was presented for two seconds before the screen then went blank for one second until the matching frame was presented. Observers were instructed to use the mouse to rotate the matching frame until it appeared to have the same slant as the test frame. The screen then went blank for a further second and the next test frame was presented.

Procedure

Observers again completed three session of data collection. Each session consisted of 180 presentations, split into 6 blocks of 30 presentations. Each block had 10 presentations of each image size ratio, in a random order. The size ratios used were the same as in the replication experiment.

Results

The average perceived slant for each image size ratio was calculated for each participant. Similarly to the replication experiment results, these averaged data were normalised by subtracting the perceived slant for the equal image size ratio condition from all three conditions. This compensates for any slant biases.

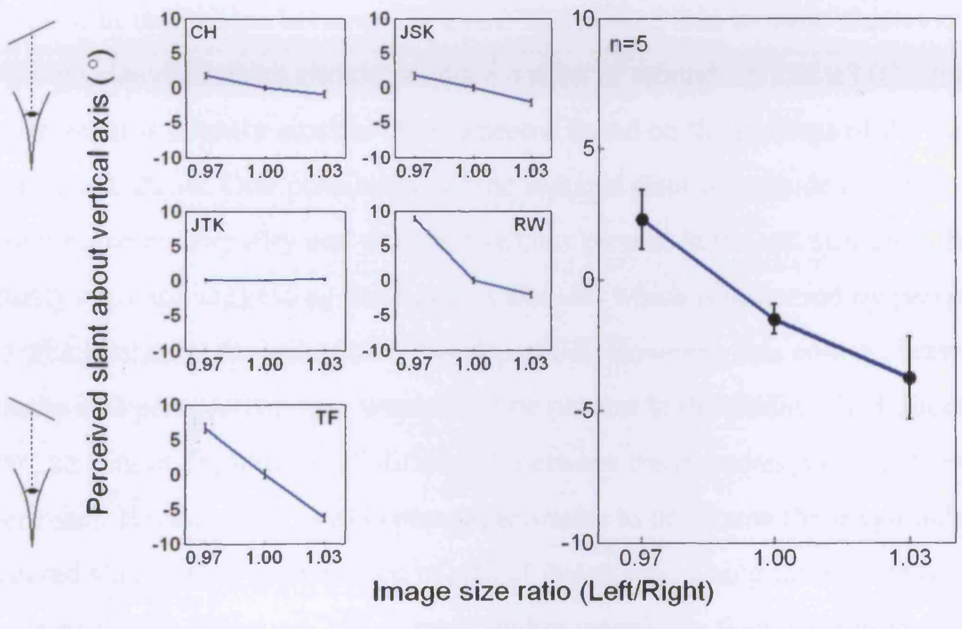

Figure 3.3: The slant perceived in stimuli with adjusted image size ratios
As with figure 3.5, the smaller plots show the individual results for each experimental subject and the larger plot shows the group means. The image size ratios of the test frame are shown on the horizontal axis and the perceived slant values on the vertical axis. A positive slant value indicates an anticlockwise rotation of the matching frame from a frontoparallel position, as shown in the illustrative diagram to the far left of the figure. As mentioned in the main text, the errors bars denote standard error within observers for the individual plots and between observers for the averaged plot.

Figure 3.3 shows the results for each observer, with the slant matching values averaged across the three sessions of data collection completed by each observer, and the data averaged across all observers. The averaged plot shows that observers did perceive a slant in our experimental stimulus, in line with previous research (Kaneko & Howard, 1996; Pierce & Howard, 1997; van Ee & Erkelens, 1998). A one way ANOVA, performed on the averaged, un-normalised data plotted in the right of Figure 3.6 confirms that a slant is perceived in the stimulus ($F(2,8)=5.37$, $p<0.05$).

Discussion

The slant matching task has shown that a slant was perceived in the experimental stimulus used in the replication of Banks, Ghose & Hillis (2004), although observer JTK seems not to perceive any stimulus slant. This perception of slant fits with that noted in previous work. In terms of magnitude of perceived slant, of the works cited above (Kaneko & Howard, 1996; Pierce & Howard, 1997; van Ee & Erkelens, 1998), none explicitly state the slant magnitudes found when using a 3% difference in image size between the eyes. The plotted data in these studies suggest a 3% image size difference should produce a slant of around ±5°. At ±3.02°, the slant measurement is slightly smaller than expected based on the findings of the previous studies cited above. One possibility for the reduced slant magnitude could be due to a conflict between disparity and perspective cues present in the test stimulus. The disparity cues are suggesting the frame is slanted, which is tempered by perspective cues which suggest the stimulus is frontoparallel. However, this conflict between disparity and perspective cues would also be present in the studies cited directly above, so cannot explain the 2° difference between these studies and the above experiment. Backus et al. (1999) present formulae to determine the magnitude of perceived slant due to a difference in retinal image size. Using these formulae predicts a perceived slant of around 25°, a much higher magnitude than that found experimentally. Therefore, this would suggest that perspective cues are reducing the perceived slant by a very large amount from the theoretical measurement of 25°. Nevertheless, it is clear that slant is perceived in stimuli like those used by Banks et al.

Eye dominance switching and perception of slant

The replication of Banks, Ghose & Hillis (2004) has provided good agreement with their findings. Both studies have shown that perceived location can be affected by relative image size cues, which would suggest that eye dominance also changes with these cues. Furthermore, it has been shown that the stimuli appear slanted about a vertical axis. The question now is whether this perception of slant is linked to changes in eye dominance.

Both Banks et al. and the replication experiment presented above have used changes in perceived location to make inferences about changes in eye dominance. The presence of stimulus slant could be affecting perceived location directly, as suggested by Fogt & Mowell (1999) or could be changing eye dominance which, in turn, will affect perceived location. Whether the effect of slant is due to a change in perceived location or a change in eye dominance is not immediately clear. Therefore, a cautious approach will be adopted and, for the time being, slant will be assumed to affect perceived location directly, rather than eye dominance.

The existence of slant in the stimulus leads to three possible hypotheses for the shift in perceived location. The changes in perceived centre location are due to: (1) changes in relative image size only; (2) changes in perceived slant only; or (3) a combination of relative image size and perceived slant. To begin the investigation of the effect of slant, the surrounding frame was projected at a slant to see if perceived location was changed as a result.

Slanting the stimulus

This experiment used four slant values for the frame. This was to done to assess the effect of increasing slant, with the hypothesis that, if slant is affecting perceived location, the change in location should increase with increasing slant. The slant values used included the 3° slant that was measured in the replication stimulus. This allows the results of the replication experiment to be directly compared to results from this, and only this, slant value.

Method

Observers

Four observers took part in the experiment. All had previously participated in the replication and slant matching experiments and, as with those experiments, one was the author, another was aware of the experimental aims whereas the remaining two were naïve.

Stimuli and apparatus

All stimuli had the same dimensions and stereo parameters as previous experiments and were presented using the same apparatus. The frame was projected at a slant on the screen and its edges extended to ensure it subtended the same visual angle as the frame used in the replication experiment. This is because a slanted frame subtends a smaller visual angle than a frontoparallel one. Therefore, judging the location of the dot relative to the sides of the slanted frame may be easier than in the replication experiment since the distance from the dot to the sides is reduced. This effect is magnified as slant increases since visual angle correspondingly decreases. ‘Stretching’ the slanted frame so that it subtends the same visual angle as the frontoparallel stimulus ensures that all judgements are made relative to sides subtending the same visual angle, regardless of the magnitude of slant.

Each experimental trial was exactly the same as in the replication experiment with observers being presented with the stimulus and asked to judge whether the dot appeared closer to the left or right side of the frame. Responses were indicated with a mouse click. The screen then went blank for 2 seconds and the next stimulus was presented.

Procedure

Four magnitudes of slant were used. These were 1°, 3°, 5° and 10° (Recall that the slant matching experiment identified a 3° percept of slant in the stimulus). For each slant magnitude, three slant directions were used: no apparent slant, clockwise and anticlockwise rotation. These correspond to the slant directions seen when the right eye image is larger, left eye image is larger and the images in both eyes are the same size. The variations in horizontal dot position used in the replication experiment were also used here.

Observers completed four sessions of data collection, one for each magnitude of slant. Within each session, twelve blocks of 45 trials were completed in which four blocks used a frame slanted with a closer left edge, four with a closer right edge and four with no apparent slant. Within each block of trials, each dot position was presented five times.

Analysis and results

To make comparisons between experiments, the magnitude of shift in perceived centre is presented in the following figures. It is calculated as the perceived centre for stimuli with a larger left eye image minus the perceived centre for stimuli with a larger right eye image. Similar reasoning can be applied to calculate the shift in perceived centre for situations where the frame is slanted.

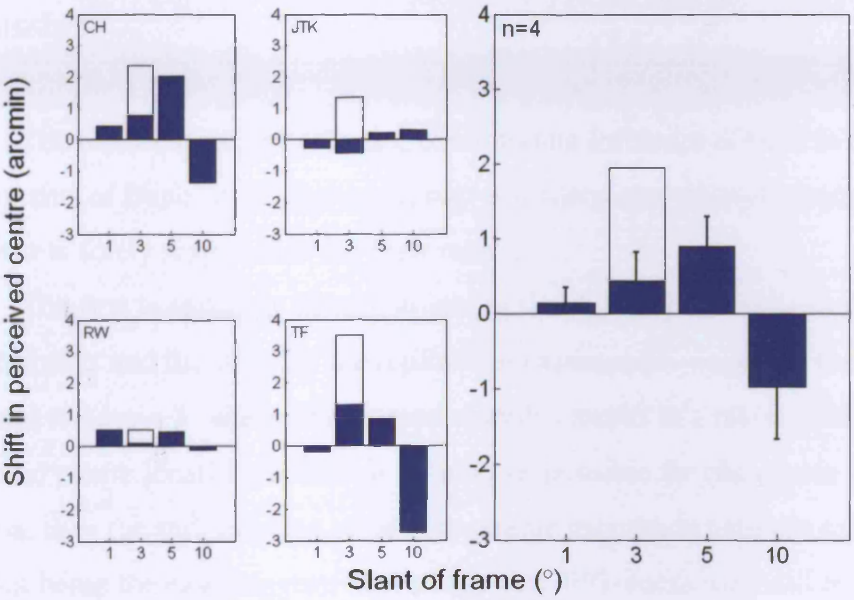

Figure 3.4: Shift in perceived location associated with physically slanted stimuli
The smaller plots show the individual data, with grouped data shown in the larger plot. The magnitude of slant presented is shown on the horizontal axis, with shift in perceived centre plotted on the vertical. The unfilled bars show the shift from the replication experiment for comparison at 3°. As for the replication experiment, one perceived centre was calculated, per observer, for each condition. Hence, error bars are only shown on the grouped plot where they denote standard errors between observers. Note that the averaged shift for the replication experiment shown below is averaged across the four observers who contributed data to this experiment – it does not include data for observer JSK who only participated in the replication and slant matching experiments.

For each observer, the results were collated according to the slant angle presented. Figure 3.4 shows the individual and grouped data collected with the slanted stimuli. Also shown is the shift for the replication experiment, at 3°. To reiterate, this is the slant value identified in the replication experiment and it is important to note that it is only at this slant value that the two experiments can be compared.

The individual plots clearly show that there is some variability across observers. However, the right-hand panel of Figure 3.4 shows that, on average, the effect of slant on the shift in perceived centre increases with slant, with the effect reversing at the largest slant. It is unclear why the reversal occurs, but three of the four observers show it. For all but the largest slant, the individual trend is for the shift in perceived centre to increase with slant.

Importantly, the effect of projected slant on perceived centre is much smaller than that found with the replication stimulus ($t(3)=4.036$, $p<0.05$). This difference is also consistently shown in the individual data. Possible explanations for this trend are discussed below.

Discussion

The results seem to indicate a confounding influence of slant in the experiments of Banks et al. However, two considerations counsel against concluding that slant is solely responsible for their results.

The first is apparent when comparing the shift in perceived centre for the 3° slant stimulus and the shift for the replication experiment – in which the stimuli also appeared to have a 3° slant. The slanted stimulus results in a much smaller shift in perceived centre location. If slant is entirely responsible for changes in perceived location, then the shifts should be of comparable magnitude between experiments. This not being the case suggests that image size differences may still be important in determining perceived dot location.

Also, a stimulus which is projected as slanted creates image size differences between the eyes, albeit much reduced compared with those used in the replication experiment. Potentially, therefore, the difference in image sizes displayed in the two experiments is the critical factor, rather than slant. The vertical sizes of the retinal image remain the same in both eyes (Howard & Rogers, 2002); the horizontal image sizes of a slanted surface can be calculated using the following formulae:

$$\theta_L = \tan^{-1}\left(\frac{2L(2D\cos\theta_S - i\sin\theta_S)}{i^2 + 4D^2 - L^2}\right)$$

$$\theta_R = \tan^{-1}\left(\frac{2L(2D\cos\theta_S + i\sin\theta_S)}{i^2 + 4D^2 - L^2}\right)$$

$$SR = \frac{\theta_L}{\theta_R}$$

where SR is the image size ratio of the plane, θL and θR are the horizontal image size in the left and right eyes respectively, θS is the slant of the plane, L is the width of the plane, D is the distance from the plane to the observer and i is the interpupillary distance. The derivation of these formulae follows from the viewing conditions of a scene containing a slanted surface.

Using the viewing conditions of this experiment gives the horizontal image sizes of the stimuli in Table 3.1.

Slant value (°)	Size ratio (left/right eye image)	Difference in image size (%)
1	1.001	0.1
3	1.003	0.3
5	1.006	0.6
10	1.012	1.2

Table 3.1: The image size ratios associated with a slanted object
These size ratios were calculated, using the above formulae, using L = 0.05m, D = 1m, i = 0.065m and θ_S as the slant values shown in the table. The size ratios are calculated assuming the left eye image is larger.

The replication experiment used a size ratio of 1.03, which resulted in a perception of 3° of slant. A stimulus that is projected with the same degree of slant has a horizontal image size ratio of 1.003, a reduction by a factor of 10. Thus, it is possible that image size ratios are affecting the location of the perceived centre in this experiment, with the reduction in horizontal image size accounting for the reduction in perceived centre shift.

Given the difficulty in fully separating image size from slant cues in the above experiments, a different approach to removing slant from the stimulus is required.

Nulling stimulus slant

Consider the geometry of eccentric viewing, particularly the fact that both horizontal and vertical image size differences are associated with eccentric viewing. As detailed above, horizontal image size is primarily a function of slant, but also eccentricity. Vertical image size is primarily a function of distance and eccentricity (Backus et al., 1999; Berends, van Ee & Erkelens, 2002; Howard & Rogers, 2002). Therefore, differences in vertical image size are the most reliable cue to eccentricity (Howard & Rogers, 2002) and differences in horizontal image size are the most reliable cue to slant (Backus et al., 1999). The relation between horizontal image size and slant has been used by Berends & Erkelens (2001a) and Berends & Erkelens (2001b) who altered the horizontal image sizes of a stimulus in order to null the slant caused by differences in vertical image size and cause the stimulus to appear frontoparallel. Using this method preserves vertical image size information, while removing stimulus slant. If the apparent effect of image size is entirely due to the slant of a stimulus, then nulling the slant in the frame should reduce the shift in perceived centre location to zero.

Method

Observers

Four observers took part in the experiment. All had participated in the previous experiments. One was the author, another was aware of the experimental aims whereas the remaining two were naïve.

Stimuli and apparatus

All stimuli had the same dimensions and stereo parameters as used previously and were presented using the same apparatus (monitor and stereo shutter glasses), located in the same position as previous experiments.

The experiment consisted of two phases. In the first, perceived slant was nulled using a method of adjustment. Observers moved the computer mouse horizontally, increasing or decreasing the horizontal size ratio, until the frame appeared frontoparallel. The central dot was not presented during nulling trials. A one second gap separated presentations. At the end of the slant nulling trials, the average horizontal size ratio adjustment for each presented image size ratio was calculated. The average adjustment for each observer was then applied to the stimulus in the main testing trials. The average adjustments in horizontal image size ranged between 1% and 4% change in size.

In the second phase, the perceived location of the central dot was assessed using the same technique as the replication experiment, with one minor change. Instead of a two second gap separating successive presentations, a one second gap was used.

Procedure

Some alterations were made to the number of stimulus variables. Since the experiment was concerned primarily with the shift in perceived centre between trials with a vertically larger left eye image and those with a vertically larger right eye image, the condition where the vertical image sizes were equal was not included. Furthermore, the number of dot positions used was reduced from the original set of nine to ±3.44, ±1.72 and ±0.86 arcmin from centre.

The testing trials consisted of three data collection sessions and observers began each session of data collection with a nulling task. The data provided by the nulling task was used to remove the slant from the stimuli used in the main testing trials. The slant nulling trials consisted of one block of 60 stimulus presentations, 30 for each image size ratio, presented in a random order.

Each session also consisted of four testing blocks of 60 presentations, 30 for each image size ratio, presented in a random order. Each possible dot position was presented 10 times, 5 for each possible image size ratio, per block and the order of block presentation was randomised between sessions and observers.

Two of the blocks presented a frame with an overall difference in image size and without any slant nulling. This is essentially a repeat of the replication experiment, carried out to provide a more up to date set of results for comparison, and will be referred to as the Original condition herein. The remaining two blocks used a similar frame but adjusted the horizontal image size by the amount indicated by the slant nulling data, with the vertical image size remaining unchanged. This will be referred to as the Nulled condition.

Results and discussion

The shifts in perceived centre for both the Original and Nulled conditions are shown in Figure 3.5.

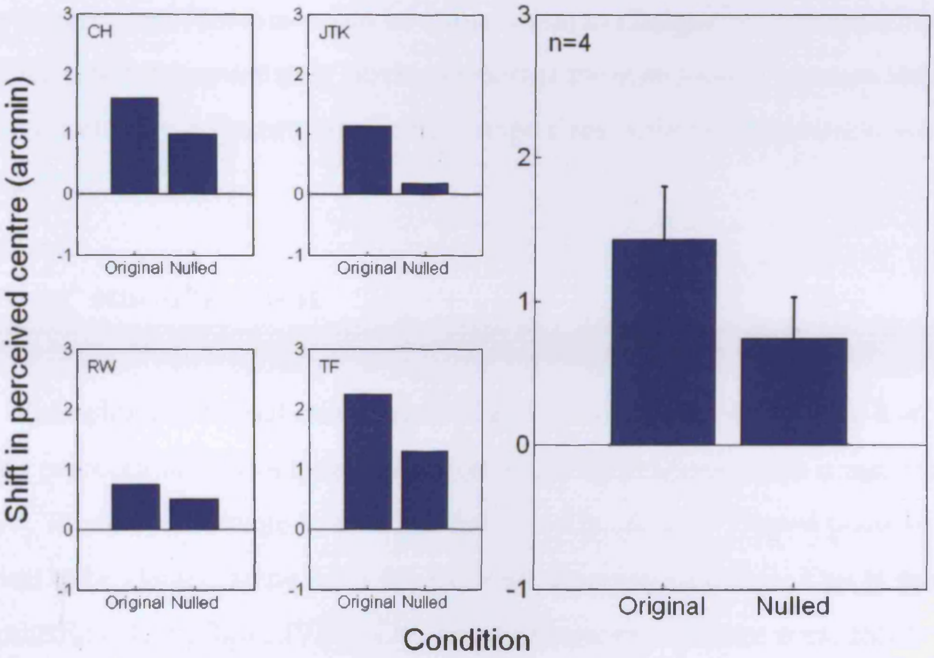

Figure 3.5: Removing the slant in the stimulus
The individual results are presented in the left hand figures, the averaged results in the right hand figure. The two experimental conditions are shown on the horizontal axis, the shift in perceived centre on the vertical axis. One perceived centre value was calculated for each condition and observer and used to calculate the shifts shown here. Hence, error bars are only applicable on the averaged plot where they denote standard errors.

Removing the perceived slant from the stimulus significantly reduces the shift in perceived centre ($t(3)=4.08$ $p<0.05$, two-tailed). This reduction occurs for all observers, with the shift for observer JTK reducing almost completely. Note that the data for the Original condition provide good agreement with the data from the replication experiment, with no significant difference between the two ($t(3)=1.59$, $p>0.05$, two-tailed).

Removing the slant from the stimulus affected the shift in perceived centre, but did not reduce it to zero. This would suggest that slant is not completely responsible for the results and, therefore, that differences in image size also play a role in determining perceived location. However, the slant nulling method is not without its imperfections. The nulling procedure adjusts the horizontal image sizes of the stimulus, while leaving the vertical image sizes intact. If observers used only vertical image size information to make the judgement, then the nulling procedure should have no effect on perceived location. If observers do make use of the horizontal image size information, however, then any adjustment of the horizontal image sizes will impact upon the judgement. The consequence of this is not only that image size information relating to eccentricity is effectively ignored, but that the change in perceived location could be entirely due to changes in horizontal image size. Since it is not immediately obvious whether the reduction in location shift is due to removing slant or adjusting horizontal image sizes, a further experiment was conducted.

'Splitting' stimulus slant

Enlarging the retinal image sizes of a planar object in one eye can lead to differing perceptions of slant, depending on which dimensions of the image are enlarged. If one eye's image is enlarged horizontally, then the viewed plane is perceived to be slanted away from the eye with the enlarged image. This is known as the geometric effect (Ogle, 1938). Conversely, if one eye's image is enlarged vertically, the plane is perceived as slanting toward the eye with the enlarged image. This is known as the induced effect (Ogle, 1938). In both cases, the magnitude of perceived slant is proportional to the amount of magnification, although there is evidence that the magnitude of slant caused by the induced effect plateaus at around 8% magnification depending on the viewing conditions (Banks & Backus, 1998). As shown by the slant matching experiment, an overall enlargement of one eye's image also causes a percept of slant. The direction of this slant matches that arising from the geometric effect, although generally the geometric effect leads to a higher magnitude of slant for the same image size magnification value (Kaneko & Howard, 1996; Pierce & Howard, 1997; van Ee & Erkelens, 1998).

The fact that the direction of slant changes depending on which dimensions of a retinal image are enlarged can be exploited to determine what effect perceived slant has on perceived location. If slant has an effect on perceived location, then the slant arising from either horizontal or overall scaling of one eye's image should produce effects similar to that seen with the replication of Banks, Ghose & Hillis (2004). That is, it is expected that a stimulus slanted away from the left eye will result in a rightward perceived centre and a stimulus slanted away from the right eye will result in a leftward perceived centre. Conversely, the slant arising from vertical scaling of one eye's image should affect perceived location in the opposite direction to horizontal scaling. This would effectively reverse the effect described by Banks et al. If slant is not a factor in determining perceived location, then the shifts should be the same, no matter which dimension is enlarged. This assumes that both horizontal and vertical scaling are given equal processing weight, a point that is considered later.

In the next experiment, the influence of horizontal, vertical and overall changes in image size was investigated. These alter perceived slant, but not the available level of image size information.

One consideration that was made in this experiment restricted the presentation time of the stimuli. The previous experiments used an unlimited judgement time, with observers free to respond at any time. This experiment presented all stimuli for one second and observers were not able to respond until this presentation time had elapsed. This follows from a study carried out by Fukuda, Kaneko & Matsumiya (2006) which concluded that slant perception due to vertical image size differences does not take place immediately, unlike slant perception due to horizontal image size differences. It takes around 500ms to fully integrate perceived slant due to vertical image size differences. Thus, if observers could respond at any time, it is feasible that observers could make the judgement before allowing adequate time for the slant induced by vertical size differences to be fully apparent. Restricting the presentation time to one second before any response can be made ensures this cannot happen.

Method

Observers

Four observers took part in this experiment. All had previously participated in the slant nulling experiment and, apart from the author and another who was aware of the experimental aims, were naïve.

Stimuli and apparatus

All apparatus used were the same as in previous experiments and the stimuli used were the same as those used in the slant nulling experiment. As detailed above, all stimuli were presented for 1 second.

Apart from this alteration, each session of trials was carried out as for the replication experiment, although (as with the nulling experiment) only a one second interval separated successive stimulus presentations.

Procedure

Three experimental conditions were used. The Overall condition used a frame enlarged equally in both the horizontal and vertical dimensions, the Horizontal condition used a horizontally enlarged frame (vertical size ratio = 1 throughout) and the Vertical condition used a vertically enlarged frame (horizontal size ratio = 1 throughout). A 3% enlargement in image size was used, as with previous experiments.

Observers performed three session of data collection. Each session consisted of ten blocks. Each block consisted of 36 presentations, 18 for each size ratio, presented in a random order. Every possible combination of experimental condition and dot position were presented once per trial block. Hence, for each session, each experimental condition was presented 120 times, 60 for each size ratio.

Results and discussion

The shifts in perceived centre for the three experimental conditions are shown in Figure 3.6 (overleaf). The results show comparable, positive shifts in perceived centre resulting from the Overall and Horizontal conditions and a smaller, negative shift resulting from the Vertical condition. There is a significant difference between shifts (3 level, one-way ANOVA, $F(2,6) = 5.72$, $p<0.05$) and, more importantly, the shifts in location match the directions of slant for the relevant conditions. However, the magnitude of perceived centre shift for the Vertical conditions is much smaller than the other two conditions. If perceived location is affected by stimulus slant, then this could be due to the vertical stimulus having a smaller perceived slant compared with the other conditions. This is easily checked by performing a similar slant matching experiment to that used above, but applying it to the stimuli used in the Horizontal and Vertical conditions. This was carried out in the same way as the previous slant matching experiment and it was found that the slant of the horizontal stimuli was approximately twice the magnitude of the vertical stimuli, for three out of the four observers. The remaining observer showed roughly equal slant magnitudes for both conditions.

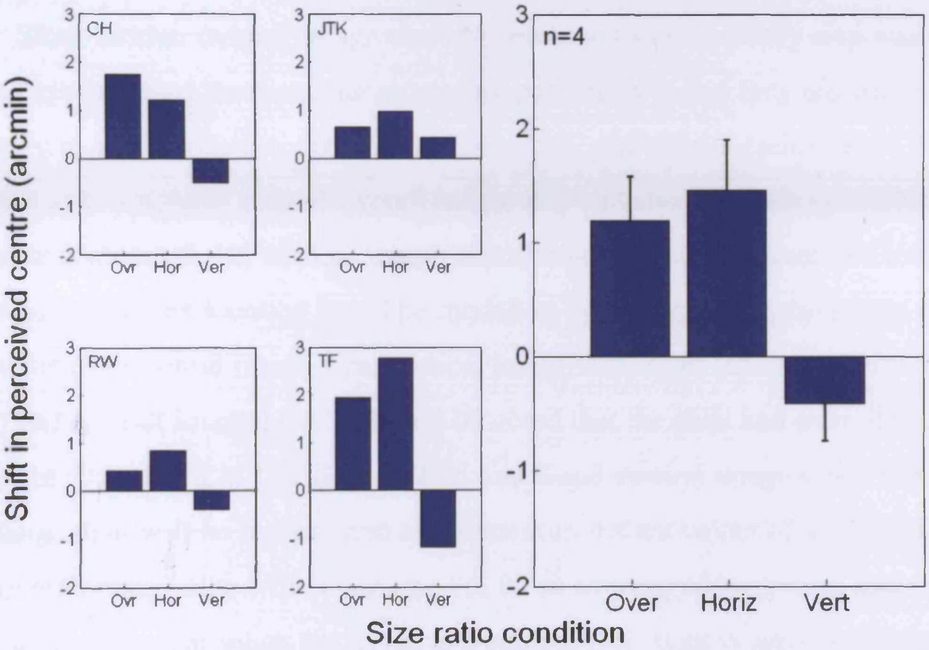

Figure 3.6: Changing the slant in the stimulus
The individual results are presented in the left hand figures, the averaged results in the right hand figure. The experimental conditions are shown on the horizontal axis and the shift in perceived centre on the vertical. As with the nulling experiment, one PSE value was calculated for each condition and observer and used to calculate the shifts shown here. Hence, error bars are only applicable on the averaged plot where they denote standard errors.

However, the level of slant perceived with the vertically enlarged stimulus does not match the shift in perceived centre arising from this stimulus. This would suggest that perceived slant is not entirely responsible for the change in perceived location, but may still have a small effect. The results clearly show a reverse in perceived centre shift accompanying the Vertical condition stimuli. Since the perceived stimulus slant in this condition opposes the slant in the other two conditions, this reversal in shift most likely arises from the percept of slant.

Modelling the data

This suite of experiments was designed to first replicate the findings of Banks, Ghose & Hillis (2004) who determined that differences in overall image size were responsible for apparent changes in eye dominance. This replication was successful and was followed by an investigation of whether the perceived slant of the stimulus could be responsible for changes in perceived location, rather than solely overall image size. An effect of slant was found, but it does not appear to be the sole cue for changing perceived location.

Since neither overall image size nor perceived slant is solely responsible for changes in perceived location, the remaining possibility is that they are combined in some way to affect location perception. Therefore, perceived location could be modelled as a weighted sum of overall image size and slant. It is also possible that the individual horizontal and vertical image size components affect perceived location. Therefore, perceived location could be modelled by a weighted combination of up to four factors: horizontal image size, vertical image size, slant (either perceived or actual) and overall image size. It should be noted that the slant and overall image size factors are considered as functions of horizontal and vertical image sizes. For ease of modelling, slant will be represented as the measured slant values of a given stimulus. Also, overall image size will be assumed to be an average of horizontal and vertical image sizes. Note that when the frame is frontoparallel, slant is zero but horizontal, vertical and overall image sizes are one. In order to localise all four factors onto the same scale, one is subtracted from the horizontal, vertical and overall image sizes in the following models.

The model fitting uses least squares regression and uses the data for each of the individual observers who participated in all experiments. Since the data from each experiment generally consist of only two data points for each observer, the models were not fitted to the data of each experiment but were instead fitted to the data grouped over all experiments. In this case, any perceived centres arising from stimuli with the same horizontal and vertical image sizes were averaged.

As a baseline, single factor models will be considered first. These will consist of one of the four factors highlighted above plus a constant. The model fits will be compared using the sum of squares value given by each fit. This sum of squares is the sum of the squared vertical distances between the model and the actual data points. The weights of the individual factors and the constant were adjusted until the sum of squares was minimised. This represents the best fit of the model to the data. The models and sum of squares fits for each observer are shown in Table 3.2.

Model	Observer sum of squares			
	CH	JTK	RW	TF
$CP = w_H(H - 1) + k$	0.895	0.521	0.152	1.079
$CP = w_V(V - 1) + k$	1.030	0.568	0.229	1.431
$CP = w_S S + k$	1.110	0.597	0.221	1.420
$CP = w_O(O - 1) + k$	1.110	0.597	0.221	1.420

Table 3.2: Fitting one-factor models

The models are shown in the left-hand column with perceived centre denoted by CP, horizontal image size by H, vertical image size by V, slant by S and overall image size by O. Their corresponding weights are denoted by w_H, w_V, w_S and w_O respectively. The justification for the (H – 1), (V - 1) and (O – 1) terms is given above. The sums of squares are shown in the table, with the smallest sum for each observer highlighted in red.

The highlighted sums of squares show the measures of perceived centre for all observers are best modelled as a function of horizontal image size. This would suggest that horizontal image size is the most important factor in determining perceived location, but gives no indication whether horizontal image size is combined with one or more factors. If this is the case then a model with two factors could give a better fit to the data. Therefore, the models that are combinations of two factors will next be considered. This follows exactly the same procedure as that for the one-factor models and the sums of squares are shown in Table 3.3.

Model	Observer sum of squares			
	CH	JTK	RW	TF
$C_P = w_H(H-1) + w_V(V-1) + k$	0.894	0.518	0.151	1.076
$C_P = w_H(H-1) + w_S S + k$	0.865	0.520	0.152	1.038
$C_P = w_H(H-1) + w_O(O-1) + k$	0.895	0.521	0.152	1.079
$C_P = w_V(V-1) + w_S S + k$	1.030	0.578	0.236	1.345
$C_P = w_V(V-1) + w_O(O-1) + k$	1.030	0.568	0.229	1.431
$C_P = w_S S + w_O(O-1) + k$	1.110	0.597	0.221	1.420

Table 3.3: Fitting two-factor models
As with Table 3.2, the models are shown in the left-hand column. The sums of squares are shown in the table, with the smallest sum for each observer highlighted in red.

The two factor models show the perceived centre measures of observers CH and TF are best modelled by a combination of horizontal image size and slant, while the perceived centre measures of observers JTK and RW are best modelled by a combination of horizontal and vertical image sizes. As with the one-factor models, these fits show the horizontal image size is still the dominant factor in determining perceived location. Comparing Tables 3.2 and 3.3 shows that the sums of squares are reduced in the two-factor models, seeming to indicate a better fit. This can be more rigorously determined by applying an F test to the data, using the following equation:

$$F = \frac{(SS_{One} - SS_{Two})/(DF_{One} - DF_{Two})}{SS_{Two}/DF_{Two}}$$

where SSOne and SSTwo are the sums of squares for the one-factor and two-factor models respectively, with DFOne and DFTwo the degrees of freedom for the models (Motulsky & Christopoulos, 2003). The degrees of freedom are calculated as the number of data points minus the number of variables in the equation. The degrees of freedom are 16 and 15 for the one-factor and two-factor models respectively. If the F value is significant (using DFOne – DFTwo and DFTwo as the degrees of freedom of the numerator and denominator respectively), then it can be concluded that the reduction in degrees of freedom is offset by the improvement in the least squares fit and the two-factor model is a better fit to the data. The F test results for each observer are shown in Table 3.4.

Observer	F test value	Significance
CH	0.48	$p > 0.05$
JTK	0.78	$p > 0.05$
RW	0.75	$p > 0.05$
TF	0.45	$p > 0.05$

Table 3.4: F test results

All tests have degrees of freedom of 1 and 15 for the numerator and denominator respectively.

Since none of the F test results were significant, it can be concluded that the two-factor models do not significantly improve the fit to the data. Therefore, it is appropriate to describe the data for each observer as a function of horizontal image size. The values for the weights and constants are shown in Table 3.5.

Observer	Weight				
	w_H	w_V	w_S	w_O	k
CH	6.95	-	-	-	0.30
JTK	4.53	-	-	-	0.57
RW	4.49	-	-	-	-0.04
TF	9.48	-	-	-	0.41

Table 3.5: Weighting of one-factor models

The values given for the weights correspond to the highlighted sums of squares shown in Table 3.2.

Despite the heavy influence of horizontal image size, the constant k, representing a natural bias in perceived location, also contributes to an observer's measure of perceived location. In conditions in which the stimulus has no horizontal image size differences and, therefore, no perception of slant, this shows that observers CH, JTK and TF should favour the left eye, while RW should favour the right eye. This is supported by the averaged data used to fit the models and also agrees with the data collected with no horizontal image sizes during the replication experiment for three out of four observers.

Although a function of horizontal image size provides the best fit to the data for all observers, it does not provide such a good qualitative fit for all data sets. Heavy reliance on horizontal image size can explain the reduced change in perceived centre shift with the slanted stimuli because those stimuli had a much smaller horizontal image size ratio than the stimuli used in the replication of Banks, Ghose & Hillis (2004). It can also explain why the slant nulling procedure was effective in reducing perceived location shift since it involved reducing the differences in horizontal image size. Presumably, if the nulling technique had involved altering the vertical image ratio rather than the horizontal ratio, then there would not have been such a great reduction in shift. However, reliance purely on horizontal image size information cannot explain the results of the final experiment, particularly the stimuli that only had a difference in vertical image size. If vertical image size data is largely ignored, as the above model fitting suggests, then there should be little or no shift in perceived location. As Figure 3.8 shows, this is not the case. Therefore, it is entirely possible that horizontal image size is not entirely responsible for determining perceived location but is favoured to such a heavy extent by the visual system that it is, effectively, 'overriding' the contribution from any other factors.

One potential explanation as to why horizontal image size is heavily favoured by the visual system could be provided when the concepts of divergence, rotation and deformation are considered. These were first outlined as part of a vector field analysis carried out by Koenderink & van Doorn (1976) and are explicitly depicted in Figure 1 of van Ee & Erkelens (1995). Essentially, divergence is a uniform increase or decrease in stimulus size, deformation involves expansion in one direction and contraction in an orthogonal direction (i.e. keeping surface area constant) and rotation is any rotation about an axis. Combining divergence and deformation in a linear combination produces a nonuniform scaling, i.e. scaling in either a horizontal or vertical direction. It follows from this that vertical scaling can be represented by changes in the horizontal dimension, i.e. a contraction in the horizontal dimension is equivalent to an expansion in the vertical dimension. Therefore, reliance by the visual system on horizontal manipulations can account for changes in the vertical direction. Furthermore, a linear combination of deformation and rotation produces a shear effect, i.e. a shear transformation carried out on a square produces a parallelogram. The study conducted by van Ee and Erkelens found that observers were able to produce slants in stimuli by linearly combining horizontal scale and horizontal shear. Therefore, since slant can also be accounted for by making only horizontal manipulations, it is unnecessary for the visual system to favour vertical size information and slant information when making the judgements required in the above experiments as horizontal size information is sufficient for any judgements required.

Conclusion

The above data and modelling have shown that vertical image size and slant are having little to no effect on perceived location and that differences in horizontal image size are primarily responsible for changes in perceived location. Since vertical image size is the primary cue to eccentricity, it may seem that dominance switching is not a function of eccentricity at all. However, horizontal image size does provide some eccentricity information. Therefore, the visual system is not rejecting eccentricity information by primarily weighting horizontal image cues. Furthermore, since horizontal image information can account for vertical scaling and slant, preference for horizontal image size cues also reduces the level of processing power required by the visual system. Therefore, the visual system needs only to rely on horizontal image size cues to make all of the judgements required in the experiments detailed in this chapter.

Chapter 4

Eye dominance and the egocentre: locating the centre of visual direction

In their first dominance switching paper, Khan & Crawford (2001) suggest that the signals used to change sighting dominance could also be used in the selection of an egocentric reference point. The follow-up paper (Khan & Crawford, 2003) also refers to the notion of a moving egocentre. Khan & Crawford suggest that their findings support the conclusion of Mansfield & Legge (1996), and by extension the findings of Erkelens et al. (1995) and Erkelens & van de Grind (1994), that the egocentre does not have a fixed location, but is able to vary in position along the corneal plane.

However, the notion of a dynamic egocentre has attracted some criticism (Banks et al., 1997; Mapp & Ono, 1999; Mapp et al., 2003). This is mainly due to methodological disagreements, particularly involving the difference between relative and absolute judgements. In essence, a relative judgement involves determining the location of two or more objects with respect to one another whereas an absolute judgement involves determining the location of one of more objects with respect to the viewer, i.e. the self. Hence, an absolute judgement can be used to infer the location of the egocentre, whereas a relative judgement cannot. Much of the criticism levelled at studies which conclude that the egocentre location is dynamic is that relative, not absolute, judgements were used. Indeed, Khan & Crawford (2003) state that their study cannot be used to draw any conclusions about the egocentric reference point due to the judgement used.

Therefore, the most direct way of testing whether the egocentre moves as the angle of gaze changes is to adapt Khan & Crawford's basic paradigm and estimate the location of the egocentre when observers are viewing eccentrically placed stimuli. Several methods of egocentric localisation exist and their corresponding methods and merits have been analysed in studies by Mitson et al. (1976) and Barbeito & Ono (1979). The method identified in these studies as the most reliable is that devised by Howard & Templeton (1966) and involves asking an observer to rotate a rod located at eye level until it appears to be pointing directly at them. Since this is an absolute judgement, the alignment axis, formed by extending the line of sight of the rod, should be pointing directly at the egocentre.

The following experiments report the findings when observers were asked to perform egocentric localisation tasks, such as those described by Mitson et al. (1976) and Barbeito & Ono (1979), at various eccentric stimulus locations. If the location of egocentre does change with gaze direction, then the egocentre could move along the corneal plane, as shown in Figure 4.1a.

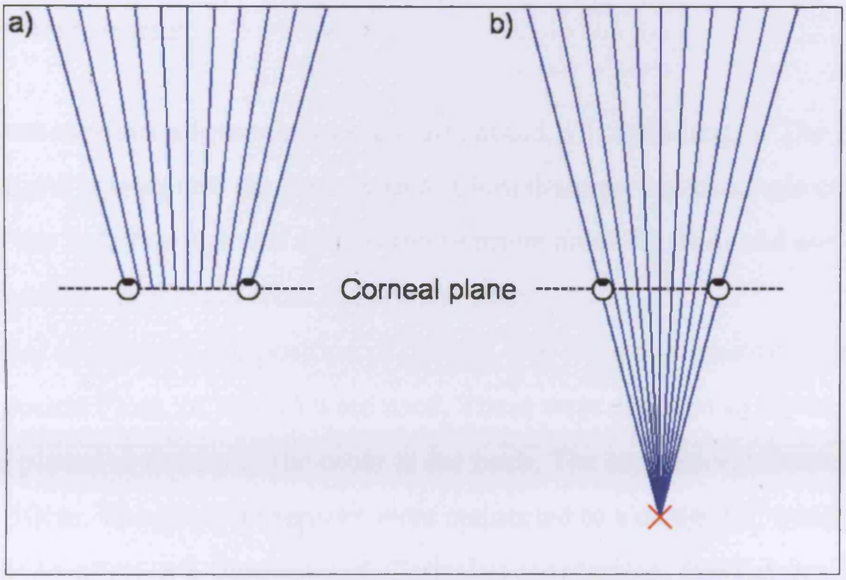

Figure 4.1: Expected pattern of egocentre alignments
The blue lines represent alignment axes, which point directly at the egocentre. The observer is represented by a pair of eyes on the corneal plane. If the alignment axes shown in a) are extended behind the corneal plane, they meet at the point denoted by a red cross in b).

In the figure, each alignment axis is assumed to originate at the top of the figure and point directly at the egocentre. The distribution of the axes would indicate that the egocentre moves along the corneal plane. However, if the axes are extended behind the corneal plane, as in Figure 4.1b, they intersect at the same point. Since all alignment axes should point at the egocentre, this would suggest that the egocentre does not vary along the corneal plane but is in fact fixed behind the corneal plane. This now raises the possibility that evidence of an egocentre which can vary in position along the corneal plane is simply a result of an egocentre which is fixed behind the corneal plane. Therefore, if the egocentre is found to lie behind the corneal plane, this strongly suggests that the egocentre cannot vary with eccentric gaze.

Method

Observers

Five observers took part in the rod alignment task. All were experienced psychophysical observers and were postgraduates recruited from within the School of Psychology, Cardiff University. Of the five observers, one was the author and the rest were naïve as to the purpose of the experiment.

Stimulus and apparatus

The rod used for alignment was a solid cuboid, 12 cm in length. The cross section of the rod was square (2x2cm) with a 0.7cm diameter circular hole cut through the centre of the rod. The rod was able to freely rotate about its front end and was placed at a distance of 70.8cm from the corneal plane.

In order to measure the position of the rod, two magnetic position sensors (Inition Ascension Flock of Birds) were used. These were attached to the top of the rod with one placed at the front, the other at the back. The separation between the sensors was 10cm. The position sensors were connected to a computer, which recorded their location in 3-dimensional, Cartesian coordinates. The sensors has six degrees of freedom and were accurate to within 1.8mm and 0.5° for position and orientation, respectively.

In order for observers to be able to see the rod, all trials were completed in dimmed light. The head was kept stable with a chin rest.

The rod was placed at the required horizontal eccentricity or height and held in position by the experimenter. Observers were instructed to adjust the rod until it appeared to be pointing directly at them and encouraged to use the hole in the centre of the rod as a sighting aid. The position of the rod was adjusted by the experimenter in response to verbal commands given by the observer. Once the observer was satisfied that the rod was pointing directly at them, a button was pressed and the position of the rod was recorded. The next trial was then initiated after at least 1s had elapsed.

Procedure

In a given trial, the rod would be placed at one of 11 eccentricities from the head, ranging from -25° to 25° in 5° intervals (A negative angle indicates the rod was placed to the left of the observer). The task was carried out twice at each eccentricity for a total of 22 experimental trials, with the order of trials randomised for each session of data collection. In addition, the direction in which the rod pointed at the start of each trial was also randomised.

Results and discussion

The data were collated and the intersection of all alignment axes was calculated. This intersection is defined as the point at which the perpendicular distances from all of the alignment axes are minimised. This is the intersection criterion that has been used in previous studies (Barbeito & Ono, 1979, Mitson et al., 1976). Figure 4.2 shows the intersections for the rod alignment task.

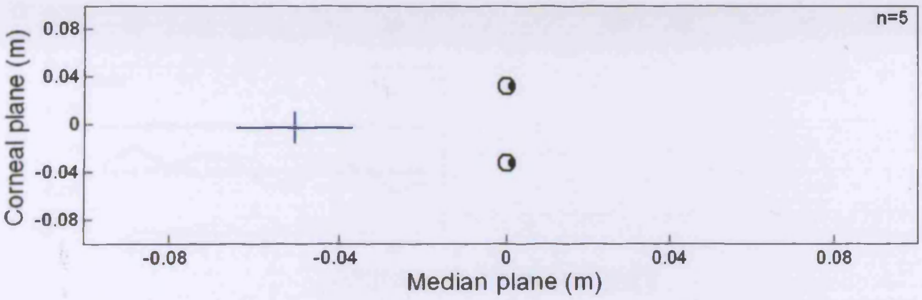

Figure 4.2: Intersections formed by rod alignment
These plots show the location of the intersections formed by horizontal alignment, viewed from above the head. The horizontal axis represents distance along median plane and the vertical axis represents the distance along the corneal plane. A negative median plane measurement denotes a location behind the corneal plane. A negative corneal plane measurement denotes a location to the right of the head. The length of the arms of the crosses denotes standard errors.

The rod alignment data clearly show an intersection located behind the corneal plane. Since the intersection can be considered an approximation of the egocentre location, this location seems to be compatible with either the existence of either a single, fixed egocentre behind the corneal plane or an egocentre moving along the corneal plane. Before any proceeding any further, consideration should be given to a variation of the moving egocentre hypothesis, namely that observers are aligning stimuli to the left of the head with the left eye and stimuli to the right of the head with the right eye. This would also produce an intersection behind the corneal plane. This possibility can be investigated by plotting where the alignment axes cross the corneal plane. If observers are aligning the rod with one eye or the other, the leftward alignment axes should cross at the left eye, the rightward alignment axes should cross at the right eye and there should be a sudden switch from the left end to the right end of the corneal plane. To show this, the alignment axes arising from the same eccentricity were averaged (reducing 22 lines to 11) and the point where they cross the corneal plane plotted in Figure 4.3.

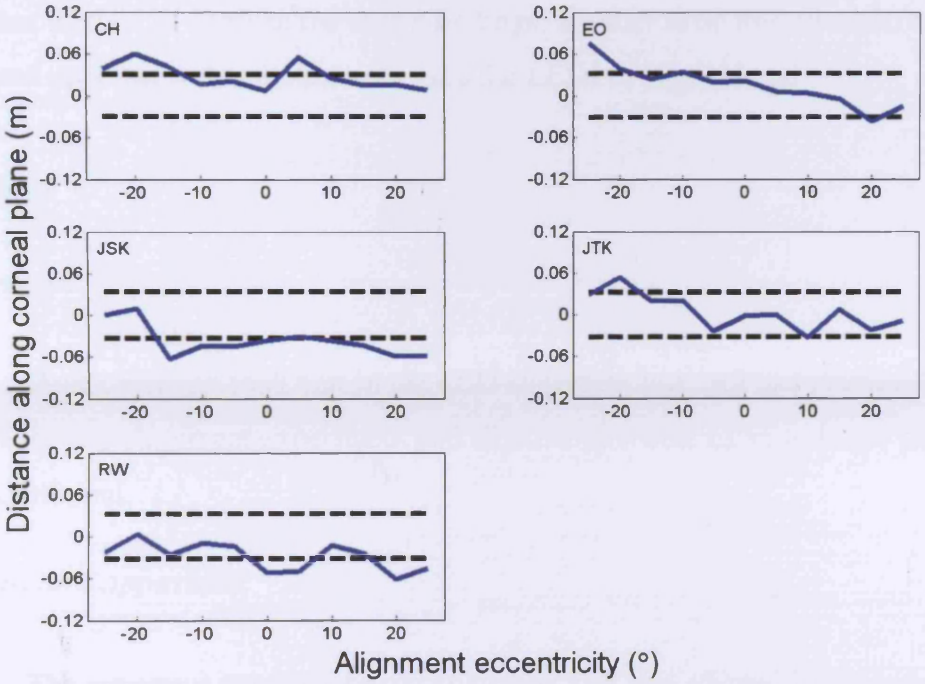

Figure 4.3: Intersections with the corneal plane – Rod alignment
These plots show where the averaged alignment axes cross the corneal plane. The left side of the corneal plane, i.e. the left side of an observer, is given a positive sign. The eccentricities, however, follow the convention given in the text in that a negative eccentricity denotes alignment carried out with stimuli to the left of an observer. The dashed lines give the location of the eyes for each observer.

Only observer JSK shows an abrupt, and permanent, switch between the left and right eyes, with that switch occurring when the rod is located at 15° to the left of centre. Observer JTK shows an abrupt switch, but does not then consistently align with the right eye. The other observers show either preference for one eye consistently or, in the case of observer EO, a gradual shift between the eyes. Any preference for one eye over the other can be explained by an egocentre located slightly towards one eye. This likely also applies to observer JSK since an egocentre located close to, and behind, the right eye will cause the far left alignment axes to pass through the left eye. Therefore, it is appropriate to conclude that observers are not simply aligning with one eye or the other, and that the egocentre could well be fixed behind the corneal plane.

An intersection location behind the corneal plane has been found in previous studies using both the Howard & Templeton (1966) method and other methods (Barbeito & Ono, 1979; Mitson et al., 1976). For these latter studies, the Howard & Templeton method was adapted by replacing the rod with a pair of lights, separated in depth. These studies also show variation in the location of the egocentre, even within the same methodology. For this reason, it is useful to repeat the experiment using a different method to confirm the above findings. In order to do this, two LEDs were mounted upon the rod and observers used the LEDs to align the rod.

Method

Observers

Four observers took part in the LED alignment task. All had previously taken part in the rod alignment experiment and all observers were naïve as to the purpose of the experiment.

Stimuli and apparatus

The apparatus used for the rod alignment task was adapted for this experiment. A green LED was mounted on top of each of the magnetic position sensors attached to the top of the rod. The vertical placements of the LEDs were offset slightly to ensure both LEDs could be seen at the same time. In addition, a small square of black card was mounted on the front of the rod in order to prevent observers merely aligning the rod instead of the LEDs. The observer's head was kept stable with a chin rest and trials were completed in both dim light and darkness. This was carried out to determine the effect of extra positional cues on egocentric localisation. The dim light condition will have extra cues to enable adjustment for the stimuli and, as such, other objects in the background can aid in alignment. Therefore, the dim light condition should be closer in intersection location to the rod alignment task than the darkness condition.

For all trials, observers were asked to align the LEDs such that an imagined line between them was pointing directly at them. As with the rod alignment task, the experimenter adjusted the position of the rod in response to verbal commands given by the observer. At least 1s elapsed between trials.

Procedure

In a given trial, the rod and LEDs would be placed at one of the 11 eccentricities used in the rod alignment experiment. The task was carried out twice at each eccentricity for a total of 22 experimental trials in each session, with the order of trials randomised for each session of data collection. In addition, the direction in which the rod pointed at the start of each trial was also randomised. One session of data collection was completed in darkness, another in dim light.

Results and discussion

The intersections of all alignment axes in each condition were calculated as for the rod alignment data. Figure 4.4 shows the calculated intersections.

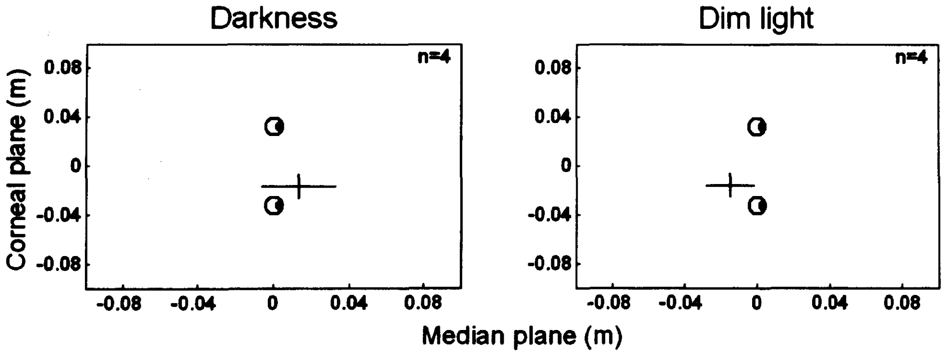

Figure 4.4: Intersections formed by LED alignment
These plots show the location of the intersections for darkness and dim light conditions in the left-hand and right-hand plots respectively. As in Figure 4.2, the horizontal axes in both plots represent the median plane and the vertical axis represents the corneal plane. As with previous data, the length of the arms of the crosses denotes standard errors.

The data collected in dim light agree with the data for the rod alignment experiment in that the intersection is located behind the corneal plane, although the intersection for the dim light data is very close to the corneal plane. The intersection for the data collected in darkness is also close to the corneal plane, but is slightly in front of it. Considered individually, these data might suggest an egocentre located near the corneal plane, rather than one placed behind as was found for the rod alignment task.

As with the rod alignment task, the intersections of the alignment axes with the corneal plane are plotted in Figure 4.5.

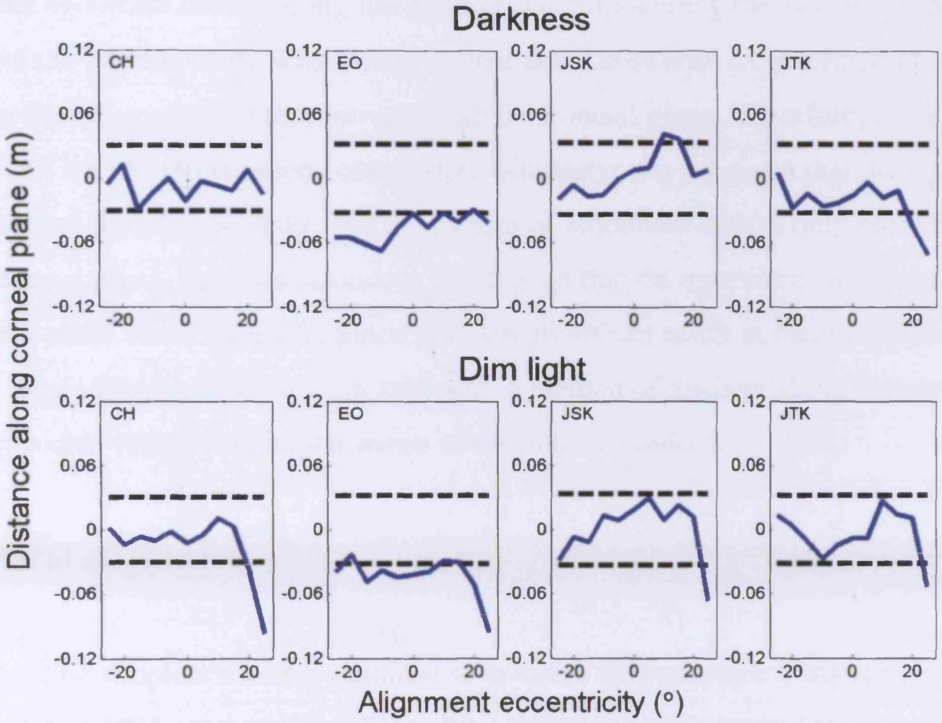

Figure 4.5: Intersections with the corneal plane – LED alignment
These plots show where the averaged alignment axes cross the corneal plane for the darkness (top row) and dim light (bottom row) conditions. The axes are as defined in Figure 4.3, with the dashed lines denoting the position of the eyes.

Neither the darkness nor dim light conditions show evidence of observers aligning with the left eye for leftward stimuli or with the right eye for rightward stimuli. Furthermore, the dim light plots show a sudden 'tailing-off' for the most rightward stimuli locations. Unfortunately, this cannot yet be explained. While these data show much more variation than the rod alignment data, the same conclusion can be made in that there is no evidence of alignment with either eye.

Returning to the intersection locations, there is evidence in support for the hypothesis that the intersection found in the dim light condition is closer to the rod alignment intersection that that found in the darkness condition. This would suggest that in both the dim light condition and the rod alignment task, observers are making use of the extra visual cues to aid in alignment.

The rod and LED alignments in dim light both suggest an egocentre lying behind the corneal plane. However, there is even variation between the results of these methods. Furthermore, further consideration of Figure 4.1 suggests that alignment tasks in the horizontal plane might not be enough to determine whether the egocentre is fixed or can vary in location. Consider the situation in which it is known that the egocentre moves along the corneal plane. Extending the alignment axes behind the corneal plane would suggest that these axes arise from a fixed egocentre, rather than an egocentre that moves along the corneal plane. Therefore, extending the axes can lead to an erroneous conclusion. Similarly, if it is known that the egocentre lies behind the corneal plane, but the pattern of alignment axes is only considered at the corneal plane, then the erroneous conclusion that the egocentre varies along the corneal plane could be made. Since both situations can result in identical patterns of data, depending on how they are analysed, a method of distinguishing between the two possible underlying explanations of the data is required.

Vertical alignment

The simplest method available is to locate the egocentre using rods located at different vertical eccentricities. Since the egocentre is not assumed to vary along the median plane, an egocentre localised using this method should distinguish between the two. If the egocentre is fixed behind the corneal plane, then the location of the vertical alignment egocentre should match the location of the horizontal alignment egocentre. If there is no agreement between the locations of the vertical and horizontal alignment egocentre locations and, furthermore, the vertical alignment egocentre lies in the corneal plane, then previous reports of a moving egocentre would be validated.

Method

Observers

The same observers who participated in the rod and LED alignment tasks took part in their vertical counterparts.

Stimuli and apparatus

These matched those used in the horizontal alignment tasks, with the only difference being alignment judgements were carried out in a vertical plane directly ahead of the observer.

Procedure – Rod alignment

The vertical experiment used three vertical rod heights. One was at the observer's eye level; the others were 10cm below and above the eye line. The task was carried out twice at each height for a total of 6 trials, with the order of trials randomised for each session of data collection. In addition, the direction in which the rod pointed at the start of each trial was also randomised.

Procedure – LED alignment

The vertical experiment used the same vertical rod heights as the rod alignment experiment, measured relative to the LEDs. The task was carried out twice at each height for a total of 6 trials per session, with the order of trials randomised for each session of data collection. In addition, the direction in which the rod pointed at the start of each trial was also randomised. As with the horizontal data collection, both darkness and dim light data were collected.

Results

The intersection of all alignment axes was calculated, as with previous data. Figure 4.4 shows the intersections for all of the vertical alignment tasks.

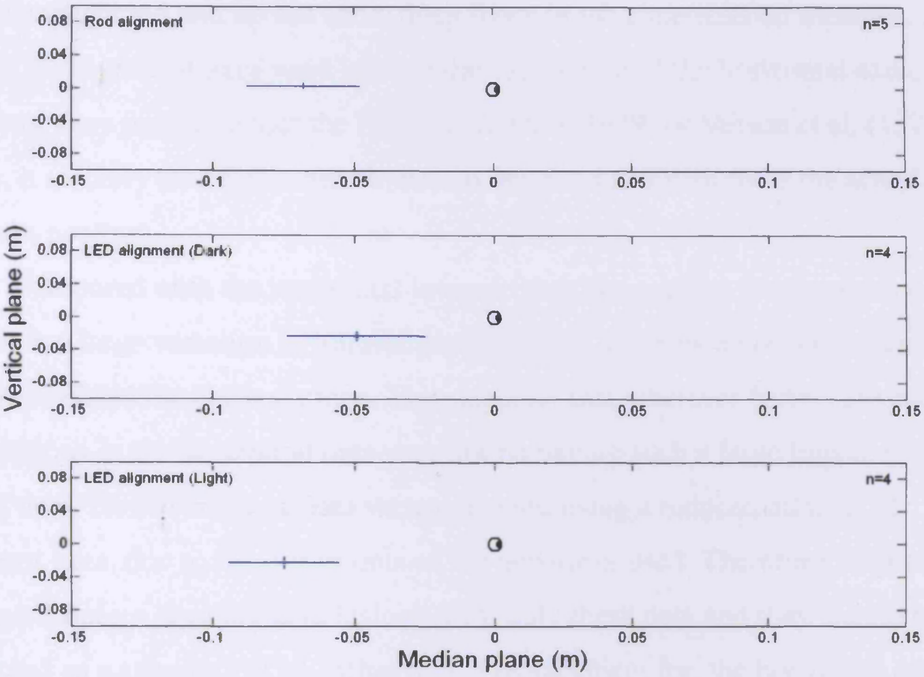

Figure 4.4: Intersections formed by vertical alignment

These plots show the location of the intersections formed by vertical alignment axes, viewed side on. The horizontal axis in all plots represents the distance along the median plane and the vertical axes represent the distance, vertically, along the corneal plane. A negative median plane measurement denotes a location behind the corneal plane. A negative vertical plane measurement denotes a location below the horizontal plane of the eyes. The length of the arms of the crosses denotes standard errors.

The figure clearly shows that, in all conditions, the intersections of the alignment axes lie behind the corneal plane. While there is a large variation along the median plane, at no point do the intersections intersect the corneal plane. Therefore, there is no evidence that the alignment point lies in the corneal plane. This suggests that the egocentre does not move along the corneal plane, but is fixed behind it.

General discussion

The above experiments were carried out to determine if the egocentre has fixed location, or if it varies in location as a function of viewing conditions. Several methods of localising the egocentre were used and the results for horizontal alignment suggested the egocentre lies behind the corneal plane, but there was definite variation between methods. This variability in egocentre location has been found before (Barbeito & Ono, 1979; Mitson et al., 1976) and is regarded as a result of inherent inaccuracies in the egocentre localisation methods (Ono, 1991). Due to these inaccuracies, the variations in the locations of the egocentre given above are not entirely unexpected and do not show deep flaws in the experimental methods. Indeed, because 22 alignment axes were used in the calculation of the horizontal axes, much more than were used in either the Barbeito & Ono (1979) or Mitson et al. (1976) studies, it is likely the intersection locations are good estimations of the actual egocentre position.

Compared with the horizontal intersections, the vertical intersections do not show such a large variation in intersection location. All show evidence for an egocentre behind the corneal plane. This suggests that whatever factors are causing the variations in the horizontal data may not be having such a large impact upon the vertical data. However, these data were collected using a reduced number of alignment axes, due to the constraints of the apparatus used. Therefore, caution should be adopted before drawing conclusions from only these data and they should be considered as a supplement to, rather than a replacement for, the horizontal data.

Considering both the horizontal and vertical alignment data, the prominent conclusion would appear to be that the egocentre lies behind the corneal plane and that evidence of a moving egocentre is simply an artefact of this location. This would explain the patterns of data that have been interpreted as a variable egocentre location in other studies (Erkelens et al., 1995; Erkelens & van de Grind, 1994; Khan & Crawford, 2003; Mansfield & Legge, 1996), as explained in Figure 4.1.

An additional consideration is that an egocentre that lies behind the corneal plane would also be closer to the centre of rotation of the head. This would reduce the recalibration needed when making egocentric judgements while moving the head. This has been suggested as a possibility in previous studies (Ono, 1991; Roelofs, 1959). The intersection locations found in the above experiments suggest the egocentre is located somewhere between 5 and 10cm behind the corneal plane. This placement is close to the centre of rotation, suggesting that both Ono and Roelofs were accurate in their suppositions.

However, there is also another explanation for the pattern of data presented by Khan & Crawford (2003). Following a critique of their work by Banks et al. (1997), Mansfield & Legge (1997) expanded on their conclusions and discussed how their findings point to the existence of an effective viewpoint, which is used as the basis for relative judgements of direction. They suggest that this viewpoint moves based on viewing conditions, while the location of the egocentre is unaffected. Therefore, Khan

& Crawford's 2003 findings could be the result of a change in effective viewpoint, rather than a change in the location of the egocentre. Unfortunately, the above results cannot provide evidence for or against the theory of a changing effective viewpoint. Therefore, in the absence of further data, the conclusion that evidence of a moving egocentre arises from one fixed behind the corneal plane remains valid.

Chapter 5

Eye dominance and the future: drawing conclusions on dominance switching

This thesis has addressed some of the issues relating to eye dominance changing with gaze angle, as found by Khan & Crawford (2001; 2003) and Banks, Ghose & Hillis (2004). Khan & Crawford (2001) hypothesised that dominance switching was a mechanism by which the visual system could optimise field of view. They suggest this because, in their task, dominance switched to the eye that was closest to the stimuli and, therefore, had a wider field of view than the other eye simply because the vision in the other eye is occluded by the nose and head. Banks et al. (2004) expanded on this finding and reported that it was the eye with the larger retinal image that was treated as dominant by the visual system. This still fits with Khan & Crawford's hypothesis of a mechanism that changes dominance in favour of the eye with the widest field of view since, by definition, the eye with the larger image has the wider field of view.

The question that now arises is why the visual system should prefer the eye with the larger field of view. The simplest explanation is that the eye with the larger field of view can provide more visual information to the visual system. The term visual information is used here to denote all the external information that can be transmitted from the eyeball to the brain in order to build a complete picture of the surrounding environment. Therefore, it can be assumed to include sources of information such as luminance, contrast and even colour. This information is then used in order to govern interactions with the environment. It follows that dominance switching allows the visual system to gather as much information about the surrounding environment as possible, particularly since the dominant eye activates a larger area of the primary visual cortex than the non-dominant eye (Rombouts, Barkhof, Sprenger,Valk & Scheltens, 1996). The main issue that will be addressed in this chapter is whether the data presented in the preceding chapters fits into a theory of global dominance switching mechanism based on maximising the amount of data the visual system can receive about its surroundings.

The introductory chapter outlined the case for which forms of dominance are likely to change, with sensory and sighting dominance being identified as the possible candidates. The issue of variable sighting dominance has already been addressed in previous studies (Khan & Crawford, 2001; 2003), so Chapter 2 was concerned with the effect a change in viewing conditions had on sensory dominance. The results showed that, when image size cues were nonexistent, manipulating gaze direction had little effect on reaction time. When image size cues were introduced in the second experiment, sensory dominance appeared to change based on gaze direction. This result fits with earlier studies which have shown that sensory dominance can be altered by external manipulations (Toch, 1960; Porac & Coren, 1975; Leat & Woodhouse, 1984). It also suggests that image size cues govern changes in sensory eye dominance as well as sighting dominance.

Consideration should also be given as to whether luminance could be a trigger for a dominance switching mechanism. Luminance could act as a trigger if the luminance is reduced sufficiently that one eye is unable to clearly distinguish the stimulus from the background. This would force the visual system to switch dominance to the eye with the higher luminance in order to be able to make the required judgement. However, during the reaction time experiments, luminance was not reduced to such an extent that one eye was unable to resolve the stimulus. Therefore, it is highly likely that the visual system did not need to switch dominance based on luminance and so changed dominance based on image size cues.

The importance of image size information to the dominance switching mechanism was emphasised by the findings of Banks, Ghose & Hillis (2004) and the findings of the experiments detailed in Chapter 3. The experiments were designed to address the effect perceived slant has on dominance switching. The raw results consistently suggested at least a small effect of perceived slant. However, the mathematical modelling indicated that the effect of slant was vanishingly small and the data were best represented as a function of horizontal image size only. The lack of reliance on slant information could suggest that the findings of the Fogt & Mowell (1999) study are correct and that slant is simply introducing a bias into perceived straight ahead and is not a factor in the dominance switching mechanism. It could also be the case that, as discussed in Chapter 3, changes in horizontal scale and shear can be used to represent any changes in slant and thus only horizontal image size information is required by the visual system to switch dominance. A lack of reliance on slant information to trigger changes in eye dominance makes sense if dominance switching is designed to be used during everyday viewing situations since isolated, slanted surfaces are rarely encountered.

The second Khan & Crawford study (Khan & Crawford, 2003) attempted to link dominance switching to the centre of visual direction, the egocentre. The experiments in Chapter 4 were designed with the same goal in mind. While these experiments were not able to categorically locate the egocentre, they did offer strong evidence that the egocentre is fixed in position. Since the egocentre is used as a reference point for directional judgements, it makes sense for it to have a fixed location. Judgements made relative to an egocentre that changes location based on viewing conditions would need to be constantly recalibrated, a significant drain on the processing power of the visual system. A fixed egocentre reduces the need for recalibration. An egocentre close to the centre of rotation of the head would need even less recalibration, since it should not be greatly affected by head movements.

If the egocentre is fixed in position, it cannot be linked to a dominance switching mechanism. However, studies such as Charnwood (1949), Francis & Harwood (1952), Erkelens & van de Grind (1994), Erkelens (1995) and Mansfield & Legge (1996) have suggested that the egocentre does move depending on viewing conditions. As has been previously discussed in the introduction, this is a controversial theory and has come in for much criticism (Banks et al., 1997; Mapp & Ono, 1999; Mapp et al., 2003). However, Mansfield & Legge (1997) introduced the concept of the effective viewpoint, the point of reference used for relative judgements. There is much more scope for the effective viewpoint to move based on viewing conditions. Charnwood (1949) showed that either blurring or reducing the luminance in one eye caused the effective viewpoint to move towards the other eye. This could mean that the effective viewpoint is also controlled by a switching mechanism. It could be further hypothesised that this viewpoint switching mechanism could also be based on providing the visual system with the maximum amount of useful data about the surroundings.

Further evidence of dominance switching

While the experiments and studies considered above have been directly connected to eye dominance switching, there is some evidence that dominance switching impacts upon other visual processes. For example, consider the study conducted by Coren & Porac (1976) which found that observers tended to perceive the image presented to the dominant eye as slightly larger than the image presented to the other eye. Since changes in dominance can be triggered by changes in retinal image size, it seems likely that eye dominance is highly sensitive to retinal image size. Therefore, it is possible that when identical images are presented to each eye, the dominance switching mechanism affects the perception of size. Since the visual system tends to associate a larger image with the dominant eye, it stands to reason that the visual systems 'assumes' that the dominant eye must be viewing a larger image which leads to the difference in perception noted by Coren & Porac (1976). However, Coren & Porac separated the stimuli such that observers were unable to fuse the monocular images. Therefore, this misperception of size might only apply when fusion is not possible.

However, Mefferd & Wieland (1969) linked size perception to eye dominance using fused stimuli. They found that, when asked to mark the centres of lines, left eye dominant observers tended to overestimate the length of the right side of the line and right eye dominant observers overestimated the left side length. At first glance, it may seem that this result does not agree with that of Coren & Porac (1976) but consider the consequences of the dominant eye having a perceptually larger retinal image. If, say, the right eye is dominant, then the right side of the line should appear larger than the other. In order for the centre of the line to appear correctly placed, the left side of the line would have to be overestimated to compensate for the existing overestimation of the right side of the line due to eye dominance. Therefore, both Mefferd & Wieland (1969) and Coren & Porac (1976) show evidence of the size of the retinal image in the dominant eye being overestimated by the visual system, with this overestimation likely arising from the dominance switching mechanism.

Some studies have shown evidence of dominance changing, but as a result of training, rather than as a result of a dominance switching mechanism (Toch, 1960; Porac & Coren, 1975). The study conducted by Toch (1960) presented discrepant stereograms to observers with the image designated as dominant during preliminary trials was always presented to the same eye. Toch found that sensory dominance tended to change to that eye, although the change in sensory dominance was not significant. Presumably, the image in the stereogram that was classified as dominant could transmit more visual information to the brain than the other eye in order to facilitate the switch in dominance. However, the slight change in dominance would indicate that the difference in visual information transmitted by the eyes was not sufficiently large to trigger a strong dominance shift.

Likewise, the Porac & Coren (1975) study also found evidence of sensory dominance changing with training. Rather than use discrepant stereograms, Porac & Coren separated the monocular images such that fusion was not possible and asked participants to perform simple eye-hand coordination tasks. They found a marked, although not significant, change in sensory dominance and attributed their result to their increased training time over Toch. With Porac & Coren's task, it is difficult to ascertain the amount of visual information presented to the eyes, but it is likely that the differences in visual information between the eyes were minimal since they simply consisted of separated monocular images. Therefore, it is possible their effect is small due to the lack of a large discrepancy in visual information between the eyes, as with the Toch (1960) study. However, the results of Porac & Coren's study suggest that the dominance switching mechanism can still affect the visual system even if there is only a slight difference in visual information between the eyes, providing a long enough exposure period is provided.

While the Toch and Porac & Coren studies do not provide evidence against the dominance switching mechanism, the study on sensory dominance conducted by Leat & Woodhouse (1984) does seem to. Leat & Woodhouse showed sensory dominance varied across the visual field, but there was no definite pattern of dominance between observers. Some observers showed strong right eye dominance when viewing stimuli presented in the right visual field and left eye dominance with stimuli in the left visual field. Others showed a reverse effect, i.e. left eye dominance in the right visual field and so on. These results appear to show that dominance changes based on visual field, but not in a consistent manner, directly contradicting the apparent consistency of the dominance switching mechanism based on image size.

However, Leat & Woodhouse's data were collected using stimuli presented at optical infinity, and so appeared to be a great distance away from the observer. Therefore, any differences in size between the two retinal images would have been infinitesimal, thereby removing any useful image size information. Without this information, there is no trigger for changing eye dominance and so the result that dominance changes across the visual field is entirely independent of a dominance switching mechanism which makes use of image size information to change dominance.

Looking to the future

While the experiments detailed in Chapters 2 to 4 have dealt with a broad range of issues arising from the existence of a dominance switching mechanism, there are still some outstanding issues that need to be addressed.

The reaction time experiments in Chapter 2 used luminance to cause one eye to become sensorially dominant over the other. One avenue of exploration could be to determine if luminance itself is sufficient to cause changes in dominance between the eyes. As discussed earlier, if the luminance was reduced such that the stimulus was difficult to distinguish from the background, then it is possible that the eye with the higher luminance would then be favoured by the visual system. This could be tested by running the reaction time experiments again and manipulating the luminance rather than gaze direction. However, a simpler task might just involve presenting rivalrous stimuli and manipulating the luminance of one of the monocular images.

Meegan, Stelmach & Tam (2001) reported the effect of blurring and pixilation on eye dominance. While their study discussed the relation between changing visual information and eye dominance, they never specifically tested whether the blurring and pixilation actually affected dominance. Therefore, the effects of these manipulations on dominance could be investigated in much the same manner suggested for luminance above.

Chapter 3 showed that horizontal image size differences had a greater effect of dominance switching then vertical image size differences which, in turn, had a greater effect then perceived slant. Continuing to determine the effect of slant is a possibility, but since the modelling showed that the effect of slant is vanishingly small and it is difficult to completely separate slant from image size differences, this would likely be a fruitless direction of exploration.

One study has shown that vertical size differences do affect perceived direction after an adaptation period (Berends et al., 2002), so the effect of vertical image differences on dominance switching could increase following an adaptation period and could possibly be due to altering perceived direction. This is easily determined by introducing an adaptation period into the image size paradigm. However, the dominance switching mechanism is likely used for near instantaneous changing of eye dominance, rather than occurring after a period of adaptation. Therefore, it would be questionable whether an adaptation period would affect the mechanism directly and also that any effect on the mechanism could also be due to vertical image size differences recalibrating perceived direction.

The experiments in Chapter 4 were designed to localise the egocentre and so none of the data could easily be related to the concept of the effective viewpoint. Clearly, determining the efficacy of the effective viewpoint concept is an important next step, as numerous studies have suggested or inferred that this viewpoint varies in position depending on viewing conditions (Charnwood, 1949; Francis & Harwood, 1952; Erkelens & van de Grind, 1994; Erkelens, 1995; Mansfield & Legge, 1996). The first step would be to design an experiment that could compare the location of the effective viewpoint with the location of the egocentre. The most logical method of achieving this goal would be to use stimuli that could be used to locate either the effective viewpoint or the egocentre depending on the precise nature of the judgement made by observers. However, this may not be practical to design and carry out.

Determining the location of the egocentre in Chapter 4 revealed that while the egocentre appears to be fixed in location, there is considerable error associated with locating it. It is possible that this error is due to a misperception of distance associated with the various experimental paradigms. This is likely to have the greatest effect on the alignment task performed in the dark and, hence, explains the discrepancy in intersection locations between this task and the other alignment tasks. However, a misperception of distance should also affect the vertical alignment data. This is not evident within the vertical alignment data.

If misperception of distance is having some effect, however, one way to reduce it would be to use a rod as a stimulus. This is because a rod is a continuous stimulus and should be more impervious to misperceptions of distance than the isolated LEDs. Therefore, any further experimentation with egocentre localisation could use a type of continuous stimulus such as a rod in order to enable the most accurate localisation of the egocentre possible before comparing it to the effective viewpoint.

The results of several studies have shown that eye dominance is correlated with concepts such as stereo prevalence (Ehrenstein et al., 2005; Kommerell et al., 2003). Therefore, it can be hypothesised that stereo prevalence could also be controlled by the dominance switching mechanism. This can be determined by investigating how stereo prevalence changes with variables such as image size or possibly luminance. However, since most tests for stereo prevalence require the alignment of two stimuli, it might be more straightforward to begin with the effect of luminance on stereo prevalence rather than image size to prevent any changes in image size affecting the accuracy of the alignment judgements.

Final conclusion

The experiments presented in this body of work have shown that eye dominance is not a static phenomenon, as was believed for centuries, but is adaptable to a variety of viewing situations. Dominance switching tends to favour image size as a cue to switching as a larger visual image contains more data that can be used by the visual system. This adaptability will likely impact upon several other visual processes, such as directional judgements, and the true extent of dominance switching remains to be discovered with this work providing a solid basis for all future studies.

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