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Oculomotor Responses and 3D Displays

By

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DECLARATION

The research contained in this thesis was carried out by the author between November 1993 and December 1997 while a postgraduate student in the Department of Psychology at the University of Durham. None of the work contained in this thesis has been submitted in candidature for any other degree.

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ABSTRACT

Katy A. Fulford, PhD 1998

Oculomotor responses and 3D displays

This thesis investigated some of the eye movement factors related to the development and use of eye pointing devices with three dimensional displays (stereoscopic and linear perspective). In order for eye pointing to be used as a successful device for input-control of a 3D display it is necessary to characterise the accuracy and speed with which the binocular point of foveation can locate a particular point in 3D space. Linear perspective was found to be insufficient to elicit a change in the depth of the binocular point of fixation except under optimal conditions (monocular viewing, accommodative loop open and constant display paradigm). Comparison of the oculomotor responses made between a stereoscopic 'virtual' and a 'real' display showed there were no differences with regards to target fixational accuracy. With one exception, subjects showed the same degree of fixational accuracy with respect to target direction and depth. However, close target proximity (in terms of direction) affected the accuracy of fixation with respect to depth (but not direction). No differences were found between fixational accuracy of large and small targets under either display conditions.

The visual conditions eliciting fast changes in the location of the binocular point of foveation, i.e. saccade disconjugacy, were investigated. Target-directed saccade disconjugacy was confirmed, in some cases, between targets presented at different depths on a stereoscopic display. However, in general the direction of saccade disconjugacy was best predicted by the horizontal direction of the target. Leftward saccade disconjugacy was more divergent than rightward. This asymmetry was overlaid on a disconjugacy response, which when considered in relative terms, was appropriated for the level of vergence demand. Linear perspective depth cues did not elicit target-directed disconjugate saccades.

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Dedication

To my parents, with love
To Mark, with love
To the spirit of adventure.....

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Introduction

This thesis is an investigation of eye movement factors related to the development and use of eye pointing devices with three dimensional displays. In particular, the overall aim was to examine the visual conditions under which disconjugate saccades occur and an accurate vergence response achieved. As demonstrated in the ensuing chapters, these factors specifically relate to the effectiveness of eye pointing in a three dimensional environment.

Three dimensional displays

Two dimensional virtual image displays, such as the head-up display (HUD) and the helmet-mounted display (HMD) are becoming more common in the aircraft cockpit environment. A virtual image is defined as 'an optical image formed by the apparent divergence of rays from a point, rather than their actual divergence from a point'. HMDs and HUDs provide many advantages to a pilot. For example, through enabling the overlay of symbology on the pilots view of the outside world, an outline of a runway can be displayed where it is obscured by fog. They enable the presentation of information to pilots without the need for them to look away from the window, particularly advantageous during complex low-level flying. However, HMD or HUD are limited in size and a disadvantage is that they can become easily cluttered with information. One solution to this problem is to display the information in different depth planes, for example, by placing the most important information at a different depth to the background information i.e. a three dimensional (3D) display. 3D displays are also an effective method for displaying complex information (Wickens 1989). They can provide a more 'natural' representation and therefore reduce the need for mental integration of two dimensional information with separate depth information. For example, they increase pilot-vehicle performance and situational awareness (Parrish *et al.* 1992). Conversely, the added dimension can be used to represent some other non-distance factor. 3D displays have been implemented in a variety of applied settings. For example, meteorology, molecular modelling, computer-aided-design, medical imaging, air-traffic control and the aircraft cockpit. Various depth cues have been utilised in the design of 3D displays. The two depth cues considered in this thesis are stereopsis and linear perspective.

What is eye pointing?

An eye pointing device is a system which determines and tracks the point on a display at which the eye's visual axis (line-of-sight) is pointing. The visual axis is defined in terms of the nodal points of the eye and for practical purposes may be considered to be the line joining the fovea to the object of regard (refer to page 15 for further details). Typically, the operator is "connected" to some eye movement measuring equipment, sat in front of a computer display and before tracking can begin, a calibration procedure is carried out.

Eye pointing as a novel computer input-control device

Typically, when we fixate or attend to an object we are, in fact, directing our line-of-sight (visual axis) towards that object. Since we perform this task naturally, and in general unconsciously, when we scan our visual world attending to various things, it has been suggested (for example, Ware & Mikaelian 1987) that eye pointing could serve as a very natural device for selecting objects visually present on a display. The human eye's line-of-sight has been of interest for centuries. For example, Hutchinson (1993) points out that the earliest record of such an interest may be attributed to a second century B.C. Chinese jade dealer who employed gaze analysis to determine customer interest in his product. More recently, the pattern of movements of the eye's line-of-sight has been used by the psychology and ergonomics communities to improve design layout of, for example, instrument panels in the cockpits of fighter aircraft. Although the interest in and techniques for measuring the eye's line-of-sight have been available for some time, until recently these techniques have been operationally crude with regard to an applied setting. For example, they have not allowed the operator freedom to move his/her head. However, the introduction of more sophisticated helmet-mounted devices have enabled the integration of eye and head position to give the eye's line-of-sight with free head movement. This has paved the way for considering in a more practical fashion the possibility of using eye pointing as a way of interacting with computers.

Human-Computer Interaction (HCI) can be defined as "the discipline concerned with the design, evaluation, and implementation of interactive computing systems for human use and with the study of the major phenomena surrounding them" (Dix *et al.* 1993). Within the framework of the discipline of human-computer interaction, the term interaction relates to the exchange of information between a computer and a human or user. One goal of HCI is to increase the bandwidth of communication between a computer and a user, ensuring that the means of exchanging information is both faster, more convenient and more natural to the user.

To date there are a number of styles by which a person can interact (i.e. convey and receive information) with a computer, which are supported by a range of input and output devices. Kraiss (1985) describes a variety of the more esoteric input devices. An interaction style or technique is a way of using a physical input device to perform a generic task in a human-computer dialogue (Foley *et al.* 1990). Early systems all relied on the user entering specific remembered commands from a command language into the computer using a keyboard. For certain tasks or systems this style was soon supplemented by the display of appropriate menus so that the next desired command had to be recognised and picked rather than remembered and entered. This interaction style was fully taken advantage of with the advent of the graphical user interface (GUI). It firmly set the agenda towards designing computer interaction styles and input/output devices, which supported the user by increasing the quantity, speed and ease with which information could be traded. The GUI is characterised by the use of windows so that users can have several tasks running at the same time; the iconic display of information, command selection via menus rather than a command language; support for the display of graphical as well as textual information. Finally, information is not only input into the computer via the keyboard but icons or menus can also be selected using a mouse or trackball (picking devices).

The majority of eye pointing applications implemented to date view eye pointing as a new form of picking device similar to and complementing those such as the mouse, trackball or sip and puff technologies which utilise the mouth and a straw. It increases the bandwidth of communication between a computer and user by virtue of being an extra input device, which can be used alongside or instead of more conventional picking devices. However, two important differences from conventional input devices have been noted (Ware & Mikaelian 1987). Firstly, a conventional picking device, such as a mouse, gains much of its accuracy by being a closed loop system, i.e. feedback on the position of the pointer is given on the display. Any measurement or aiming inaccuracies can be corrected for. However, due to the unsteady characteristics of fixational eye movements, it seems likely that any feedback information on position would need to be based on an on-line calculation for the length of the fixation. The pointer may not feel as responsive or controllable. To avoid this situation feedback could be given by lighting the item to be selected if the eye fixated it for a certain period of time. In this situation, since no direct position feedback is being given, a more precise measurement and a more precise aiming of eye gaze would be necessary. If this were not obtainable the size of the item to be selected would need to be increased. This would most likely result in having to use larger selectable items than those used with a conventional picking device. Ware & Mikaelian (1987) suggest one degree of visual angle. Secondly, because the eye continually scans any display jumping from one "stable" gaze position to another, some generic consent signal is needed to indicate which "stable" gaze position is to be picked i.e. the eye has no inherent consent "button". Suggestions for a consent button have included an increased dwell time, a generic hand or voice operated consent button and blinking. Despite these differences, eye pointing as a picking device is viewed as advantageous for a number of reasons depending on the user group and the application.

Certain disabled users only have the use of their "facial" muscles and consequently are unable to manipulate a hand held picking device. Eye pointing enables them a speedier picking device than current sip and puff technologies. Further, a small group of disabled users only have the use of their eye muscles and consequently eye pointing is the only input device which they can use. For example, Stephens (1987) gives a very graphic account of the difficulties that some disabled children have communicating with others. He notes that using eye pointing to interact with a computer may be one of the only mechanisms they can use for communicating with others let alone a computer.

Eye pointing has been developed to support a range of tasks for this user group. For example, various word processor applications have been developed which utilise the eye's picking ability. As early as 1976 Anderson *et al.* described an eye position controlled typewriter which they developed to enable severely handicapped individuals to communicate. The user was required to fixate on a particular character on a screen, for a certain amount of time, and then that character was typed. At about the same time Holt & Leavitt (1976) published a NASA Brief regarding an eye controlled teletypewriter which they had developed in 1974. Again a typewriter keyboard was displayed in front of the subject and, by looking at a specific character, the individual could cause the teletypewriter to type that letter on its page copy .

Hutchinson *et al.* (1989), at the University of Virginia, have developed a "unique prosthetic device" called the Eye Response Interface Computer Aid (ERICA) which they have currently applied to four tasks under the umbrella of one application. The four tasks are control, for example, environmental control or non-vocal communication of personal needs; communications, for example, word-processing and synthesised speech; recreation, for example, games and music; and text reading, including a small library of books. However, due to the relatively large resolution area of eye gaze coupled with recording uncertainty, only nine menu boxes (switches) or "areas that can be picked" can be displayed at any one time on a standard 19"-diagonal computer monitor. For example, within the word-processing application, only six boxes correspond to a letter of the alphabet with the three other boxes functioning as control keys. To pick a box the user must first point their gaze at the box and then secondly, to indicate that this is the correct box, stare at the box for a particular amount of time, typically one to two seconds. Consequently, although eye pointing enables the disabled user to input information into the computer, the large switch size required and the need to use a consent signal means that typing is a slow process. Performance has been speeded up by using such additional features as a character prediction algorithm. Even so, the time required to enter an average page of text is only just reduced to less than an hour (Frey *et al.* 1990). Evidently, this rate of communication is an advantage to disabled users with no other alternative but illustrates why eye pointing cannot currently directly compete as a replacement for such input devices as the keyboard.

There is some evidence that a smaller resolution of gaze can be achieved in a practical setting. For example, Spaepen & Wouters (1989) describe a system which uses a laboratory based NAC-V EyeMark eye movement measuring system together with a communication board containing 54 cells. They do not provide the dimensions of these cells or the board. However, with such a layout they claim a mean communication rate of 72 characters per minute (~17 words). In conjunction with this project Hine *et al.* (1990) are developing a non-mechanical eye gaze tracking system for use outside the laboratory. Davidson (1992) reports the existence of a system called EyeGaze from LC Technologies, Virginia which was displayed at the Imagina audio-technology festival in Monte Carlo. Here, up to 98 cells, displayed on a standard VDU monitor, were capable of being individually picked using eye pointing. Cairns *et al.* (1992) are currently developing a multi-modal office system for the disabled, which has utilised eye pointing along with other non-conventional input devices as a means of increasing the bandwidth of communication from the user to the computer.

Other researchers have also investigated eye pointing for the purposes of selecting letters or words. For example, Knysh *et al.* (1985) have developed a low cost, robust, eye glass mounted device which enables a user to select words or phrases from a menu thereby giving a disabled user some control over the environment. Charbonnier & Massé (1993) have investigated the influence of a feedback cursor, various selection confirmation mechanisms and the arrangements of letters on a display in order to ascertain the most efficient method of eye typing. Lastly, Laurutis *et al.* (1993) have compared an operator's ability to control a cursor with their eyes rather than using their hands or head.

Eye pointing has also been suggested as a picking device similar to the mouse within environments such as the super cockpit. Modern cockpits increasingly use computer displays as more and more information is being made available to the pilot (Calhoun 1986, Calhoun & Arbak 1984). Indeed, research in cockpit design is ultimately aimed at creating a virtual world around the pilot in the form of a helmet-mounted virtual panoramic display. Using conventional inputting control devices, for example joy-sticks, to access this displayed information would add to the pilots' already heavy workload. As it is they need to manage numerous hand held devices and hand operated switches. Consequently, the suggestion is that these displays can be manipulated by picking, for example, certain switches or icons using the eye's line-of-sight. For example, the pilot would gaze at a virtual image of a switch either for a pre-specified amount of time, or until he/she presses a confirming control, in order to activate it. Thus, eye pointing has the advantage that it leaves the pilots hands-free.

Schroeder (1993a) suggests that eye pointing is also a more direct input control device, having speed advantages over a hand operated device. For example, with a mouse, you have to find the cursor. With eye pointing, your gaze is the cursor. With a hand controlled device the pilot must first look at the object to be picked and then move the joy-stick or mouse so that the cursor is on the object. With eye control this element of eye/hand co-ordination is removed. As Jacob (1993a) notes "what you look at is what you get". However, when considering the speed of eye pointing, the time required to complete the consent operation, as well as switch activation, must be included in the total eye pointing switching time. Even so, Schroeder (1993b) has demonstrated, using a prototype eye-slaved target acquisition interface, that the eye is both faster and more accurate at picking and following a moving target than a hand operated device. He used the space bar on the keyboard as the consenting action. Calhoun & Janson (1991) have also directly tested the proposition, that eye pointing should be faster than hand picking, using length of gaze and voice consent as consent actions and found that even without training subjects were marginally faster at stationary switch activation using eye pointing (of the order of 1/2 s). They also assessed the impact of eye pointing on a concurrent tracking task. The subject had to ensure that a joy-stick manipulated cross-hair always overlaid a sinusoidally moving target. They found that performance on the tracking task was not impaired.

Other applications, involving the use of eye pointing as a picking device, which have been suggested are cueing and eye slaved aiming. Cueing refers to the use of the eye line-of-sight measurements to facilitate communication of such things as target positions between a pilot and a co-pilot. Assuming that both pilots are wearing helmet-mounted displays, at an appropriate time the co-pilot could indicate that he/she wished the helmet to display what the pilot is looking at. Eye controlled aiming might be either at a directly viewed target or at a virtual image of the target presented on the helmet display. Borah (1989) notes that an aiming accuracy of about 0.125 degrees would be required and that this accuracy is well within the capability of people to align one or more visual images, as in traditional aiming tasks. However, he notes that it would not be reasonable to expect such a degree of accuracy using eye pointing. Rather, the suggestion is that the pilot be required to aim within an envelope surrounding the target. Accuracy of one degree is probably sufficient for this type of target designation. Once again it is felt that eye pointing would be advantageous for this type of target designation task because it would offer potentially faster target acquisition times and also might give a capability to function in high gravity environments.

Lastly, eye pointing has been implemented in prototypical form, for the purpose of teleoperator control. This environment is typified by the existence of a video camera which relays its image to a remote computer display. The operator typically controls the position of the camera by observing this display and manipulating a joy-stick. Razdan & Kielar (1991) describe such an application where instead the user's eye line-of-sight is used to change the position of the teleoperated camera, the user's gaze position being fed back to the computer display. Charlier *et al.* (1993) also describe a teleoperator application where eye movement measuring equipment has been integrated into the eye piece of a surgeon's microscope used for microsurgery. The surgeon's point of eye fixation is then used to control the position of the microscope.

Hence, we can see that the technology for using eye pointing as an interaction device has been in existence for some time and that practical applications have been developed for certain specific tasks and/or user groups. For example, for hands-busy tasks or for disabled users. These applications have incorporated the "eye pointing device" into the human-computer dialogue as an additional or replacement picking device, in an interaction style based on the current use of the mouse, and as Jacob (1993b) notes have enabled the user to acquire an otherwise impossible new ability.

They have required the user to make specific, conscious eye movements in order to direct his/her gaze towards a target of some sort and then to activate some sort of consent signal. The ability to move ones eyes in this way needs little or no training. However, moving the eyes in such a conscious manner and then, for example, staring at an object for up to one or two seconds is not the normal mode of eye movement behaviour. It does require conscious effort and could not be termed natural.

Although the initial impetus towards using eye pointing, as a means of interacting with a computer, was given by the natural and largely unconscious way we scan our visual world, to date, as Jacob (1993b) points out, current eye pointing applications have not fully recognised the "naturalness, fluidity, low cognitive load and almost unconscious operation" of eye movements. Jacob sets out to remedy this situation. His aim is to develop an interaction style that utilises eye pointing in a more natural and convenient way. His basic research stance has been " to obtain information from the natural movements of the user's eye while viewing the display, rather than requiring the user to make specific trained eye movements to actuate the system". He has then searched for patterns in the raw data which correspond to tokens of higher meaning and incorporated these tokens into meaningful dialogues. This approach is indicative of a new general interaction style which is being hailed as the fifth generation user interface paradigm (Nielsen 1993, Jacob *et al.* 1993).

This style is based on a non-command style of interaction, the essence of which is that the user does not issue specific commands. Rather, the computer observes the user and makes appropriate responses, for example, if a certain number of fixations occur within a particular area of the display. In some senses these fixations can be construed of as commands. However, the user is not consciously or explicitly issuing them. They are instead, implicit in the natural way the user performs the task. The emphasis is on the non-intentional quality of the input, which is continuous, subject to real-time constraints and supports parallel input streams unlike current input to computers which consists of a single stream of discrete, serial commands. Examples of such fifth generation paradigms are play-along accompaniment, artificial realities and agents. As Foley (1987) notes, new artificial reality interface technologies are being developed which allow computers to be responsive to such natural human behaviours as speech, gesture, touch and eye contact. The aim is for these artificial realities to be so real that the user can use their existing communication abilities to interact with the computer. However, because of this non-intentional quality care must be taken not to allow inadvertent responses. For example, when a user looks at a display their gaze is continually jumping from one point of interest to another. A single fixation may not necessarily indicate that the user wishes the related function to be performed. Jacob (1993b) has termed this problem the Midas Touch. As previously mentioned, early command based eye pointing interaction styles sought to overcome this problem by implementing some sort of confirmation mechanism. For example, staring at the point of interest for a particular amount of time. However, all of these methods interfere with the natural operation of the eye's movements.

An example of a solution which is more in keeping with an implicit, non-command based interaction style is given by Jacob (1991). He describes a hypothetical "command and control" system for a fleet of navy ships. The display is split vertically into two halves, one larger than the other. On the larger half a map of the ships positions and direction of travel is displayed (small rectangles). On the smaller half, text is displayed concerning one of the ships. Raw eye movement data is continuously collected and is processed to reveal where the user is fixating. Where more than two fixations cluster closer to one ship than any other, then the textual information is changed so that it relates to that ship. The text is far enough away from the user's point of fixation to ensure that they are unaware of the change. However, whenever they want to see information about the ship they are interested in, i.e. looking at, they merely have to glance over at the text and it is automatically the relevant text. Hence, although this application does use an accumulated time approach to object selection, it relies on the user's natural tendency to cluster their fixations around an object rather than forcing them to fixate on an object for a specific dwell time.

Schryver & Goldberg (1993) also describe an eye pointing application which utilises a non-command interaction style. They call their method an "intent inferencing methodology" and comment that it does not particularly rely on an accumulated time approach to object selection but on other eye movement characteristics. Their application displays a set of three-dimensional objects on a computer display. By continuously monitoring the user's eye fixations they infer when the user is likely to want to rotate, translate or zoom in on a particular object. The particular eye fixation criteria used vary according to the specific task which is being attempted and are determined by observing the users natural sequence of eye movements when attempting rotation or zooming using more conventional interaction devices such as the mouse. Zooming-in or zooming-out requires more complex criteria than rotation or translation (Goldberg & Schryver 1993). However, this facility is particularly helpful in graphics, process control or telerobotics computer display interfaces, where for example, a camera mounted on the end of a robotic arm or mobile platform must be controlled by an operator who is watching a video display of this actual set-up.

Lastly, Starker & Bolt (1990) describe a non-command based system called The Little Prince. The computer screen shows a 3D graphic model (perspective & interposition cues to depth) of the planet the little prince lives on accompanied by a continuous narration. While the user is exploring the scene in general the narration concerns the planet in general. However, if a certain number of eye fixations cluster about a particular feature of the planet, then the narration changes from being general to being concerned with that specific feature. Hence, the user is not explicitly instructing the computer to output narration about a specific feature. Instead, the computer is observing the user's natural eye movements implicit in the task and from this inferring the narration sequence.

Eye pointing and three dimensional displays

Hence, in summary, eye pointing has been used both as a replacement device for the more conventional 'mouse' and as a means of inferring a user's intentions whilst they are interacting with a display. It has been implemented for a variety of tasks and user groups. However, to date, it has been used only in conjunction with two-dimensional displays. Hence, the location of the eye's line-of-sight on the display need only be specified in x,y co-ordinates and only one eye need be monitored. However, when interacting with three-dimensional displays, in addition to the x,y co-ordinates, the z co-ordinate must also be specified. This presents difficulties for conventional hand operated devices since users typically need considerable practice to be able to, for example, manipulate a joy-stick in three dimensions. However, this should create no additional difficulties with regard to 'learning to eye point', since in natural viewing both eyes line-of-sights are directed to and intersect at the location in space at which the user is looking (provided binocular vision is intact).

What are the main factors influencing the effectiveness of eye pointing?

There are various equipment factors which will influence the effectiveness of eye pointing. Firstly, how accurately can a particular eye tracking technique measure the movement of each eye's visual axis? Secondly, the accuracy with which the distance from the eye's centre of rotation to the display is known will affect the precision with which the eye's point-of-regard on the display, during a fixation, can be calculated. Typically, in the laboratory, this distance is measured using a ruler with the head stabilised so that it cannot move. However, under operating conditions it would not be feasible to have the head stabilised. Consequently, measuring this distance is likely to involve also measuring the location and movement of the head in space. This procedure will inevitably involve an additional source of errors. These factors are discussed more fully in chapter two.

There are two main eye movement factors which will influence the effectiveness of eye pointing in a three dimensional environment. Firstly, how accurately and reliably each eye fixates a target i.e. are the eye's visual axes actually pointing at the target or are they pointing slightly off the target. Secondly, the time course of the response of the binocular point of fixation in fixating a target i.e. how long will it take for the eyes to "get on-target". These factors are discussed more fully in chapter three.

2

Main equipment factors influencing eye pointing

This chapter will summarise the various equipment factors which can affect the effectiveness of eye pointing. It will include a summary of the various eye movement measurement techniques currently available, how accurately they can measure movement of the eye's visual axis and the potential measurement errors which the different techniques may introduce.

The eye as a rotating optical system

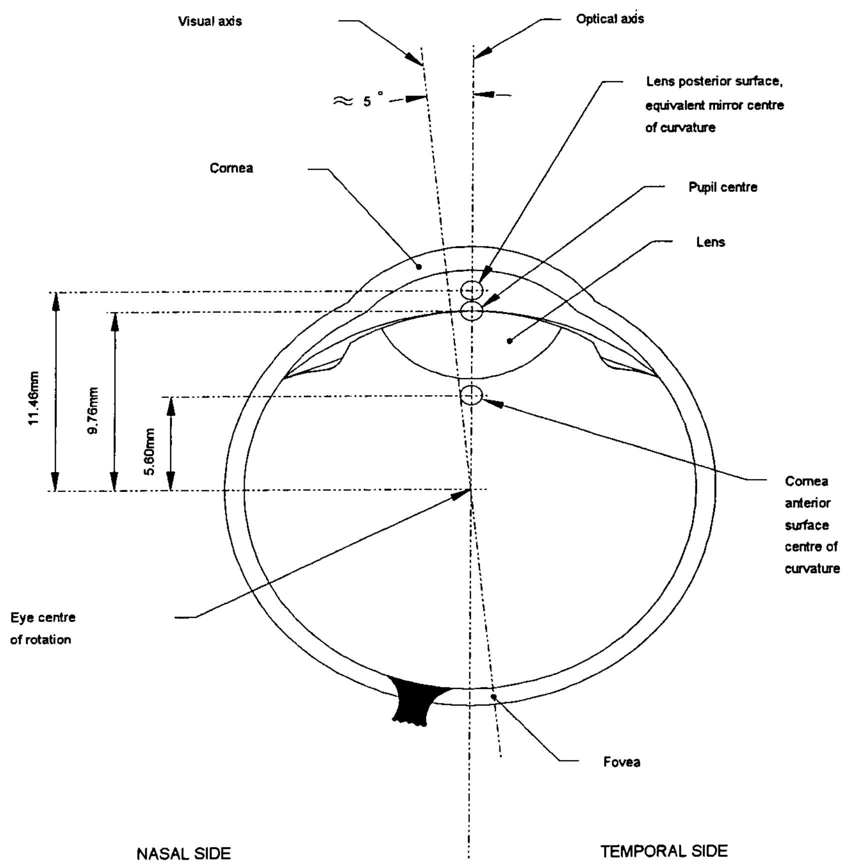

Figure 2.0 Structure of the eye (Young & Sheena 1975)

The eye can be considered to be a sphere tightly housed within an eye socket of the head, whose movements are almost entirely rotations about a nearly static centre of rotation. In fact, since the eye is housed in spongy rather than rigid orbital tissue, it is capable of making very small translational movements. Consequently, the eye's centre of rotation is not entirely fixed with respect to the head. However, this discrepancy is small enough to be of no consequence when it comes to making practical measurements of the eye's rotations. Recent evidence from Deubel & Bridgeman (1995) also suggests that the eye is not totally inelastic and that during eye movements the lens may move a small amount relative to the rest of the eye. This has an effect on eye tracking using the fourth Purkinje reflection and will be discussed in more detail in a later section. In addition, Enright (1994) has recently demonstrated that the eyeballs may be pulled slightly backwards in their sockets whilst a subject scrutinises a target. Typically, any rotating sphere has three degrees of freedom; vertical, horizontal and torsional. However, it has been found that the eye generally only makes use of two of these three degrees of freedom. Consequently, rotation of the eye can be entirely described by referring its movements to a vertical axis (typically chosen as the line joining the centre of rotation of each eye) and a horizontal axis (a line perpendicular to the vertical axis and in the plane of the face). Torsional rotations about the line-of-sight can be described entirely by the degree of horizontal and vertical rotation of the eye (Donder's Law). Another way of stating this, known as Listing's Law, is that each particular gaze direction in the horizontal or vertical plane is associated with a predetermined amount of ocular torsion.

The eye is an optical system consisting of four refractive surfaces (figure 2.0). The four refractive surfaces are the anterior and posterior surfaces of the cornea and the anterior and posterior surfaces of the lens. If the centres of curvature of each of these refractive surfaces lie on a straight line, which typically they do, then this line is called the eye's optical axis (figure 2.1). A pair of nodal points (N and N^1) can be defined on the optical axis, such that the ray ON "outside" the eye will emerge as N'O' "inside" the eye, where ON and N'O' are parallel (Carpenter 1988). In the eye the two nodal points are very close together and are often referred to as the nodal point.

The majority of light entering the eye is focused by these refractive surfaces onto the retina to form an inverted image of the visual scene. Where the optical axis of the eye is perpendicular to objects in the visual scene, their images can be considered to be a similarity projection i.e. the angles and relative distances between the objects in the visual scene are preserved. Objects which are at an angle to the eyes optical axis have their images distorted by perspective.

Someone observing an object of interest will move their eyes so that the rays of light from that object fall onto their fovea and this line is called the visual axis (figure 2.1). Typically, the optical axis does not fall onto the fovea. Hence, there is an angle between the optical axis and the visual axis and this is called the angle alpha.

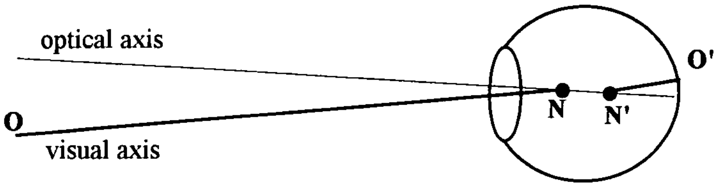

Figure 2.1 Diagrammatic representation of the eye's visual axis and its nodal points (N & N^1)

The line joining the centre of rotation of the eye to the object of regard is called the fixation axis.

These considerations need to be kept in mind when evaluating eye recordings.

Errors introduced by the equipment component of the system

Most eye movement recording systems work by tracking some location (physical or optical) referenced to the eye. When measuring eye movements, a distinction must be made between the movements caused by eye rotation and those unwanted ones caused by head translation. Typically this is done by either tracking two features on the eye which will move in unison when the eye rotates but differentially when the head translates or by attempting to completely stabilise the head. It is difficult to completely stabilise the head and some movement or physical slippage of the eye measurement system relative to the head inevitably occurs. The amount of error this introduces depends on which eye feature is being tracked. Further, with some eye movement tracking equipment there may be electronic drift due to, for example, temperature fluctuations.

If the position of the visual axis relative to a scene or display is to be measured, then the exact distance from the centre of the eye's rotation to the object in the scene must be known. Evidently it is difficult to be extremely precise about this figure, without a complex optical set-up. Errors of the order of ± 2.5 mm might be expected. This would result in the angular displacement of an object from a subject as being either 9.9° or 10.1° rather than say precisely 10°.

Lastly, errors may be introduced by using an inadequate calibration procedure. For example, failure to control for any non-linearity in the eye tracking data. McConkie (1981) provides some guide-lines regarding appropriate procedures both for obtaining and reporting the data. For a one-dimensional eye-tracking situation he suggests using three to five calibration points at equal distances apart with the two outermost points being at the outer edges of the stimulus region. Subjects should then be asked to look at each of the calibration points twice before the experimental task and twice afterwards. An average of these four data sets can then be used to linearly map the measurement signal to the position of each calibration point. The difference between the before and after calibration data sets gives an indication of location uncertainty caused by, for example, any movement of the eye tracking apparatus relative to the head during the experimental trials. Lastly, the accuracy of the mapping function can be assessed by using five equally spaced calibration points rather than three. The mapping function is carried out using the average of the four sets of data from the central and outermost calibration points only. Based on this information the theoretical position of the two midway calibration points can be calculated and subtracted from their absolute positions to give a mapping error score.

Choice of eye movement measurement technique

There is currently no ideal eye movement measurement technique. Each method has advantages and disadvantages. The method chosen will depend on the task. For example, whether it is desirable for some head movement to be allowed, and also on the characteristics of the particular eye movements which are to be measured. For example, if saccade velocity is to be measured then a high sampling rate must be used. There are various techniques on which the majority of commercially available eye trackers are based. These are electro-oculography, the scleral sensor-coil and those techniques which involve tracking points of light reflected from different surfaces of the eye. The different techniques assess the rotation of the eye's visual axis not only using different technology but also by tracking different features of the eye and relating these features to the visual axis. Consequently, each technique is susceptible to different sources of error. Hence, they vary in terms of the accuracy, resolution and range of eye movements they can measure. Resolution is defined as the smallest change of input to an instrument, which can be detected with certainty. Accuracy is defined as the extent to which repeated measures of the same value are correct. Hence, accuracy refers to the ability to determine absolutely the eye position whereas resolution is a relative measure. The different techniques also vary in terms of, for example, how invasive the technique is, how portable the apparatus is and how high a sampling rate can be used. Financial cost is not considered. The main points concerning each of the techniques are listed below. Fuller explanations can be found in Young & Sheena (1975), Carpenter (1988) and Green (1992).

Electro-oculography technique

The eye maintains a 0.4-1.0mV electrical potential between the cornea and the retina which is generally accepted as being responsible for setting up the electrical field in the tissues surrounding the eye. This field varies as the eye moves and can be measured by placing electrodes around the eye socket. This technique can be used to measure the full range of horizontal and vertical eye movements, although above 30° excursions linearity is lost. Frequent re-calibration (every few minutes) is necessary to correct for a gradual drift in the baseline readings. No head stabilisation is necessary.

Source of errors:- noise from electrode skin contact points, for example, from muscle action potentials or external electrical interference, skin resistance varies over time, eyelid interference, basic non-linearity in the technique, variation in the cornea-retinal potential because of level of light adaptation or state of alertness.

Accuracy:- typically ± 1.5-2.0°

Resolution:- 0.5-1.0°

Range:- ± 30°

Scleral sensor-coil technique

The subject wears a plastic ring or annulus, containing two coils of fine wire at an angle to each other, around their corneal bulge. The fine wire exits from the corner of their eye and is connected to a recorder. The subject is sat so that their head is placed between two large coils, at right angles to each other, which generate a uniform alternating magnetic field. This magnetic field induces a voltage in the eye coils, which is proportional to the sine of the angle between the plane of the eye coils and the direction of the magnetic field. The eye movement measurements are insensitive to head translations provided that the magnetic field is uniform in space. However, the eye coil temporarily raises intraocular pressure, thus limiting its duration of use to less than 30 minutes. It is also uncomfortable to wear and a local anaesthetic is required. Very high sampling rates may be used.

Accuracy:- 5-10'

Resolution:- 5-10'

Linear Range:- 10-15° horizontally and vertically without sine correction, ± 20° horizontally and vertically with sine correction.

Techniques which track a point of light reflected from the eye

The various optical surfaces of the eye not only refract light but also reflect and scatter a proportion of the incident light. These reflections can be tracked either singly or in pairs to determine the movement of the eyes. A major advantage of these techniques is that they are non-invasive, although limbus tracking does rely on the subject wearing the measuring apparatus on their head.

Limbus tracking

The boundary between the white sclera and the darker iris of the eye, known as the limbus, can be tracked due to the fact that the sclera and iris scatter different proportions of light. Typically, this boundary is illuminated with spots of infra-red light and photo-detectors are carefully lined up over the limbus. The quantity of light received is proportional to the area of sclera lying under the light spot. For small movements (± 10°) this is proportional to the eye's movements in the horizontal plane. The best limbus tracking techniques use multiple infra-red sources and detectors and then integrate the detector outputs in an intelligent way. The Skalar Iris system does this crudely. A system by BOUIS is more sophisticated. The system is not good at detecting vertical eye movements, since here the limbus is usually covered by the eyelids. However, limited vertical measurements can be made either by tracking the lower eyelid or by placing light spots and detectors in north west and north east positions. The main disadvantage of this method is that any head movement relative to the detectors will be interpreted as eye rotation. Taking the rotational radius of the eye to be 13mm, a displacement of the head by only 1mm will be misread as an eye movement of nearly 4.8°. Consequently, the head must be stabilised, for example, by using a mouth bite.

Accuracy:- typically ± 0.5° horizontally, ± 2° vertically

Resolution:- 0.1°

Range:- ± 15° horizontally, ± 10° vertically

Tracking of pupil centre

The pupil-iris boundary is even sharper than the iris-sclera boundary but under normal illumination the contrast is much lower. However, if the illumination (≈ 100cd/m^2 i.e. pupil diameter < 2.5 mm) is collimated and is parallel to the eye's optical axis, then the illumination is reflected from the interior of the eye. The pupil then appears bright when viewed along the optic axis and can easily be distinguished from the iris. Conversely, if the illumination is lowered so that the diameter of the pupil is > 3.5 mm then the pupil is most easily distinguished from the iris if it is dark rather than light i.e. if the illumination is not collimated with the eye's optical axis. Unlike the limbus, the edge of the pupil changes position according to the level of illumination, fatigue etc. Hence, the centre of the pupil, which is proportional to the position of the optical axis, is tracked. The main advantage of this method is that the entire pupil is visible over a wide range of eye movements. One disadvantage is that if the iris constricts asymmetrically then the centre of the pupil will change position with respect to the centre of rotation of the eye by a very slight amount. However, this can be corrected for by using computer linearisation techniques. Eye translation of 1mm parallel to the plane of the sensor will be misread as an eye rotation of 5.8°. Consequently, the head must be stabilised. The sampling rate obtainable is limited by the amount of information which must be gathered to calculate the pupil centre.

Tracking the Purkinje images

The four refracting surfaces of the eye reflect some of the incident light producing secondary images of the source light. These secondary images are called the 1st, 2nd, 3rd and 4th Purkinje images. P1, P2 and P3 are formed by the anterior and posterior surfaces of the cornea and the anterior surface of the lens all of which are convex to the incident light and so are virtual and erect whereas P4 is formed by the posterior surface of the lens, which is concave to the incident light, and so is real and inverted. P2 is very dim and since it is formed very close to P1 is never used. Similarly, P3 is also never used for tracking since its image is formed in a plane far from P1 and P4. P1 and P4 are formed approximately in the plane of the pupil. Since P4 is formed by the reflection of light from the posterior surface of the lens its position changes slightly with different accommodation levels of the eye. P4 is viewed through the entrance pupil but is obscured by the iris. Consequently the range of angles from which it can be viewed depends on the diameter of the pupil.

P1 or corneal reflex

The first Purkinje image, which is formed by the reflection of a point light source from the anterior surface of the cornea, lies ≈ 3.5 mm behind the corneal surface. Since the centre of rotation of the eye (≈ 13 mm) is not in the same place as P1, then when the eye moves the apparent position of P1 also moves and this can be recorded photographically. The light source can be very bright light enabling normal photographic techniques to be used. Conversely, an infra-red light source may be used. P1 is very sensitive to head movements. Assuming the corneal centre of curvature to be 5.6 mm, a head movement of only 0.1 mm will be misread as a rotational eye movement of 1°. Consequently, the head must be stabilised. The range of measurable eye movements is ≈ 10-20°. Larger excursions than this place the reflection on the outer edge of the cornea which is rougher and non-spherical. Complex calibrations and linearisation procedures are then needed to extend the range.

Accuracy:- 0.5-1°

Range:- ± 10-20°

Source of errors:- movement of light source relative to head, variations in corneal shape from a spherical one, thickness of tear fluid, pickup of reflections in any spectacles worn.

Dual tracking of optical features

One way of controlling for the inaccuracy of measuring eye movements due to head movements is to measure the translations of two features, which are at different radii from the centre of the eyeball. The relative movement between these two features enables movement due to head translation to be distinguished from movement due to eye rotation, since when the eye rotates the two features will move together but when the head translates they will move relative to one another.

Dual tracking of P1 and entrance pupil centre

Both P1 and the pupil centre are tracked. The range of this technique is limited vertically by the occlusion of the pupil edges or P1 by the eyelids and horizontally by the disappearance of P1. This gives a horizontal range of ≈ ± 25° and a vertical range of +30° to -10°. The sampling rate is limited by the amount of information necessary to determine the pupil centre. The measurement method is insensitive to translational movements and therefore head movement is allowed to the extent that P1 and the pupil edges can still be optically imaged. Various video image analysis systems (for example, Iscan or SMI) use this technique.

Accuracy:- ≈ 1° due to uncertainty of how the pupil centre is related to the optical axis over a changing pupil diameter.

Range:- ± 25° horizontally, + 30° to -10° vertically

Dual tracking of P1 and P4

This technique is more accurate than the former one since the location of P4 is more fixed. P4 is very dim and complex. Complex optical equipment is needed to detect it. The horizontal range of measurements obtainable is limited by the diameter of the pupil to ≈ ± 10-20° above which P4 is usually obscured by the iris. The use of a bright display, for example, a white rather than a black background reduces this horizontal range in most subjects. Very high sampling rates, for example 500 Hz, can be achieved. Some head movement is allowable since the eye movement measurements are independent of translational movements. However, head movement is restricted by the need for the P1 and P4 reflections to stay in view on the surface of the entrance pupil.

Accuracy:- ≈ 1'

Resolution:- ≈ 1'

Range:- ± 10-20°

Deubel & Bridgeman (1995) found that tracking P4 can lead to artefacts in the eye movement record at the start, end and during a saccade. They studied these artefacts by simultaneously measuring subjects' eye movements using the scleral sensor-coil and dual Purkinje image techniques.

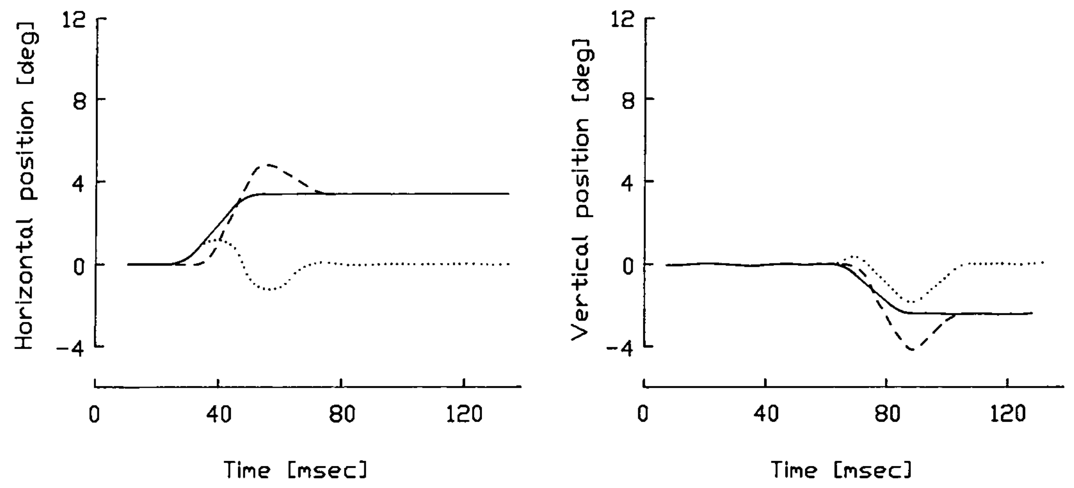

Figure 2.2 4° saccades recorded simultaneously using the scleral sensor-coil (solid lines) and the Purkinje eye tracker (dashed line) along with their difference (dotted line) (from Deubel & Bridgeman 1995).

They found that the dual Purkinje measurement technique introduced three artefacts (figure 2.2):

(1) small backshoots at the beginning of a saccade in the opposite direction to the eventual saccade. Mean backshoot size was 0.15° at near accommodation (22cm, 4.5D) and was 0.09° at far accommodation (390cm, 0.26D). Backshoot amplitude was related to saccade magnitude for one subject at both near and far accommodation and only for far accommodation in the other subject. Backshoot duration was less than 30 msec.

(2) small overshoots at the end of a saccade. The size of the overshoots were much larger than the backshoots. Larger saccades tended to be accompanied by larger overshoots. Mean overshoot size was 1.30° for saccades averaging a 6.1° amplitude at near accommodation and was 0.94° for saccades averaging a 5.79° amplitude at far accommodation. Again overshoot duration was typically less than 30 msec.

(3) the peak velocity of the saccade was nearly twice that measured with the coil.

The artefacts are thought to be due to lens movement relative to the eye caused by the fast acceleration (over 20,000°/sec2 for a 10° saccade) of the eye during a saccade. This movement is possible because the lens in held on each side by the zonular fibres which are elastic. Hence, the small backshoots are thought to be due to the lens lagging behind the eye at the start of the saccade. The small overshoots are thought to be due to the lag of the lens behind the eye at the end of the saccade. In between these two events the lens moves faster than the eye. Deubel & Bridgeman (1995) note that "both types of movement (over- or back- shoot) have longer durations with large magnitudes (of saccades) suggesting a viscous load is affecting lens movement as well as an elastic one". The size of the artefacts suggest that the dual Purkinje eye tracker technique may be unsuitable for measuring (a) the peak velocity reached during a saccade and (b) saccade overshoots.

Specific eye movement measurement systems used in this project

IRIS infra-red light reflecting eye-tracking system - model 6500

The IRIS infra-red light reflecting eye-tracking system tracks the limbus using nine infra-red sensitive photo detectors and infrared emitting diodes. The nine photo detectors are positioned above the line-of-sight of each eye and the array of nine diodes below each eye, so that the detector-diode pairs are on the temporal and nasal side of each eye. The photo detectors detect any reflected infra-red light and transduce the quantity into a voltage and the voltage of the nasally positioned detector is subtracted from the voltage of the temporally positioned detector. The voltage difference is demodulated to remove the chopping effects and amplified. The resulting voltage signal is proportional to the rotational movements of the eye with respect to the head. However, the signal amplitudes for an abducting and adduction eye movement of the same extent are only equal when the diodes are positioned symmetrically with respect to each eye.

The infra-red illumination is chopped enabling higher energy infra-red light to be used, while the overall exposure remains the same. This helps to minimise interference from ambient light and improves the signal to noise ratio. The whole system is head mounted and light weight. It is manufactured by Skalar Medical b.v. Their figures for accuracy and resolution are quoted.

Accuracy:- no specification given

Resolution:- 2'

Range limited by equipment:- ± 30° horizontally

± 20° vertically

Dual-Purkinje-Image eyetracker

The system used was manufactured by Fourward Technology. It is a large, heavy table mounted device consisting of a complex arrangement of lenses, motors and electronic sensors, which enable the dual tracking of the first and fourth Purkinje images (using infra-red light illumination of the eye) of one eye (right eye). The subject is required to sit with their head supported by a chin rest and resting on two forehead supports. Whilst eye tracking the subject must not move their head away from the supports since such a large movement may result in breaking the eyetracker's finely tuned tracking mechanisms. The accuracy and resolution figures quoted below are those of Fourward Technology.

Accuracy:- 1'

Resolution:- 1'

Range is limited by pupil size:- ≈ 20° by 20°

3

Implications of eye movement characteristics for the effectiveness of eye pointing?

This chapter provides a brief introduction to eye movements and vision. It will then summarise the various eye movement factors which may influence the effectiveness of eye pointing. In the first place, the stability of eye movements while fixating a target will be considered. The form of oculomotor response when moving to a target in (a) the same depth plane but a different direction and (b) the same direction but in a different depth plane will be considered. This latter section will discuss the precision with which the visual axes meet at the same point on an object (i.e. fixation disparity). Lastly, the form of oculomotor response when moving to a target in a different direction and in a different depth plane will be considered.

Brief introduction to eye movements and vision

In man, both eyes are forward looking giving a field of view at any one time of approximately 180°. Hence, given that we can freely move our heads and that a mechanism exists for holding an image steady on the retina, it is not obvious that we need to move our eyes at all. The reason lies in the fact that the level of visual acuity across the retina is not uniform - we cannot "see" equally well in all parts of our field of view. The central area of the retina, known as the fovea, is capable of high levels of visual acuity, whereas the surrounding area or periphery is not. In fact, as Carpenter (1988) notes, by the time 1° from the centre of the fovea has been reached, visual acuity has fallen off by a factor of 2 or 3. Hence, the fovea gives us a small tunnel of clear vision. One of the reasons that we do not perceive such a tunnel of high acuity, when we observe the world, is that our eyes are continually on the move, jumping from one location to another, rapidly sampling our field of view with this small tunnel of vision. Typically, during normal scanning of the visual scene, the eye will hold this tunnel of vision on an area of interest for about 200 milliseconds (Borah 1989). This is called a fixation and is where the majority of visual information is acquired. The rapid jumps between these fixations are called saccades. The peak velocity of these jumps may be in the range of 20° - 800°/s, with a duration of 20 - 100 msec (figure 3.0).

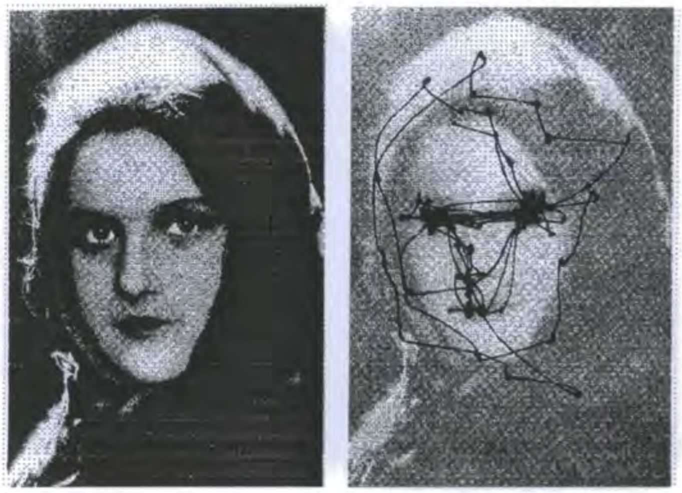

Figure 3.0 Scanpath of eyes *(right)* in looking at a picture *(left)* for 1 minute (from Yarbus 1967)

Very little visual information is acquired during the saccade because of the high speed with which an image moves across the retina and because the visual threshold for detecting a stimulus is elevated (Mitrani *et al.* 1973). However, when explored in the laboratory the suppression does not seem to be total. For example, Gresty & Leech (1976) reported that the subjects in their experiment could perceive the general location of a target which was presented only during their saccades.

More than 85% of naturally occurring saccades jump less than 15°, although their amplitudes can range from a few minutes of arc to 90°. The high velocities plus the short durations of these saccades enable fixations to keep the image of an object in the real world held in a roughly constant position on the retina for about 95% of the time. As Carpenter (1988) notes, our perception of the visual world is consequently equivalent to a situation in which the entire retina is capable of high acuity vision.

An image needs to be held roughly constant on the retina (as occurs in a fixation), since movement of an image over the retina significantly degrades the acuity of vision. However, this is not to say that the image needs to be held completely stable in a particular retinal position. Indeed, very small movements occur during fixations, without which the retinal image would "fade" (Carpenter 1988). These small movements can be categorised into 3 different types of fixational eye movements (figure 3.1):

1. Tremor
2. Microsaccades
3. Drifts

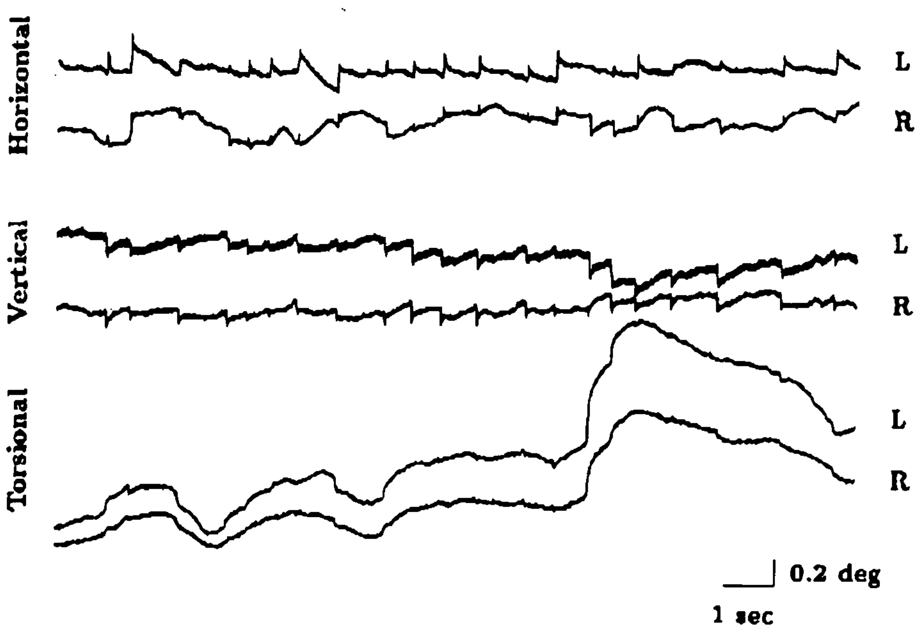

Figure 3.1 Representative recording of eye rotations in the horizontal, vertical and torsional plane during 15s of steady fixation. Tremor, drift and microsaccadic eye movements are present within the recording (from Ott *et al.* 1992).

Tremor movements are fast (20-100Hz), small and involuntary. Their mean amplitude is about 20" (Steinman *et al.* 1982), which is roughly equal to the distance between cones in the foveal bouquet. Consequently, on their own they are insufficient to stop retinal fading and are held to have little visual significance. They are usually considered to be the result of physiological noise.

Microsaccades are larger, having amplitudes in the range of 5' - 30' depending on whether the subject's head is fixed or not. They are very fast movements and under experimental conditions typically occur once or twice a second although some subjects don't make them at all (Winterson & Collewijn 1976). They have the same velocity - amplitude characteristics as larger saccades. Their size and most frequent direction varies from subject to subject. They occur simultaneously in each eye and are usually but not necessarily conjugate (although the two eyes very rarely actually move in opposite directions) (see later section on disconjugacy). They usually have a corrective function i.e. they tend to bring the centre of a target closer in line with the fovea.

In between these microsaccades both eyes drift slowly with velocities of 5'/s - 15'/s, generally in the opposite direction to the previous microsaccade. These drifts are superimposed on the tremor movements. The drifts occur simultaneously in each eye but may be conjugate, convergent or divergent (Ditchburn & Ginsborg 1953). They may be corrective or uncorrective (Nachmias 1959, 1961; St Cyr & Fender 1969). For example, upon instructions subjects can easily suppress the number of microsaccades they make. Drift movements are then sufficient to keep the eye on target. Under natural conditions (i.e. no head stabilisation) drift movements are also sufficient to stop retinal fading.

Given this information, what is the function of microsaccades? The answer to this question still evokes controversy. The main issue centres on whether microsaccades are necessary to correct each eye's position or whether they have no obvious function (Ditchburn 1980; Kowler & Steinman 1980). For example, given that drift can maintain eye position and stop retinal fading, it can be asked why microsaccades, which may momentarily suppress visual acuity, occur at all. Steinman *et al.* (1973) suggest that under normal rather than laboratory viewing conditions, where fixations usually only last for 200msec, they in fact rarely occur at all. Further, as previously mentioned, even under stabilised conditions some subjects make no microsaccades. Neither the cat or rabbit make microsaccades and the rhesus monkey only does so after extensive training. Microsaccades do not seem to aid visual processing. For example, Kowler & Steinman (1977) found that they did not improve the counting accuracy of items confined to a small region. Naive subjects performing visuomotor tasks such as threading a needle or aiming a rifle suppress the number of microsaccades they make either just before the critical part of the task or during the whole task (Winterson & Collewijn 1976).

Other types of eye movement, which serve to keep images in a particular location on the retina, are vestibuloocular eye movements and optokinetic eye movements. These are involuntary eye movements which work together to compensate for head movements.

Smooth pursuit eye movements serve a similar purpose but they compensate for slow movements of objects of interest in the real world rather than head movements, i.e. they enable an individual to continuously track a slowly moving object with their fovea.

Lastly, we have vergence eye movements. For us to perceive a single field of view from the input of two eyes, it is necessary for the image of an object to fall on corresponding points of the retina of each eye. For viewing distant objects this is achieved by the two visual axes being parallel. When the object moves in the same depth plane, both eyes would need to move in unison, i.e. conjugately, to maintain the object within the fovea of both eyes. However, if the object moves towards the observer, the two visual axes will have to converge in order to maintain retinal correspondence. Vergence eye movements are responsible for this task, which they perform with precision but not perfection.

The stability of fixation

When a person fixates on a target various small fixational eye movements occur such as tremor, drift and micro-saccades (refer to page 27). The amplitude of these small fixational movements generates a dead zone within which, for any one reading, it is impossible to ascertain the precise point at which the person is fixating. Steinman *et al.* (1982) (binocular recording) found that when a person's head is stabilised by a bite board this dead zone is of the order of 3' in the horizontal axis i.e. 95% of the time the visual axis was within 3' of the target centre. When the person's head is unclamped and they are trying to sit or stand as still as possible this dead zone was of the order of 15' and lastly when the person was moving in a natural way it increased to about 30'. Further, they found that the precision of vergence, i.e. fixation disparity, also deteriorated with increased bodily movement i.e. the small movements were not the same in each eye. Under stabilised conditions Steinman estimated fixational disparities to be approximately 10' compared with 118' during bodily movement. Ferman *et al.* (1987) found slightly lower standard deviations of gaze positions (monocular recordings). In the horizontal and vertical direction, with the subject trying to hold their head still they found a variation of 7'; mean non-saccadic retinal image speeds of 20'-30'/sec and when the subject moved their head they found a variation of 16' and 1 deg/sec.

Ferman *et al.* (1987) also measured the eye's stability in the torsional direction and found it to be much worse. With the head still it was about 17'; 46'/sec. Ott *et al.* (1992) also conducted an experiment to assess the stability of binocular eye orientation in the torsional as well as the horizontal and vertical axes during fixation with the head stabilised. They confirmed the previous results, where horizontal and vertical eye rotations were found to be a mixture of slow drifts and resetting microsaccades, yielding an average standard deviation of 0.10°. However, in contrast, they found that torsional rotations showed unsystematic slow drifts with fewer corrective microsaccades yielding a higher standard deviation of 0.18°. They attributed this difference to the fact that although torsion will create some retinal image motion in the periphery, there are no visual consequences of torsional rotations at the fovea. In other words retinal encoding provides no position feedback information as to when torsional movements have occurred. This discrepancy between the encoding of the retinal image in two dimensions and the control of ocular movements in three dimensions means that ocular torsion is undetermined. They concluded that the level of torsional variability observed was the result of noise inherent to the ocular system.

However, Van Rijn *et al.* (1994) have recently examined spontaneous variations in binocular torsion to a single dot i.e. in the absence of torsional cues. They measured variability over trials which were 32 seconds long after ascertaining that variability did not increase if measurements were taken over a longer trial period. They found that the variation was largely conjugate implying that cyclovergence is more stable than cycloversion. Further, cyclovergence and horizontal vergence were more stable when a background of random dots was displayed, i.e. torsional cues were provided, whereas cycloversion was unaffected. These findings seem to suggest that torsional stability can be affected by visual feedback and that the ocular system does seek to ensure that the two eyes move in torsional unison. The most obvious consequence of this unison is that retinal correspondence is then maintained. Although Van Rijn *et al.* (1994) found no direct implications of the stability of torsional vergence on slant or tilt perception, they do cite evidence to suggest more indirect links.

The horizontal and vertical stability of any fixation is thought to depend on visual feedback since gaze becomes more variable if the subject is asked to look at an imaginary target in darkness (Ott *et al.* 1992). The stability of fixation may also depend on which direction the eye is pointing in. To my knowledge no data for normal subjects exists on this issue.

For practical eye pointing purposes Borah (1989) quotes the dead zone as being approximately ± 0.3° of visual angle. However, if the eye pointing data is being processed in retrospect then it is possible to take an average of the total sample of instantaneous fixation positions, which were measured while the subject was "on-target", to obtain a better estimate of where the subject is looking.

Eye position deviation during a fixation also sometimes increases with fixation duration (Borah 1989). Borah suggests that a reasonable choice for a fixation duration is between 0.5 and 1.0 seconds after which performance starts to decline.

On average, during a fixation, is the eye's visual axis pointing at the target?

During a fixation a subject might not look at the precise centre of the target but rather at one or other edge of the target. This introduces a potential error of ± half the size of the target. Kaufman & Richards (1969) determined subjects' spontaneous fixation tendencies for simple forms. They used the phenomenon of "Haidinger's brush" to locate each subject's fixation position on a display. The stimuli were projected, using slides, onto an aluminised screen, that preserved the polarisation of the reflected light. A glass filter was placed in front of the projector in order to obtain only blue light. When a Polaroid filter was rotated in front of the projector the observer perceived

"Haidinger's brush". This is thought to be caused by the thousands of blue-light absorbing radially orientated crystals in the macular region. Hence, its reported location corresponds to the orientation of the fovea. Interestingly, they found that the subjects' fovea were not always oriented towards the point at which they believed they were looking. Subjects were asked "to look at the projected display". They tended to fixate on the centres of small stimuli (<2° visual angle). However, they reported that they were looking more or less randomly throughout the stimuli. For larger stimuli subjects tended to fixate on the boundaries between different areas.

It must be remembered that the eye movement instrumentation is measuring the subject's visual axis, that is the line drawn from the object of regard to the fovea. It is not known to what extent people always tend to fixate an image of a target on the centre of the fovea or on the exact same spot on the fovea (between successive fixations). The diameter of the central fovea or foveal bouquet, where receptors are most tightly packed, is approximately 0.2° (Carpenter 1988). Hence, potential errors of this type would be in the order of ± 0.2°.

Steinman (1965) investigated the effect of target size, luminance and colour on the stability of monocular fixation (one eye covered) for two subjects whose heads were unclamped but stationary. He found differences, of the order of 2-4', in the mean fixation position of larger targets (87.2') compared with smaller ones (1.9'). One of the subjects also showed differences in mean fixation position when viewing identically sized targets of different luminance values and when viewing identically sized targets of different colours. Subjects showed more variability around the mean position for larger targets, no differences in variability between the differently coloured targets and decreased variability as luminance increased. Neither subject showed any difference in the amount of drift for targets of differing size, colour or luminance. Both subjects showed fewer microsaccades with the largest target.

A subject's visual axis may move off-target, particularly towards the end of a recording session, due to momentary lapses of attention or fatigue.

Changing fixation to a target in a different direction but in the same depth plane: saccadic eye movements

To date, most studies of saccades have involved examining their characteristics using iso-vergence targets i.e. targets in the same depth plane. These characteristics are described below.

Dynamics of saccadic eye movements

Saccadic eye movements function to bring an object of interest, such as a target, into the line-of-sight of the two eyes, (i.e. onto the fovea of both eyes). They are voluntary eye movements, i.e. they do not have a physical stimulus which spontaneously elicits them. Saccades are very high velocity eye movements. Their peak velocities may range from 20°-800°/s and they may have a total duration of 20-100 msec. The amplitude of movement of each eye during a saccade to an iso-vergence target is very similar. Indeed, the oculomotor control of each eye appears to be controlled by a common saccade generator system (Leigh *et al.* 1989, Bains *et al.* 1992). However, during such saccades, the abducting eye (temporal direction of movement) tends to move by a larger amplitude, a higher peak velocity and a shorter duration than the adducting eye (nasal direction of movement) (Collewijn *et al.* 1988a). Consequently, at the end of the saccade the eyes may have diverged by up to 0.3°. This asymmetry may be the result of the signals to the lateral muscle arriving slightly earlier than at the medial muscle. Alternatively, Collewijn *et al.* (1988a) suggest that this difference may be due to a difference in the mechanical properties of the lateral and medial rectus muscles. Zee *et al.* (1992) suggest that this is a reasonable assumption since their sizes are indeed different. An asymmetry also exists between centrifugal and centripetal saccades. The peak velocity reached by centripetal saccades is about 10% higher than that reached by centrifugal saccades (Collewijn *et al.* 1988a).

Model of mechanics of saccadic eye movements

Eye movements are controlled by six extra-ocular muscles (Solomons 1978). These are as follows (figure 3.2):

Muscle	Tends to move the eye
Lateral rectus	Abduct (out)
Medial rectus	Adduct (in)
Superior rectus	Up
Inferior rectus	Down
Superior oblique	Down (obliquely)
Inferior oblique	Up (obliquely)

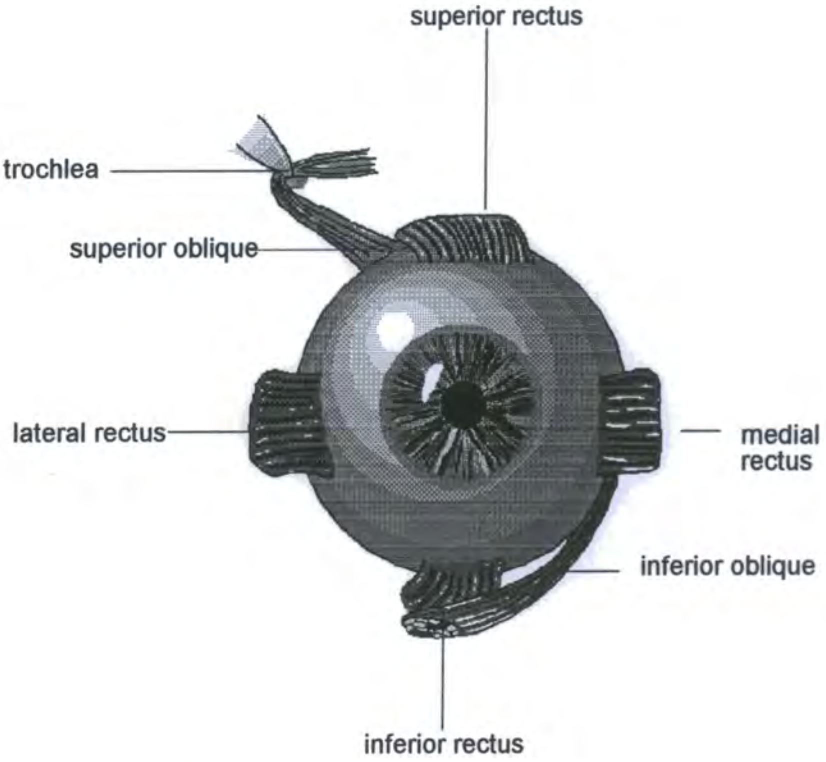

Figure 3.2 Extra-ocular muscles

Horizontal saccadic and vergence eye movements are controlled by the lateral and medial rectus muscles. Various models have been put forward concerning the pattern of innervation to these controlling muscles both during and after a saccade. These models seek to explain how the eye's position is very quickly changed and how the eye is brought to a new steady position. The simplest of these characterises a saccade as a pulse of innervation followed by a step of innervation. The duration of the pulse determines the amplitude of the saccade. Conversely, the step is a steady level of innervation which holds the eye in its new position. According to this model the time course in which the eye is brought to a stable new position after the pulse is specified entirely by the ratio of the pulse to the step. If the pulse and step are not matched, then at the end of the saccade the eye will slowly move to the position corresponding to the step rather than immediately being in the new position. This model accounts for the observations of postsaccadic glissade movements which may take up to 1 sec to complete (Carpenter 1988). Postsaccadic drift, a similarly slow movement but more common in the adducting eye (Kapoula *et al.* 1986) is explained as variations in the steadiness of the step innervation.

Other models also include the concept of active braking. It is suggested that the active braking is carried out by a small pulse activated in the antagonist muscle which is in the opposite direction to the initial pulse. This braking is not against the inertia of the eyeball, which is negligible, but rather against the elastic properties of the muscles. Errors in braking may account for dynamic over or undershoot. These movements are faster than glissades or drift returning the eye to its new position within 15-20 msec. Lastly, Robinson *et al.* (1991) have reviewed a third model which includes the concept of a slide rather than active braking. In this model the initial pulse is held to be larger than required, decreasing exponentially (the slide) until it matches the step level of innervation.

Visual control of saccadic eye movements

Saccades are described as ballistic rather than guided movements. That is, their trajectory and final destination are pre-programmed and once started usually cannot be altered by an external stimulus, for example, if the target of interest moves during the saccade. Hence, the saccadic control system must decide in advance where the final destination is to be. What information does the eye use to compute the amplitude of its primary saccade? Initial work assumed it was simply the position and direction of the object of interest. However, Coren & Hoenig (1972) found that non-target stimuli in the vicinity of the object of interest affected the amplitude of the primary saccade. They suggested that the amplitude of the primary saccade was computed on the basis of some estimate of the centre of gravity of all the stimuli in the vicinity of the object of interest. They suggested that the "weight" of each non-target in acting as a stimulus was affected by its size, contrast and luminance. Deubel *et al.* (1988) looked at the effect of texture elements of varying orientation around the target. They found that these elements affected the amplitude of the primary saccade. Within the laboratory, trajectories made to a nearby single target at the same depth tend to be fairly accurate. For trajectories covering larger amplitudes (e.g. > 10°), however, the initial saccade is less accurate and a secondary saccade is usually made. When viewing natural scenes, 85% of saccades made have an amplitude of less than 15°. Lemij & Collewijn (1989) found that primary saccades to stationary targets were more accurate than those to sudden-onset targets.

The latency of a saccade is the time between the appearance of a target and the start of the saccade towards the target. Presumably this represents the time required for the pre-processing to compute the saccades trajectory. Latencies can vary from 120 msec up to 350 msec. Typically, however, latencies will be around 200 msec. Latencies have been shown to be affected by the predictability of a target either spatially or temporally (i.e. when a target is oscillating regularly between 2 positions it is predictable). Latencies do not appear to be affected by the number of surrounding non-target stimuli (Deubel *et al.* 1988).

Walker *et al.* (1995) have shown three independent effects of visual attention on saccade latency. These are (a) the 'central cueing effect', (b) the 'gap effect' and (c) the 'bilateral target effect'. Differences in latency are thought to reflect differences in how the saccades were programmed under these conditions.

(a) When visual attention was covertly orientated[1] to one hemifield, by a central cue prior to target onset, consistent changes in target-directed saccade latency were observed. Target-directed saccade latency was increased when attention was covertly orientated to the non-target hemifield. Conversely, it was decreased (but to a lesser

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[1] i.e. the subject continues to fixate the target but is attending to an alternate location.

extent) when attention was covertly orientated to the target hemifield. These results support the theory that the mechanism for orientating attention toward a location in the visual world is closely involved with the programming of saccades toward that location.

(b) Walker *et al.* (1995) corroborated the finding that the introduction of a time gap, between the offset of fixation and the appearance of the target, results in decreased target-directed saccadic latency (gap effect). It had been previously suggested that the 'gap effect' indicated that programming a saccade toward a new location included the step of 'disengaging attention from the current point of fixation'. Hence, it might be expected, for example, that orientating prior covert attention to the non-target hemifield together with the introduction of a time gap between fixation offset and target onset, would result in a saccade latency that was not as slow as when the central cue alone was used. Walker *et al.* (1995) found no such interaction and therefore concluded that the 'central cueing effect' and the 'gap effect' involved two independent aspects of saccade programming and that the gap effect is not the result of the disengagement of attention from current fixation.

(c) Lastly, Walker *et al.* (1995) found a third independent influence on saccade latency. Saccade latencies made to one of bilaterally presented targets were slower (20-30 msec) than saccades made to a single target (bilateral target effect). The magnitude of this effect was not altered by introducing 'a gap' or by 'the prior orientation of covert attention'. The slowing effect occurred even when the subject knew, within a block of trials, that the target was always going to be presented on the right. Hence, they concluded that the slowing effect is unlikely to be due to the extra decision process required to select which of the bilateral targets to saccade towards. The slowing effect occurred when the 'other target' appeared with, 20-40 msec before or 20-40 msec after the onset of the saccade target. However, if the 'other target' appeared more than 160 msec before the target (in either the target or non-target hemifield) target-directed latency was decreased. It would appear that in this situation the 'other target' acted as a warning. Hence, the effect of a bilateral target in slowing saccade latency only operates with simultaneous or near simultaneous bilateral target presentation (i.e. it is a short-lived inhibitory effect).

The duration of a saccade of a given amplitude is fairly constant, within a particular individual, but increases with increasing amplitude (figure 3.3).

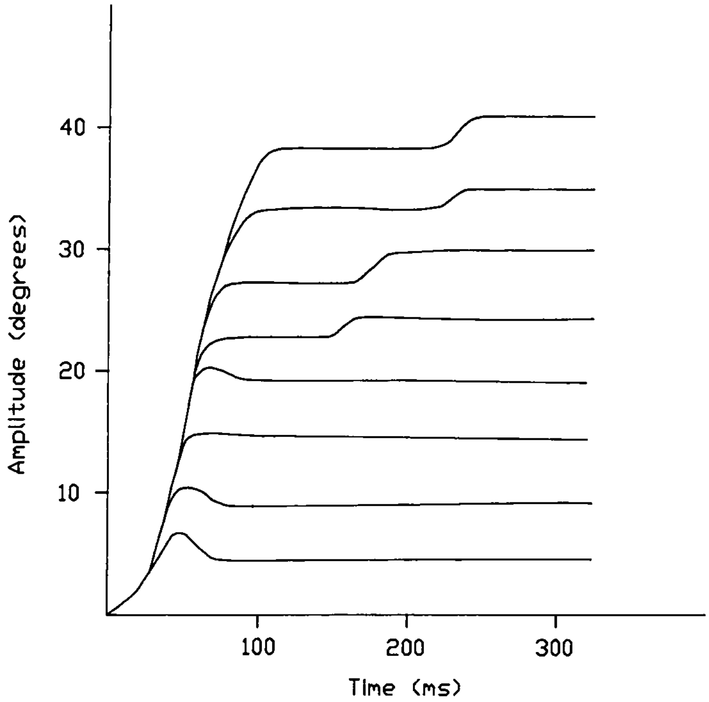

Figure 3.3 Saccades of different sizes showing the dependence of the duration of a saccade on its amplitude (Carpenter 1988)

For saccades larger than 5° amplitude, their duration is ~ 20-30 msec plus ~ 2 msec for every degree of amplitude (Robinson 1964). Almost identical patterns of acceleration at the beginning of a movement are found, whatever the saccades amplitude. The peak velocity of a saccade of a given amplitude is also fairly constant but increases with increasing amplitude (figure 3.4). This relationship between amplitude, peak velocity and duration is known as the 'main sequence'. There have been various lines of research to discover if the 'main sequence' is affected by other factors. As Carpenter (1988) notes factors such as age (infants), darkness, alcohol and certain clinical conditions affect the main sequence, the saccade duration becoming longer. However, factors such as the occurrence of a saccade within a smooth pursuit eye movement or saccades made after oculomotor nerve damage do not affect the main sequence.

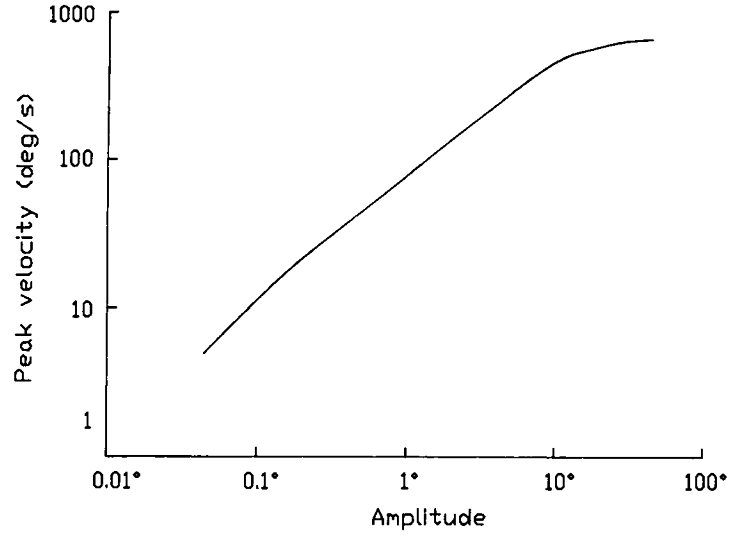

Figure 3.4 The main sequence, a graph of the peak velocity of human saccades as a function of their duration (Bahill *et al.* 1975).

Changing fixation between midline targets at different depths: Vergence eye movements, Panum's area & fixation disparity

For us to perceive a single field of view from the input of two eyes, it is necessary for the image of an object to fall on corresponding points of the retina of each eye. This correspondence is usually defined in geometric terms taking the fovea as the origin. For viewing distant objects it is achieved by the two visual axes being parallel. When the object moves in the same depth plane, both eyes would need to move in unison in the same direction, i.e. conjugately, to maintain the object within the fovea of both eyes. However, if the object moves towards the observer, the two visual axes will have to converge in order to maintain retinal correspondence i.e. the two visual axes will need to move in unison in different directions (disconjugate). Horizontal vergence eye movements are responsible for this task, which they perform with precision but not perfection. Where the image of an object does not fall on precisely corresponding points of the retina of each eye, the angle subtended by the horizontal distance between the two points is termed the horizontal disparity. The angle subtended by the vertical distance between the two points is termed the vertical disparity. Horizontal vergence is generally specified as the angle θ between the line-of-sight of each eye, which is the angle subtended by the inter ocular distance (I) at the fixation point (F), which is at a distance (d) from the subject's midline in the horizontal plane (figure 3.5).

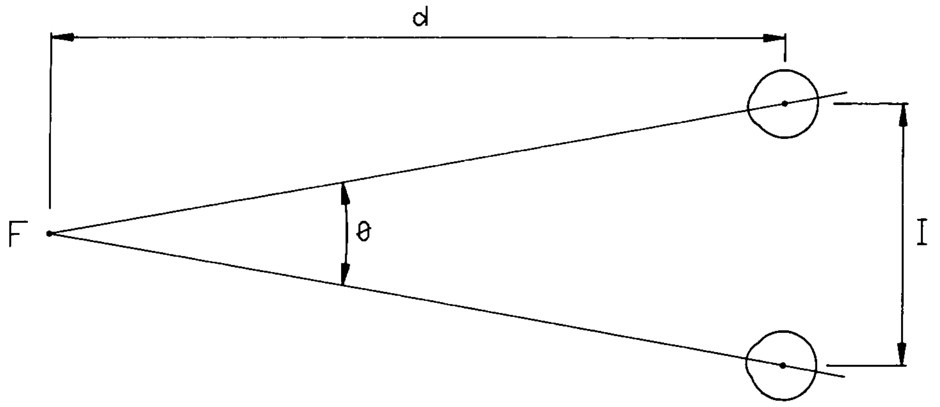

Figure 3.5 Horizontal vergence is defined as the angle ø between the line-of-sight of each eye. This is the angle subtended by the inter ocular distance (I) at the fixation point (F), which is at a distance (d) from the subject's midline (horizontal plane).

What is the role of horizontal vergence eye movements in the perception of depth i.e. stereopsis? There is no definitive answer to this question at present. "Stereopsis is the perception of depth based on retinal disparity, a cue that derives from the presence of horizontally separated eyes" (Patterson & Martin 1992). However, the magnitude of horizontal disparities between a pair of points does not by itself specify the magnitude of the difference in depth. This is because the same magnitudes of disparity can be generated by an object with a different depth at a different viewing distance. The disparity needs to be scaled. One controversial suggestion is that the angle of convergence provides this scaling information. It enables determination of how far away an object is. Other suggestions are the horizontal gradient of vertical disparities (differential perspective) and the projected angle of familiar objects (Rogers & Bradshaw 1995). Rogers & Bradshaw (1995) looked at subjects' perception of frontoparallel surfaces and compared the potential contribution of vertical disparity and the angle of convergence to the scaling of disparities. They concluded that differential perspective provides the scaling for large displays (>30°), overriding convergence information, and that the angle of convergence provides the scaling information for smaller displays (<20°) (where vertical disparity gradients cannot be easily computed).

Many studies have shown that stereopsis is not veridical across various viewing distances. For example, Foley (1980) showed that perceived distance depends on physical distance as well as disparity. He found that perceived distance of near targets exceeded physical distance and that perceived distance of far targets is less than physical distance. Johnston (1991) showed that stereopsis can lead to distortions in the shape of objects. A circular cylinder appeared elongated at close viewing distances, the correct shape at intermediate distances and appeared flattened at far distances. Both these authors conclude that it is "errors in calculating" the scaling factor of stereopsis which lead to these distortions.

In conclusion, vergence eye movements seem to play a scaling role, albeit an inexact one, in stereopsis. However, they are not a pre-requisite for stereopsis. Indeed, tachistoscopic studies have shown that stereopsis can occur without eye movements.

However, vergence eye movements may have a role in bringing an object of interest onto the fovea of each eye. For large stimuli we have relative depth discrimination for absolute disparities of up to 10° (covering from 17 cm to infinity). Hence, subjects fixating a near object 17cm away (vergence 10°), can determine the relative depth of another distant object solely on the basis of the horizontal disparity which will exist between their retinal images of the more distant object (i.e. they will not have to fixate the far object). Hence, there seems to be little need to build up a 'relative depth map' using roving vergence eye movements. However, there is not a one:one relationship between disparity and depth across this 10° range (figure 3.6).

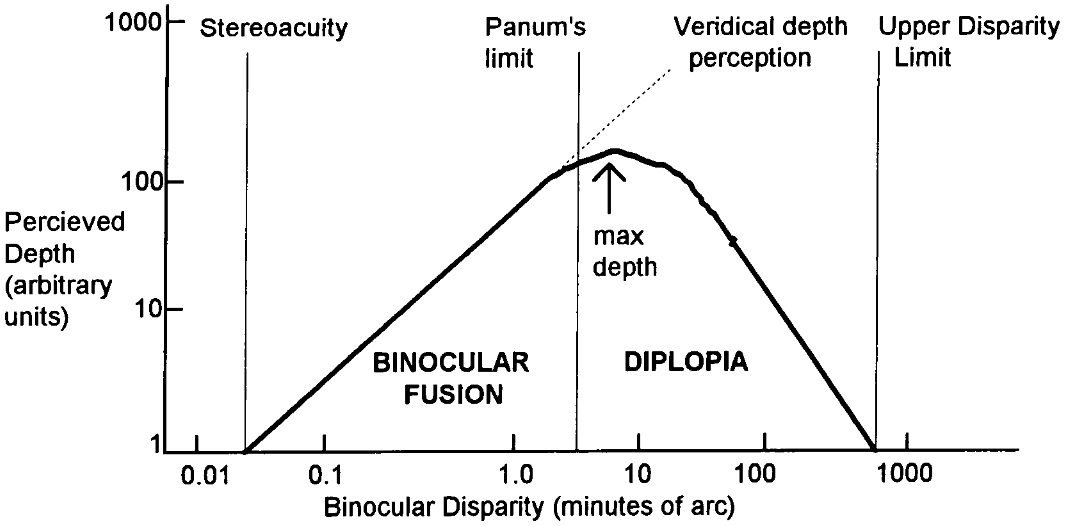

Figure 3.6 Perceived depth as a function of disparity

As disparity increases, the magnitude of perceived depth increases proportionally up to D_{max}. This is the disparity at which maximum depth is perceived. Disparities larger than D_{max} give rise to a diminishing impression of depth (and generally diplopia) until the upper disparity limit (UDL). This is the maximum disparity at which any depth can be perceived i.e. stereopsis can occur. D_{max}, UDL and the threshold for diplopia vary according to a target's size, its spatial frequency content and its eccentricity. Differences in these measures have also been found between random dot and solid stimuli (Tyler & Julesz 1980). As can be seen from the table below although the disparity range of stereopsis is large for large stimuli, it is much more limited for small stimuli. Consequently, it may be that the primary role of vergence eye movements, like that of saccadic movements, is to bring the object of interest onto the fovea of each eye where, for example, stereo acuity is best.

Interestingly, Enright (1991) has shown that eye movements may also have an independent role to play in interpreting the third dimension. He found that looking (saccading) back and forth between two targets improves our ability to discriminate the distance between them, even where stereopsis is impossible because one of the targets is imaged in the blind spot.

Table 3.0 Representative disparity limits for diplopia, D_{max} & UDL for two stimulus sizes and two retinal eccentricities (Patterson & Martin 1992)

	Small size stimuli (< 15')			Large size stimuli (1.0-6.6°)		
	Diplopia threshold	D_{max} 1:1 stereopsis	UDL	Diplopia threshold	D_{max} 1:1 stereopsis	UDL
Foveal area	10'	20'	2°	20'	2°	8-10°
6° eccentricity	20'	2°	3.5°	-	-	-

Vergence eye movements do not occur in isolation but are intimately linked to changes in accommodation and pupil diameter through the near response. This refers to the response of the visual system to changes in target depth. Three responses take place as follows:-

1. An accommodative change, i.e. a change in the dioptric power of the eye's lens
2. Changes in the pupil's diameter
3. Vergence eye movements

Various independent cues to the near response have been identified. These are as follows:-

- binocular cue of retinal disparity (Westheimer & Mitchell 1956)
- monocular cue of blur
- change in size of retinal image
- perspective
- change in image overlap (occlusion)
- knowledge of nearness of object
- the resting positions of accommodation & vergence under certain conditions

Each of these stimuli taken individually is capable of eliciting all 3 components of the near response. The strength of each of these individual stimuli in determining the near response seems to vary considerably among individuals (Adams & Johnson 1991).

However, retinal blur and retinal disparity are the main stimuli. In turn the near response directly modifies the amount of invoking stimulus. Lens movement i.e. accommodation reduces retinal blur. Vergence eye movements reduce retinal disparity. Changes in pupil size theoretically modify blur because a change in diameter would modify the depth of field of the lens. However, over normal pupil sizes this effect is negligible.

The total vergence response can be factored into various more or less independent components related to the particular stimulus which elicits that aspect of the response. Maddox proposed the first classification in 1886 which is still in operation today. The various components, which are considered to act in parallel, are as follows:-

- Disparity vergence
- Accommodative vergence
- Tonic vergence
- Proximal vergence

Disparity vergence refers to vergence eye movements elicited solely by the disparity between the left and right retinal images of an object. The properties of horizontal disparity are described below in more detail.

Accommodative vergence refers to vergence eye movements elicited solely by the object blur, that occurs when an object is closer or further away from the current fixation point. A fuller description is found on page 50.

Tonic vergence refers to the influence of the resting vergence position (which is assumed to be the position in a darkened environment) on any vergence response.

Proximal vergence refers to vergence eye movements elicited by the knowledge of the proximity of an object. This knowledge includes factors such as perspective, size of known objects, overlap etc.

Dynamics of horizontal disparity vergence eye movements

Retinal disparity occurs when the image of an object on the left and right retina is not in the same corresponding position on each retina. The difference or disparity in the two positions acts as a stimulus to vergence eye movements. The latencies for horizontal disparity vergence movements are typically between 130 - 250 msec but usually near 160 msec (Krishnan *et al.* 1973). Hence, disparity vergence movements are initiated slightly faster than saccadic eye movements. The initial response is one of uniform acceleration lasting for approximately the same duration as the latency period so that peak velocities of 7-10°/s per degree of disparity are reached (approximately linear over the range of ± 5°). This is followed by a gradual slowing of velocity until the end of the response approximately one second later. Hence, the entire response lasts for approximately two seconds. The initial response is unmodified by feedback. However, the ensuing response can be modified thus indicating that it is under continuous feedback control and not ballistic control like a saccade. Hung *et al.* (1994) measured the relationship between the amplitude and peak velocity (main sequence) of midline vergence responses in both natural space (all depth cues present) and stereoscopic space (only disparity depth cues present). They found that peak velocity was proportional to the amplitude of vergence (4:1) for all the stimulus conditions. This suggests there is a similarity in the control of vergence under these conditions. In addition to these findings Enright (1984) has found that horizontal vergence movements between two targets at different depths along the subject's midline can be facilitated (i.e. speeded up) by small saccadic movements (see later section on saccade disconjugacy). Recently, Hung *et al.* (1997) have shown that horizontal convergence and divergence exhibit different response characteristics to symmetric, disparity only, blur free step targets, suggesting different control processes for convergence and divergence.

For short presentations of a disparity vergence stimulus (200 msec) the peak amplitude of the response depends on the amount of disparity (range tested 0.6° -

4.6°), the response peaking for disparities between 1-2° (Jones 1977). Interestingly, Jones (1977) showed that approximately 20% of subjects showed an anomalous vergence response to short duration vergence stimuli (200 msec). They showed a reduced or absent convergence or divergence response. This asymmetry was not evident when longer duration vergence stimuli, for example 1 sec, were used. Jones (1977) noted that these subjects did not show any obvious clinical signs of having an anomalous vergence response.

According to Schor (1979b) it was Hoffman & Bielchowsky (1900) who, at the turn of the century, first suggested that vergence is a two component process. Indeed, there is a growing body of research indicating that disparity vergence is a two stage process consisting of a vergence-initiating component followed by a vergence-sustaining component. For example, Jones & Kerr (1971, 1972) showed that the images in each eye do not need to be similar for a vergence movement to be initiated. However, they do need to be similar for the vergence movement to be completed and sustained. In the absence of similar images the subject's vergence response returns to its starting position. Westheimer & Mitchell (1969) and Mitchell (1970) found that the disparity vergence response limit was reached for disparities between 5° and 10°. Hence, it is clear that disparity vergence eye movements can be initiated by large disparities. However, Jones & Stephens (1989) found that a subject's sustained disparity vergence level was only influenced by small disparities of less than about 0.5°. Further evidence is provided that vergence is a two stage process by Jones (1980). He found that as sustained convergence increased (fusion sustaining process), the amount of divergence induced by a transient (200 msec) disparity stimulus (fusion initiating process) increased but the amount of disparity-induced convergence remained constant. Jones (1980) interprets these results as showing that the two stages of the vergence response are independent, suggesting that the increase found for divergent stimuli was as a result of accommodative influence (and not an interaction between the fusion sustaining and fusion initiating responses).
Schor (1979b) also provides evidence, detailed in a later section, that the fusional vergence system consists of two components. Lastly, Erkelens & Regan (1986) demonstrated that vergence responses to a change in stimulus size were transient whereas responses to a disparity stimulus were sustained.

Panum's fusional area

There is some leeway in the precision to which the retinal disparity must be reduced during fixation of an object of interest to enable single vision. This leeway is known as fixation disparity. The maximum fixation disparity which still enables single vision is generally considered to be limited solely by Panum's fusional area. This is defined as "an area on one retina, each point of which will produce a single image when simultaneously stimulated with a fixed point on the other retina" (Solomons 1978). It was originally conceived of as a fixed area, its size depending only on the degree of retinal eccentricity. In its horizontal extent it is smallest at the fovea but may be as large as 2° in the periphery (Ogle 1950). Tyler (1973) showed that its horizontal extent becomes larger as stimulus size increases and as the blurring of a target increases. More recent experiments have also indicated that Panum's area is a dynamic rather than a fixed entity. It changes according to a number of factors. Further, its horizontal and vertical dimensions are affected differently by these factors. For example, spatial and temporal factors interact to affect the size of Panum's area. The main effect of temporal modulation occurs at low spatial frequencies. The horizontal diameter of Panum's area is larger for low temporal frequency stimuli than for high temporal frequency stimuli whereas its vertical diameter is unaffected (Schor & Tyler 1981). The main effect of spatial frequency modulation occurs at low temporal frequencies and affects horizontal and vertical fusional ranges. Panum's area is larger for low spatial frequencies (Schor & Tyler 1981).

Fixation disparity

Maximum fixation disparity has horizontal and vertical differences in size similar to Panum's area. For example, prism induced vergence results in maximum horizontal fixation disparities which are larger than similarly induced vertical fixation disparities. Vertical fixation disparity is linearly related to vertical vergence stimuli, this function varying little between people. However, the relationship between horizontal fixation disparity and horizontal vergence stimuli, such as a prism, is more complicated. Ogle *et al.* (1967) observed three different types of response to a horizontal prism vergence stimulus shown by different subjects and since then a fourth abnormal response has also been observed. These are as follows:-

Type 1:- fixation disparity increases equally to both divergent and convergent horizontal prism vergence stimuli

Type 2:- fixation disparity increases more for divergent than convergent horizontal prism vergence stimuli

Type 3:- fixation disparity increases more for convergent than divergent horizontal prism vergence stimuli

Type 4:- indicates abnormal binocular vision. Nearly constant fixation disparity with an abnormally small amplitude of vergence responses to horizontal prism vergence stimuli. This is a very rare condition.

Fixation disparity is usually mapped by asking a subject to subjectively align two nonius lines. However, some researchers have found that subjective and objective measures (actually recording eye movements) of maximum fixation disparity are different (Jones 1983). Hence, it may be that single vision can occur despite large fixation disparities (i.e. vergence errors) and is not solely limited by Panum's area. For example, under certain circumstances fusion may be maintained due to the suppression of the image in one eye or because of some higher cortical function which changes the geometry of retinal correspondences between the two eyes i.e. neural remapping of retinal correspondence.

What is the function, if any, of this small imprecision of vergence called fixation disparity? Two suggestions have been put forward. Firstly, that it is a symptom of stress on the vergence system. Secondly, that it is a purposeful error that provides a stimulus to the vergence system. This last suggestion has received considerable support from experiments conducted by Schor. Schor (1979a) used base-out or base-in prisms to stimulate binocular horizontal vergence eye movements for 30 msec. Following this procedure the decay of the subject's vergence response was measured during occlusion of one eye. It was shown that the subject's vergence response did not, for some time, fully relax to the levels of phoria shown prior to the experiment. This unrelaxed portion of the vergence response is termed prism adaptation or slow fusional vergence. Most subjects show different amounts of prism adaptation to convergent and divergent stimuli. Their responses can be classified as type I, II or III in a similar manner to the classification of the response of fixation disparity (FD) to vergence stimuli i.e. forced FD curves.

Schor (1979b) found that there was a high correlation between the values of fixation disparity during the presentation of the convergent or divergent stimuli and low or high levels of prism adaptation. In the first place, Schor's experiments provide further evidence for the suggestion that the overall response of looking from one target to another at a different depth involves two vergence mechanisms. Firstly, a fast fusional mechanism which reduces fixation disparity to a few minutes of arc. Secondly, a slow fusional mechanism which operates to maintain fusion through continued maintenance of low fixation disparities while the observer is fixating the newly acquired target.

More importantly, Schor has put forward a model of how this two stage vergence system might operate. He describes the fast fusional stage as a "leaky neural integrator", the leak becoming manifest as a reduction in vergence level over a period of 10-15 seconds when one eye is covered. He suggests that this leak also operates under binocular conditions and that fixation disparity provides a stimulus to match this level of decay and maintain the vergence response of the fast fusional system at a particular level. The amount of fixation disparity necessary to achieve this will depend on the amount of fast vergence which is stimulated for each degree of disparity i.e. the gain of the fast vergence system and the speed with which its output decays. As prism adaptation or slow fusional vergence occurred it would then provide a mechanism for sustaining the particular level of vergence response over longer periods of time. The input to the fast mechanism would be retinal disparity whereas the input to the slow mechanism would be the output of the fast mechanism. As adaptation of a subject's phoria occurs the slow fusional system takes over the maintenance of the total vergence response and therefore less fixational disparity is needed to maintain the fast vergence component of that response. Schor (1979a) found that low levels of fixation disparity were indeed associated with fast prism adaptation times. Subjects with steep forced FD curves showed slower prism adaptation than subjects with flat forced FD curves. A forced FD curve is a graph of FD as a function of vergence stimulus demand. Vergence stimulus demand is typically created using prisms of various strengths (either base-in or base-out). The slope of the graph reflects the magnitude of vergence errors which occur in the presence of increasing demands placed upon sustaining fusion of left and right eye images. Figure 3.7 shows an example of flat and steep forced FD curves. The shortest time that this adaptation can occur in has been shown by Schor (1979a) to be 30 msec.

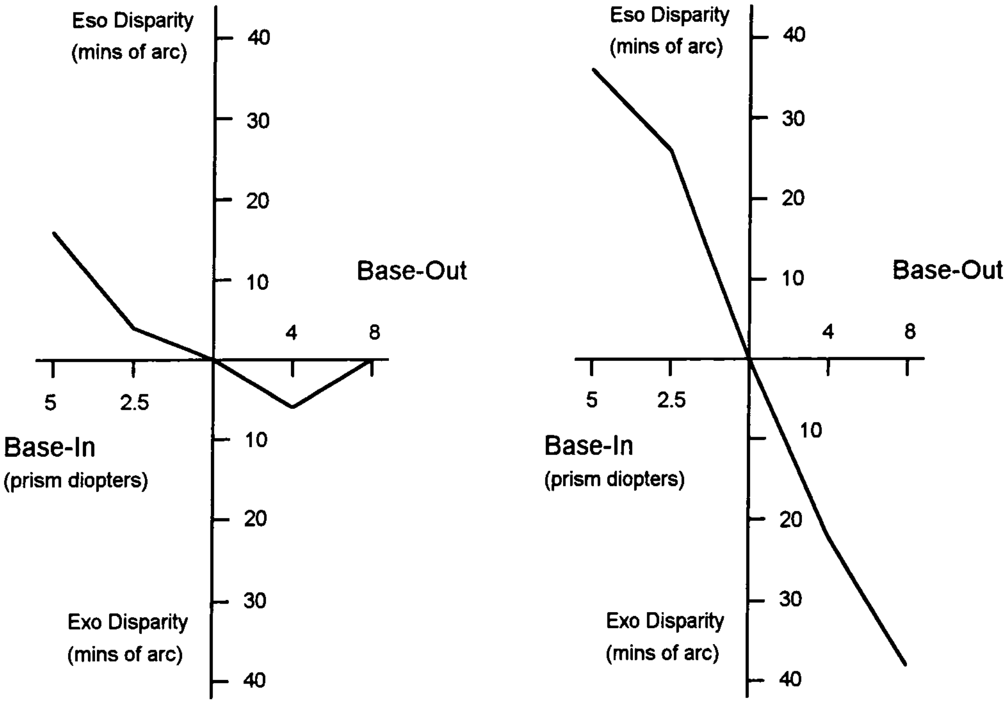

Figure 3.7 Flat (Type 2) and steep (Type 1) forced FD curves for a high spatial frequency stimulus at 3° eccentricity (Schor 1979a).

Schor *et al.* (1986a) tested out the hypothesis that the level of fixation disparity is determined by the gain and speed of decay of the fast fusional system and ultimately by the level of prism adaptation. They measured fixation disparity and the initial velocity of fast vergence as a function of retinal locus and spatial frequency in two subjects. The first subject had a steep forced FD curve, i.e. slow prism adaptation, whereas the second had a flat forced FD curve, i.e. fast prism adaptation. Vergence velocity decreased for both subjects as retinal eccentricity increased but was unaffected by spatial frequency. Fixation disparity for the subject with the flat fixation disparity curve was unaffected by the two variables. However, fixation disparity for the subject with the steep fixation disparity curve increased as retinal eccentricity and the coarseness of the stimulus increased. Hence, it would seem that when prism adaptation occurs it determines the level of fixation disparity rather than the vergence velocity (and decay time during occlusion of one eye). In the absence of adaptation

Schor *et al.* (1986a) suggest that the gain of the fast vergence component (and decay time) is responsible for determining the level of fixation disparity. This is contrary to the common explanation that Panum's fusional area (PFA) is responsible for setting the limit of FD.

Schor *et al.* (1986b) measured the extent of PFA, as well as fixation disparity, in a group of subjects with either flat or steep forced FD curves as a function of retinal locus and spatial frequency. They found that at any retinal locus PFA was larger for low spatial frequency rather than high spatial frequency stimuli. However, for a particular stimulus they found that PFA did not increase as retinal eccentricity increased. The results for FD were the same as in their earlier experiment. FD increased as retinal eccentricity increased for the subject with a steep forced-FD curve but remained constant for the subject with a flat forced-FD curve. Hence, they suggest that the increase in FD for the subject with a steep forced-FD curve is not related to the extent of PFA but rather to the dynamics of their initial vergence response (in the absence of prism adaptation).

Horizontal accommodative vergence

Retinal blur occurs when light entering the eye is not focused directly onto the retina but is focused in front of or behind it, giving a circle of diffuse light on the retina rather than a sharp point. The visual system has some tolerance for blur. With a pupil diameter of 3.0 mm or greater, which is a typical diameter under normal lighting conditions, the depth of field of the eye's lens is ±0.3 dioptres. Hence, there is a range of distance from the eye, rather than a precise distance, in which an object appears clear without a change in accommodation. Outside this range blur acts as a stimulus to accommodation. Saccadic eye movements may facilitate accommodation if initiated at the time of saccade onset (Lott *et al.* 1997). It is generally believed that the blur stimulus to accommodation is not effective off the fovea (Philips & Stark 1977). However, Enright (1986) found that targets at 6° of eccentricity, well into the parafovea, were capable of eliciting vergence eye movements when viewed monocularly i.e. the only stimulus to depth was blur.

The amount of vergence produced in response to an accommodative stimulus can be expressed using a measure called the response AC/A ratio (accommodative convergence to accommodation) in units of prism dioptres per unit of dioptre. This response ratio is largely linear and the mean population AC/A value is 4.0 ± 2.0 : 1. The latency of accommodative vergence is typically 200 msec, although a range from 130-300 msec has been reported (Ciuffreda & Kenyon 1983). Accommodative vergence has a peak velocity to amplitude ratio of approximately 5:1, i.e. a vergence movement of 1° would be associated with a peak velocity of 5°/s. Hence, they are characteristically slow movements. After 1.2 s they are typically 90% complete (Carpenter 1988). The response is guided by visual feedback rather than being ballistic. Schor (1979b) showed that in relation to his model of the total vergence response, accommodative vergence is "added to" the total response after the contribution of fast and slow disparity vergence.

Changing fixation to a target in a different direction and at a different depth

Visually guided immediate disconjugacy

It has been traditionally assumed that the two eyes always make saccades of equal size (conjugate). For example, Collewijn *et al.* (1988a) reported that the difference in amplitude between left and right eye saccades between iso-vergence targets was less than 0.5°. However, there are two separate strands of research which challenge the conjugacy of saccades. The first involves consideration of the oculomotor response when a person changes their gaze to an object at a different depth and in a different direction (visually guided immediate disconjugacy). This area of research is directly relevant to the effectiveness of eye pointing with three dimensional displays because it deals with factors which affect how long the eye takes to get "on-target" in a three dimensional environment. The second strand of research has considered both anisometropic spectacle wearers (each lens having a different refractive power) and the various factors which may change over a person's lifetime thereby necessitating a change in saccade conjugacy (long term adaptation disconjugacy). This is relevant to eye pointing in as much as it throws light on the mechanisms underlying the non-conjugate three dimensional oculomotor response.

As we look around our environment, we continually change our gaze between objects, which are situated at different depths and in different directions. The traditional picture of the eye movements made under these conditions asserts that both eyes are yoked, making an initial slow symmetrical vergence response, then equal and quick saccadic movements in the same direction (version) followed by the final stage of the symmetrical vergence response (figure 3.8). Hence, the amplitude of movement of the entire gaze change can be characterised as the summation of the version and vergence eye movements (Hering's hypothesis). The saccadic and vergence eye movements are considered to be produced by independent oculomotor sub-systems.

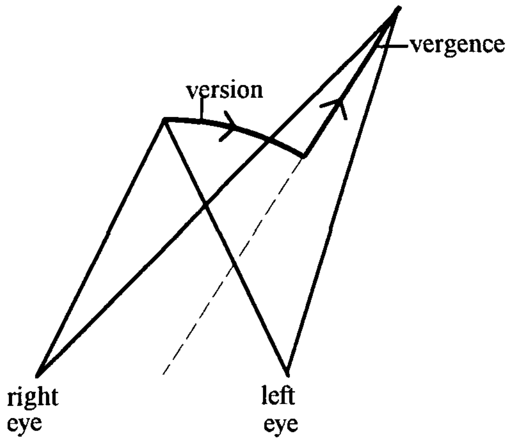

Figure 3.8 Traditional picture of eye movements made from one target to another which is in a different direction and at a different depth

Ono (1983) notes that the saccade is held to occur during the vergence movement because "the saccade latency is longer and its duration shorter than that of the disjunctive movement". For example, according to Ono (1983), Fuchs (1971) found that subjects' saccades between two targets (stepping or stationary) 3° apart had a latency of 200msec, a peak velocity of 150°/sec and a duration of 30msec the two eyes being synchronised. According to Ono (1983), Robinson (1966) found that subjects' vergence responses to a target stepping 3° away from or towards them in the median plane had a latency of 175msec, a peak velocity of 10°/sec and a duration of 2 seconds.

Consequently, the saccadic component of the response would typically be expected to take 30-50msec with the ensuing vergence response lasting about 1-2 seconds. However, evidence started to accumulate showing that more vergence was actually achieved during saccades than could be predicted from a linear summation of the vergence and version components. For example, Kenyon *et al.* (1978, 1980) and Ono *et al.* (1978) both documented the existence of such unequal saccades during non-conjugate gaze-shifts.

Subsequently, Enright (1986) found vergence amplitudes ranging from 40% during saccade responses, where required version and vergence change was about equal, to as much as 90-100% during large version movements when the vergence required was small. This contrasts with the traditional picture of eye movements shown in figure 3.8, where no change in vergence level occurred during the saccadic component (version) of the response. During monocular viewing, where only accommodation cues could induce vergence change, Enright (1986) found that 13-48% of the resulting vergence movement occurred during the saccade. It is not clear how much knowledge Enright's subjects had concerning the layout of the targets. It is possible that the vergence change could have been the result of proximal vergence rather than accommodative vergence. Nevertheless, the implication of these findings is that, in fact, saccades of unequal version were being made by each eye (i.e. disconjugate saccades) thus speeding up refoveation of the new target. This effect is smaller when the vergence response is combined with vertical rather than horizontal saccades (van Leeuwen *et al.* 1997).

Enright (1986) argued against the idea that the vergence response was superimposed (i.e. added) onto the saccadic response using the following rationale. He used a typical peak vergence velocity of value of 7°/s and using this value rather than a mean vergence velocity calculated the amount of vergence which would be expected to occur during a saccade of 83msec duration. He found that more vergence than this value occurred during the saccades in his study. However, this peak vergence velocity value considered at the time to be typical may in fact be rather low. As described below, Erkelens *et al.* (1989a) found much higher peak vergence velocities under natural conditions.

Other researchers have also noted the existence of unequal saccades or rapid vergence changes, the form of phrasing used depending on how they believe such eye movements are generated. Indeed, at this stage it is not clear if this vergence change is incorporated into an independent saccadic programme for each eye or if it is some form of interaction between symmetric saccadic and vergence systems.

Erkelens *et al.* (1989a) argue for an interaction explanation. They measured subjects binocular eye movements as they shifted their gaze between continuously visible targets differing in direction and distance (disparity and blur cues to vergence response). Under these more natural conditions, where an 11° vergence change and a 45° direction change was required, they found that the subjects' eyes did not in fact move in a yoked fashion. Rather, that the eyes made unequal saccades, which reduced the size of the subsequent vergence response needed. The amount of vergence which occurred during a saccade was more than would be expected given the saccade duration and the velocity of vergence. They also examined subject's vergence responses when they looked between two continuously visible targets at different distances along the midline (Erkelens *et al.* 1989b). They recorded higher mean and peak vergence responses than had been found in previous experiments where only disparity cues to vergence were used. For example, they found peak velocities of 50°/s for a vergence change of 5° and 150 - 200°/s for a vergence change of 34°. The relationship between peak velocity and the magnitude of the vergence response required was approximately linear - 4°/s per degree of vergence. The smooth vergence response seemed to be aided by small unequal saccades (transient saccade response) as indicated by a number of velocity peaks in the smooth vergence response. Mean vergence speeds of 16 - 55°/s for a vergence change of 4 - 34° were reported.

These findings have recently been extended by Collewijn *et al.* (1995, 1997), who studied version-vergence interactions over a wider range of amplitudes. They found that divergence was progressively facilitated by saccades of increasing amplitude. Convergence was also facilitated by saccades, but in a non-uniform manner with respect to saccade amplitude, due to the effect of the transient, intra-saccadic divergence. Further, the saccadic component of a non-conjugate gaze-shift was preceded, approximately 100 msecs, by the vergence component. It should be noted that this was in contrast to the conjugate situation where the transient, intra-saccadic divergence was found to commence at the same time as the saccadic component. The direction of the vergence component tended to be in line with the direction of the initial, rather than the fixation, target. This argues against models of gaze-shift oculomotor behaviour which suggest that the visual input to each eye is processed and responded to separately and lends weight to models suggesting an interaction of independent, symmetric version and vergence sub-systems.

Zee *et al.* (1992) also argue that the vergence response is facilitated by saccades in a non-linear way. They examined the ocular responses of four subjects as they shifted their gaze between targets which called for vergence and saccades. They found that under such circumstances horizontal vergence speed was increased compared with during a pure vergence movement. Further, that this increase could not be accounted for by the linear addition of the saccade response to the vergence response. They proposed a model to account for these findings whereby the vergence and saccade sub-systems are under the control of a common initiation system but separate local feedback loops. Krommenhoek *et al.* (1994) found evidence for such non-retinal feedback in combined version-vergence interactions.

Maxwell & King (1992) examined the ocular responses of four macaque monkeys as they shift their gaze between targets in different directions and at different depths. Under these conditions they observed that the monkeys made disconjugate saccades i.e. a saccadic movement in combination with a vergence movement. They also trained the monkeys to move their gaze between targets placed at different depths along their midline. Under these conditions they observed that the monkeys made some transient saccade movements during an otherwise pure vergence response. From these observations they initially suggest that the increase in speed of vergence during a saccade movement between two targets at different depths and in different directions was the result of a linear addition of a vergence eye movement and the saccade-related transients. However, they noted that the peak vergence speeds actually obtained during these combined movements were higher than the linear addition hypothesis predicted. Consequently, they agree with Erkelens *et al.* (1989a) findings and suggest "the presence of an additional mechanism". Their study is notable for the rigorous way in which they have analysed the raw eye movement data, with the criteria for each decision given. For example, to date researchers have assumed that the increase in peak vergence speed observed during a combined saccadic and vergence movement would result in a shortened on-target time. However, this had not been explicitly checked. Maxwell & King (1992) found that such a combination did significantly decrease the amount of time required to arrive on-target.

Mays & Gamlin (1995) have recently published a paper citing physiological evidence to support the view that the increase in vergence velocity, observed when a saccade occurs during a vergence eye movement, is due to an interaction between the saccadic and vergence eye movement systems. They hypothesised that the "saccadic facilitation of vergence results from the interruption of inhibition of the vergence burst neurones by the pontine omnipause neurones (OPN), which are involved in initiating saccades". To test this they applied electrical micro stimulation to the OPN region of rhesus monkeys during vergence movements. As predicted, they found that the micro stimulation decreased the velocity of vergence movements.

However, Enright (1997) has published data showing the occurrence of saccade-free asymmetrical convergence. This suggests that no interaction is taking place between symmetrical version and vergence sub-systems but rather that each eye can respond independently to that eye's view in programming a vergence response with a weighting toward the dominant eye. Further, Enright argues that if the oculomotor response to targets requiring both version and vergence is an interaction between symmetric version and vergence, then at the end of the primary saccade any offset from the target would be expected to be symmetrically distributed between the two eyes. Enright (1997) has shown in the majority of instances this is not the case but that one or other eye ends up closer to the target.

However, this evidence does not preclude the existence of separate boundaries between the vergence and saccade sub-systems but rather than each of these sub-systems is capable of asymmetric output. Indeed, there is a large body of data, some of which has already been mentioned, which reinforces the idea of separate saccade and vergence sub-systems. For example, recently, Semmlow *et al.* (1997) used pure vergence and version ramp stimuli to obtain data showing a quantitative difference in velocity variability between version and vergence. Ono *et al.* (1997) present evidence suggesting that vergence is controlled by interhemispheric processes whereas saccades are driven from within one hemisphere.

Long term adaptation disconjugacy

Saccade conjugacy is present at birth and is maintained despite developmental changes in, for example, the inter pupillary distance (Larson 1971). However, there are a number of reasons why this conjugacy may need to be altered during a person's lifetime. For example, a person may need to wear glasses with spherical lens of a different refractive power for each eye (anisometropic spectacles). Because these lens are worn in front of the nodal point of each eye the images in each eye are differently magnified. Hence, disconjugate saccades are necessary to maintain binocular foveation. Alternatively, disconjugacy may be necessary because the muscles of one eye become weaker. Various lines of research have considered the question of whether this plasticity in saccade conjugacy exists and if so whether the change is "hard programmed" or visually controlled.

An early paradigm partially addressing this question used stepping targets with the target consistently jumping an extra step during the subject's saccade. Conjugate changes occurred i.e. saccadic amplitude for both eyes increased by the same amount in line with the intra-saccadic jump. This change was adaptive in that it generalised to other targets jumping in the same direction by different amounts but not to targets jumping in different directions. A different experimental paradigm is exemplified by Lemij & Collewijn (1991a). They examined the oculomotor responses of subjects who habitually wore anisometropic spectacles. They found that all subjects exhibited saccades in the two eyes which were significantly different in size, both horizontally and vertically, in the correct direction. Further, the subjects' saccades exhibited these changes under monocular conditions (i.e. the visual stimulus to disconjugacy is no longer present) although to a lesser extent than under binocular conditions. This suggests that the change is essentially "hard programmed", i.e. adaptation had occurred, but with some visual fine tuning. However, each subject showed a considerable amount of variability in the extent of their saccade disconjugacy during the monocular condition. Consequently, this "hard programmed" adaptation does not appear to be an entirely fixed quantity. The adaptation also appears to be very flexible. For example, when one of the subjects was tested without spectacles the disconjugacy was reduced under monocular conditions, disappearing completely under binocular conditions.

Lemij & Collewijn (1991b) also examined the limits and time course of this plasticity of saccade conjugacy in subjects who wore anisometropic spectacles for the first time (no image blurring was present because the subjects wore contact lens of equal and opposite power to the spectacle lens). Disconjugacy in the correct direction developed for all subjects in under an hour. For horizontal saccades the amount of disconjugacy was related to the difference in the refractive power of the two lens and the length of time the lens were worn for. For vertical saccades the level of disconjugacy did not increase with increasing anisometropia and increased only slightly as wearing time was increased. This finding suggests that adaptation may occur independently along each axis. Disconjugacy was present during monocular viewing but was greater during binocular viewing.

Schor *et al.* (1990) sought to ascertain whether this adaptive disconjugacy was the result of adaptation of an underlying binocular process such as vergence (prism) adaptation (i.e. an interaction between version and vergence) or whether the saccadic system was adapted independently. They used three disconjugate (10% magnification of one retinal image) adaptation paradigms, each one lasting for two hours. In the first they adapted subject's vertical saccades to binocular target step displacements, which were unequal in each eye. In the second they adapted subject's vertical pursuit eye movements to binocular non-conjugate motion of a vertically moving target. Lastly, they adapted subject's vertical saccades to target step displacements, which were again unequal in each eye. However, during the saccade itself only one eye was allowed to view the target. For 2 seconds subsequent to the saccade both eyes viewed the target. Consequently, the initial vergence response is open-loop. They found that changes in conjugacy (as evidenced by reduction in diplopia) occurred within 15-30 minutes for pursuit adaptation but took up to 1-1.5 hours for saccade adaptation. For saccade adaptation, the eyes always adapted to the change in one direction of gaze before the other (up and down). After pursuit adaptation they found, that apart from some small changes in post saccadic phoria, the effects had not generalised to saccadic eye movements. Following saccadic adaptation, the effects did not generalise to pursuit eye movements except for limited regions of the visual field. Adaptation to the vergence paradigm took longest, most subjects still perceiving diplopia at the end of the two hour period. This adaptation generalised to saccades to a very small extent. Consequently, Schor *et al.* (1990) conclude that it is possible to adapt saccade and pursuit version eye movements separately and that this adaptation does not seem to rely on a common underlying mechanism such as vergence adaptation.

Link between disconjugate adaptations and immediate, visually guided disconjugacy?

So far, adaptive disconjugacy and immediate, visually guided disconjugacy (i.e. disconjugacy elicited by asking subjects to change their gaze between targets in different directions and at different depths) have been presented as different phenomena. However, Eggert *et al.* (1995) suggest that they may both result from similar underlying processes. They examined this suggestion by observing the effect of three different combinations of monocular depth cues on both immediate disconjugacy and adaptive disconjugacy (as evidenced by disconjugacy which persisted under subsequent monocular viewing conditions) elicited using anisometropic spectacles. Thus a gradient of disparity will occur across the target space. In condition one a random dot target was used i.e. no monocular depth cues. In condition two a square sided grid was used i.e. perspective (monocular) cues present indicating a fronto-parallel plane. In condition three a complex target containing a number of monocular cues to depth, such as overlap and objects of different sizes, were used. However, these cues were jumbled so that no consistent depth was indicated. Immediate and appropriate disconjugacy occurred in all three conditions. The largest disconjugacy occurred for the multiple, jumbled monocular cues condition. The disconjugacy induced by the grid was position dependent. Adaptive disconjugacy occurred for the grid and random dot target conditions but not for the multiple, jumbled monocular cues condition. Thus, both the immediate disconjugate and adaptive disconjugate systems are affected by monocular depth cues. Eggert *et al.* (1995) conclude that this suggests that the vergence system is involved in adaptive disconjugacy in a similar way to which it is implicated in immediate saccade disconjugacy.

These conclusions are in contrast to those of Schor *et al.* (1990) who examined whether adaptive saccade disconjugacy was the result of an underlying binocular process or was specific to the saccadic system. They concluded that disconjugacy did not involve the vergence system.

Visual control of saccade disconjugacy

Little work has specifically investigated the visual conditions which elicit saccade disconjugacy. For example, are all depth cues capable of eliciting such unequal saccades? To date it has been shown that targets, where all depth cues are present, and those where only accommodation cues are present, can elicit such responses. In their paper on saccadic averaging Findlay & Harris (1993) reported that such unequal responses also sometimes occurred when subjects attempted to switch their gaze between targets of sudden onset situated at different distances and directions, where the only cue to depth was disparity information (accommodation held constant). In contrast, Hung & Ciuffreda (1996) found, on average, no consistent facilitation of vergence by disconjugate saccades under disparity only stimulation (accommodation held constant) during non-conjugate gaze-shifts. Approximately 50% of the saccades facilitated and 50% hindered the vergence response. Further, they observed that the vergence component of the responses was initiated approximately 100 msec prior to the saccadic component which they cite as being in contrast to the synchronous start of these two components under natural viewing conditions. They have produced a model which accounts for the differences in the occurrence of disconjugate saccades between disparity only and natural viewing conditions. The model is based on the differences in the timing of the onset of the vergence and saccadic components under these two conditions. However, the most recent data regarding non-conjugate gaze-shifts, under natural viewing conditions, found that the vergence component also preceded the saccadic component by approximately 100 msec (Collewijn *et al.* 1997). Consequently, the model presented by Hung & Ciuffreda (1996) is open to question.

Aims of thesis

This thesis has endeavoured to tread the line between gathering knowledge directly practical to eye pointing in three dimensions and in contributing to more general knowledge regarding oculomotor behaviour. The first three experimental chapters (four - six) are predominantly concerned with examining the visual conditions which elicit saccade disconjugacy about which, as previously mentioned, little is known. This is relevant to eye pointing in that it determines the speed with which the binocular point of foveation can be redirected to a target of interest, where that target may be presented on different types of three dimensional displays (for example, stereoscopic, perspective). In chapter four, limited evidence for saccade disconjugacy was found under disparity only viewing conditions, both when the target position was predictable and unpredictable. Chapters five and six show that linear perspective depth cues are not sufficient to elicit saccade disconjugacy. The final experimental chapter (seven) primarily compared fixational accuracy between an array of targets (large and small) presented at different depths using 'natural' and stereoscopic viewing techniques. No differences in fixational accuracy were found between the large and small targets or between the 'real' and 'virtual' targets.

4

Shifting gaze between targets at different depths in a stereoscopic display

Introduction

The primary aim of this experiment was to look at the speed of the eye's response when someone changed their gaze between objects at different depths and in different directions on a display where the depth information was provided stereoscopically.

As we look around our environment, we continually change our gaze between objects, which are situated at different depths and in different directions. The traditional view of the eye movements made under these conditions (Yarbus 1967; Carpenter 1988) asserts that both eyes are yoked, making an initial slow symmetrical vergence response (total vergence response takes a few hundred milliseconds), during which equal and quick (30-50 msec) saccadic movements in the same direction (version) occur, followed by the final stage of the symmetrical vergence response (figure 4.0). Hence, according to this explanation, if you were looking from a near target to your left to a far target to your right, although you might almost immediately have a clear view of the far target, your eyes visual axes will not both be fully on-target for at least one second.

According to this traditional explanation, the amplitude of movement of the entire gaze change can be characterised as the summation of a fast version and a slow vergence eye movements (Hering's hypothesis). The saccadic and vergence eye movements are held to be produced by independent oculomotor subsystems.

Enright (1986, 1992) and Erkelens *et al.* (1989a) have challenged this traditional view. They found that the two eyes do not necessarily move in a yoked fashion under such conditions. Rather, that the eyes may make saccades of unequal (disconjugate) amplitude, which reduce or even remove the size of the subsequent vergence response needed (figure 4.1). Consequently, it will be much quicker for the eyes to be fully on-target. In their paper on saccadic averaging Findlay & Harris (1993) reported unequal responses also occurred when subjects attempt to switch their gaze between targets of sudden onset situated at different distances and directions, where the only cue to depth was disparity information (accommodation held constant).

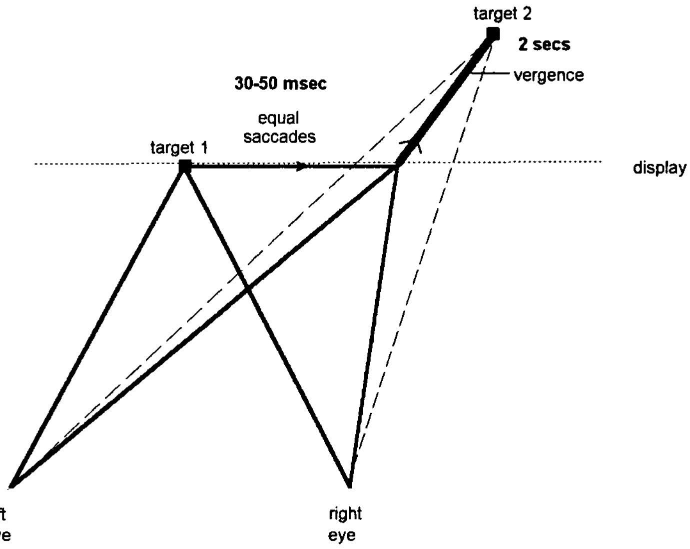

Figure 4.0 Traditional picture of eye movements made from one target to another which is in a different direction and at a different depth

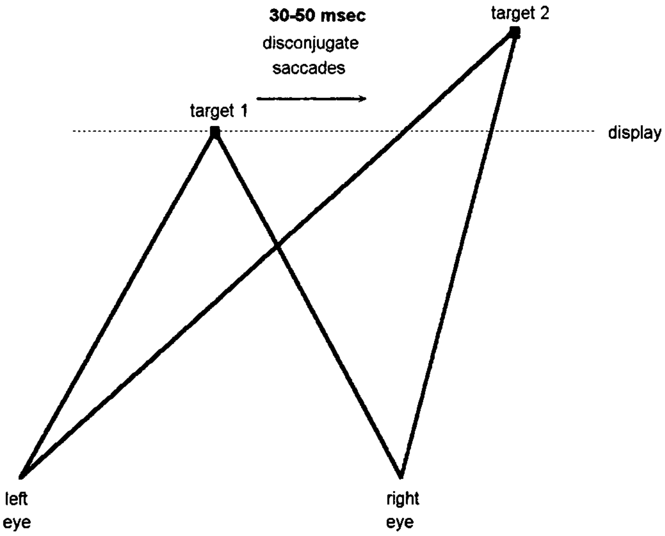

Figure 4.1 Contemporary picture of eye movements made from one target to another which is in a different direction and at a different depth

The experiment reported below sought to extend this line of research by exploring the form of saccadic and vergence responses to targets presented in different directions and at different depths in a stereoscopic display. Two different target presentation paradigms were used: stationary targets and sudden onset targets. In the first condition the target's location was known to the subject but during the second condition its location was unpredictable. Lemij & Collewijn (1989) found a difference in accuracy between primary saccades to stationary targets and sudden onset targets. Hence, a more efficient ocular response was expected for the stationary target presentation paradigm.

Method

Subjects

Four female subjects with an age range of 25 - 36, were recruited from the Durham University Psychology Department, to participate in the experiment. All subjects had Snellen visual acuity (near and far) of, or better than, 6/6 (20/20) in each eye (normally or after correction). The muscle balance (Maddox Wing test) of each subject was normal. All subjects had stereo acuity of better than 40 seconds of arc (Titmus). Subjects VB and KF had previously participated in eye movement experiments.

Apparatus

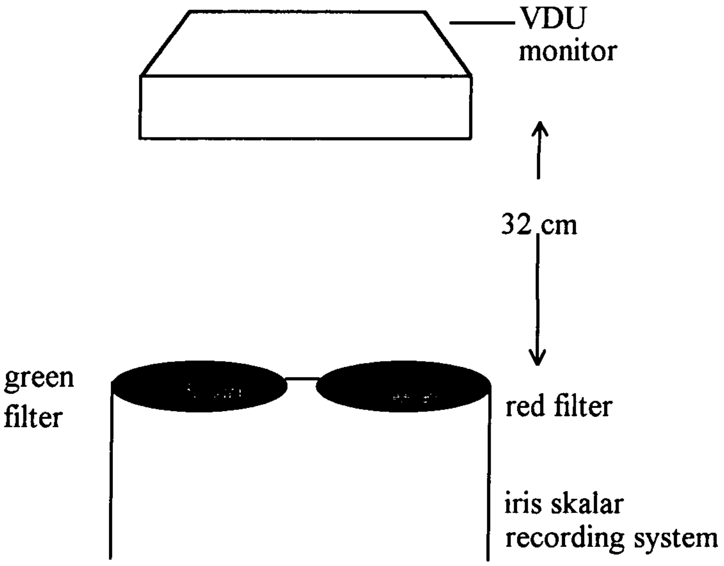

Figure 4.2 Schematic of experimental apparatus

Stimuli were generated on a display monitor (14" VGA colour monitor (43° x 33°)) located 32cm in front of the subject (figure 4.2). The subject's head was stabilised by a custom-fitted bite bar. The timing and presentation of the experimental stimuli and eye movement recording were controlled by a 386 PC. Green and red filters were placed in front of their left and right eyes respectively.

Stimuli

Four display colours (green, red, yellow & dark brown) were chosen, to match the green and red filters, using the method described by Mulligan (1986). The background luminance was 1.0 cd/m^2, the stimuli luminance 8.2 cd/m^2. The display consisted of a red/green random-dot stereogram of a target square (3° visual angle) floating in front of or behind the plane of the display (1° of disparity in both cases), either 9° to the left or right of a central nonius fixation cross i.e. the target was in one of four possible positions: near left, far left, near right or far right. A large target size was chosen to enable the subjects to fuse the targets with relative ease. Largish saccades and disparities were chosen to try to promote saccade disconjugacy. Two stimulus presentation conditions were used as follows:-

(a) **Sudden onset target (target position unpredictable)**:- A nonius fixation cross was presented for 1 second. It was then extinguished and the target square was presented for 5 seconds in one of the four possible target positions (randomly chosen). The target was extinguished and the nonius fixation cross presented again. Subjects were asked to move, as quickly and as accurately as possible, from the fixation cross to the target centre when the target appeared and to continue to fixate on the target centre until it disappeared. Five seconds allowed the subjects sufficient time to fuse the targets and for any slow vergence responses to manifest themselves.

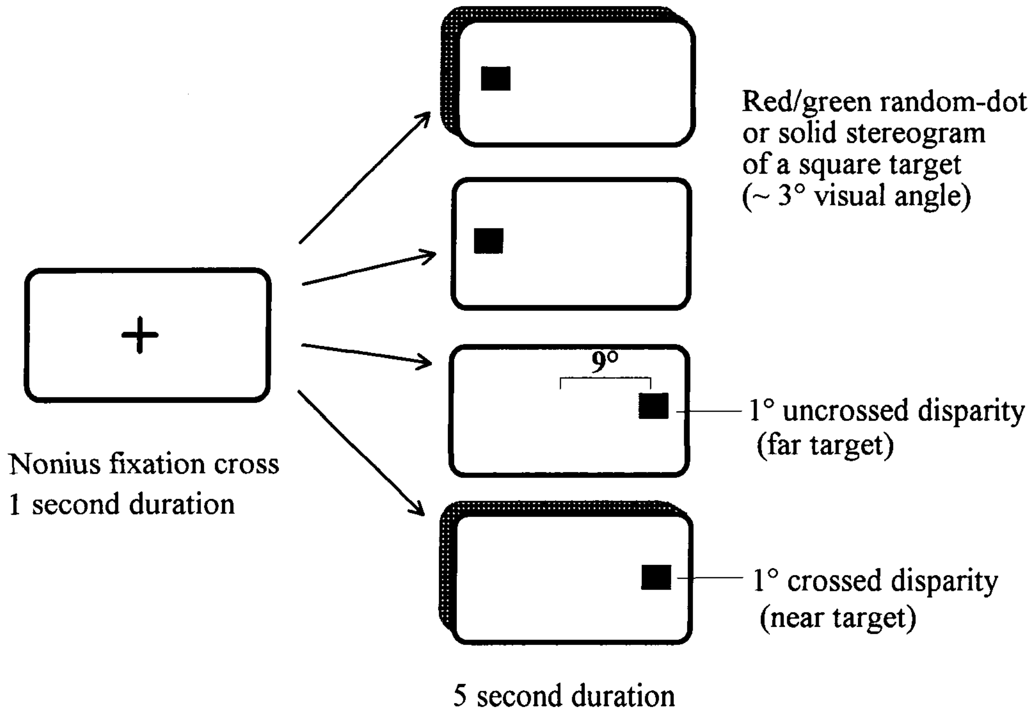

Figure 4.3 Diagram showing sequence and timing of each display in the unpredictable target position condition.

(b) **Constant target (target position predictable):-** The nonius fixation cross was continually visible. The target square was presented in one of the four possible target positions for 10 seconds. Subjects were asked to look from the fixation cross to the centre of the target and back again in time to a computer generated metronome. Subjects had time to make four saccades to the target before it was changed to one of the other positions (chosen randomly).

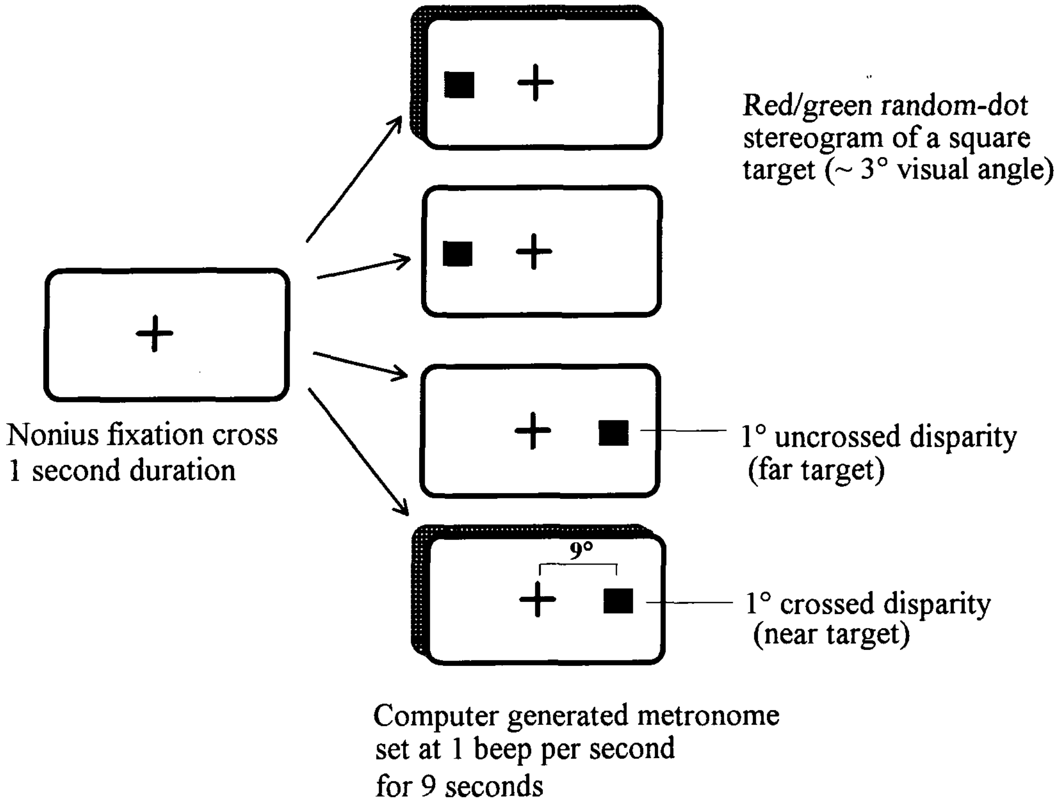

Figure 4.4 Diagram showing sequence and timing of each display in the predictable target position condition.

The two stimulus presentation paradigms were presented in separate experimental blocks. For each target position, the target was presented 10 times, in randomly chosen order. Eye movement recording began when the target appeared and stopped 5 or 9 seconds later, as appropriate. Consequently, 80 measurement records were collected and stored for off-line analysis.

The sudden onset target condition was subsequently repeated for two of the subjects using a solid stereogram of the square target.

Eye movement recording and analysis

Binocular horizontal eye movements were measured using the IRIS system manufactured by Skalar Medical. The resolution of this system is approximately 1 min of visual angle (Reulen *et al.* 1988). Subject's eye movements were sampled at 100Hz during the calibration procedure and at 200Hz during the trials. Subjects were asked to refrain from blinking during the trials to prevent eye movement effects. Data were stored off-line for subsequent analysis. The raw data were calibrated (quasi-linear), i.e. the eye movement units were converted to degrees of eye movement (see Appendix I for the calibration procedure and calculation), the centre fixation cross being defined as 0°. The left calibration target was defined as - 9° and the right calibration target as + 9°. All trials which met the following criteria were analysed:-

- Less than 5% change between initial and final calibrations.
- Subjects did not look away during the trial or shut their eyes.
- A blink did not occur.

Where the data met these criteria, the following measures were computed using a semi-automated software package (Figure 4.5). This plotted the raw data for each eye, with time on the x-axis and eye movement units on the y-axis:-

- The amplitude of the primary saccade, from the fixation cross to the target was measured in degrees, for the left eye (S_L) and the right eye (S_R). The start of the saccade in each eye was defined as the point where the velocity of the eye movement in the subject's left eye exceeded 15°/sec. The saccade's end was calculated as the point where the velocity of the left eye decreased below 15°/sec. Specifically, starting 2 sampling intervals after the beginning of each trial, for each eye movement sample x, the software algorithm compared the left eye position with its position two sampling intervals earlier (i.e. sample x-2, 10msec earlier). If the difference in eye position exceeded 0.15° (i.e. 15°/sec) then a comparison was made between the left eye position and its position one sampling interval earlier (i.e. sample x-1, 5msec earlier). If that difference exceeded one quarter of 0.15°

then the eye position at sample 1 was identified as the start of the saccade. Otherwise, sample 2 was identified as the saccade start. The same rationale was used to identify a saccade's end. The software automatically placed a line cursor at each of these points so that its selection could be checked[1].

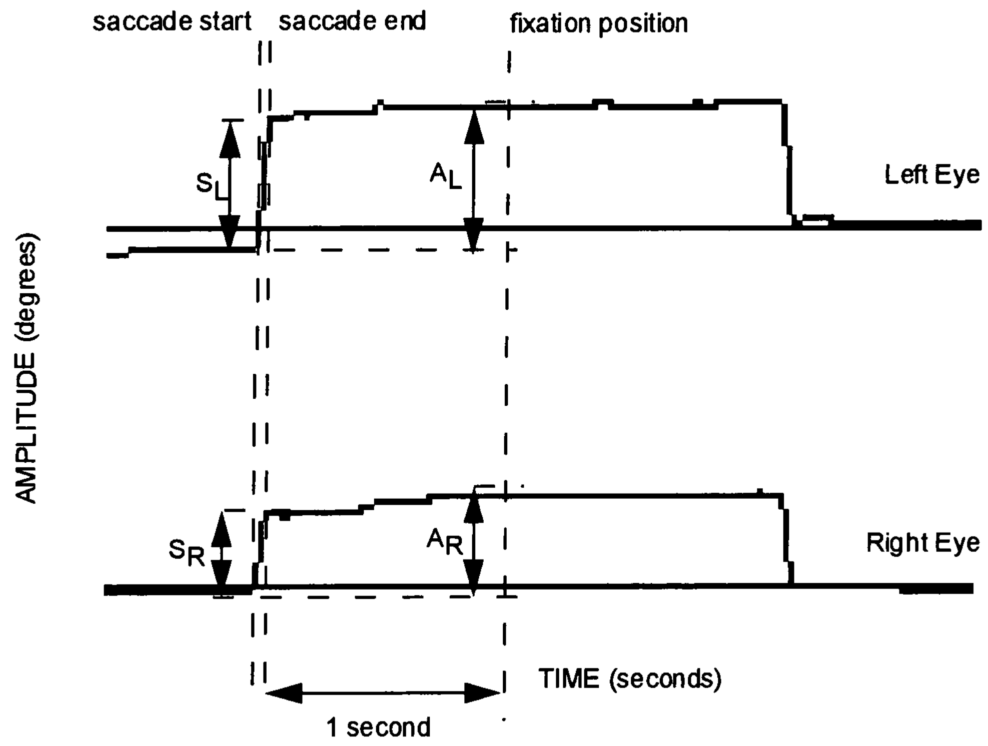

Figure 4.5 Saccade and vergence measures computed. S_L = amplitude of primary saccade of left eye, S_R = amplitude of primary saccade of right eye, A_L = amplitude of movement of left eye between saccade start and fixation position, A_R = amplitude of movement of right eye between saccade start and fixation position. Disconjugacy = $S_L - S_R$. Vergence = $A_L - A_R$.

- For each eye, the amplitude of any secondary saccades was measured. Secondary saccades were identified according to the same velocity criteria as saccades. Additionally, they were preceded by a primary saccade and larger than 0.25° i.e. not microsaccades associated with fixations.

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[1] A primary saccade was deemed to be one whose amplitude was greater than or equal to 30% of the target amplitude. The velocity of this saccade must be greater than 15-30 degrees/second and its latency greater than 60 msec, i.e. the target was not anticipated.

- The disconjugacy between the primary saccade of the each eye. This was defined as the amplitude of the primary saccade of the left eye (S_L) minus the amplitude of the primary saccade of the right eye (S_R).

- The 'on-target vergence change' was calculated one second after the end of the primary saccade i.e. at the fixation position. Vergence was defined as the amplitude of the left eye movement between the saccade start and the fixation position (A_L) minus the amplitude of the right eye's movement during the same time period (A_R). Hence, for a divergent movement the vergence value would be negative whereas for a convergent movement the value would be positive.

- The difference in disconjugacy between saccades to crossed and uncrossed disparity targets.

The vergence level during sample calibrations was checked, in a pilot test, to ensure it remained zero. This was found to be the case. See below for a representative example:-

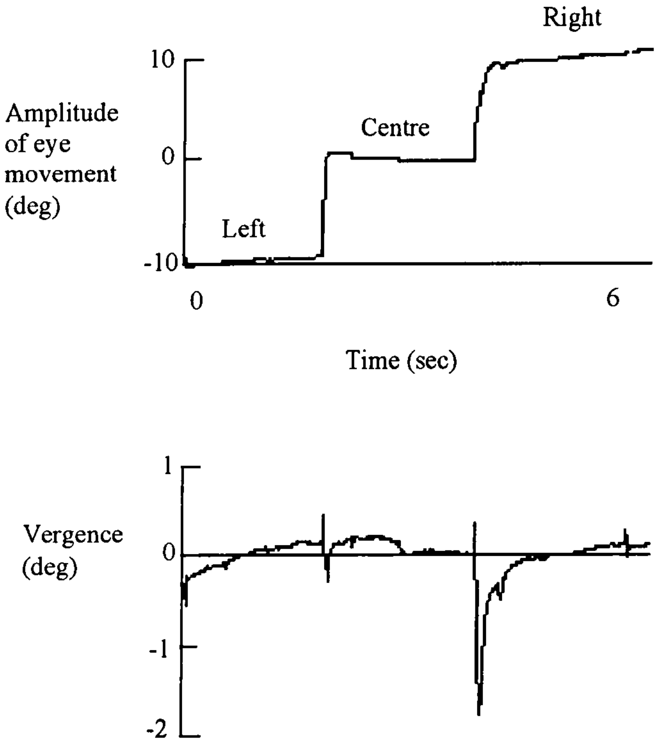


Figure 4.6 Vergence (degrees) during a calibration

Results

Subjects reported that the nonius lines were aligned when they looked at the nonius fixation cross. In most cases the target was seen as a single square.

Figure 4.7 shows the degree of disconjugacy expected if the entire depth shift was covered by unequal (disconjugate) saccades rather than a vergence eye movement.

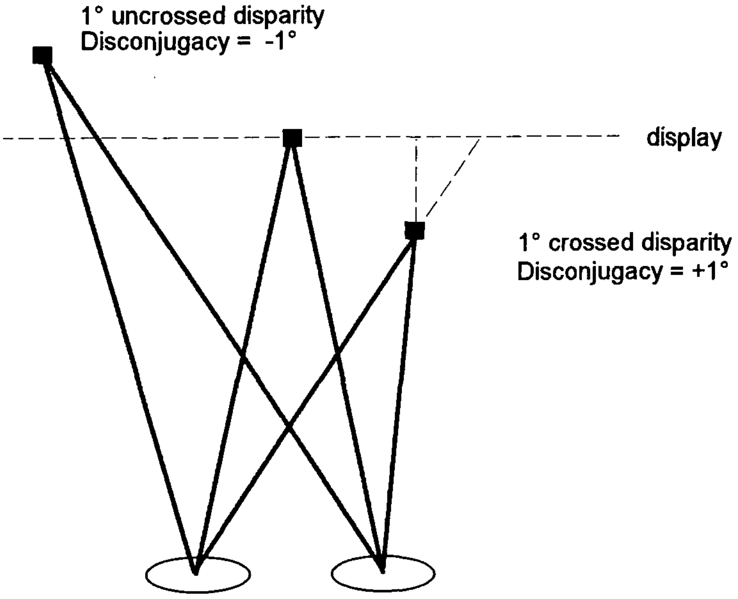


Figure 4.7 Diagram showing how much saccade disconjugacy might be expected where the entire depth shift is covered by a disconjugate saccade rather than a vergence eye movement.

Hence, the maximum expected difference in saccade disconjugacy between targets with crossed and uncrossed disparity was 2°.

At fixation, each subject's vergence level was expected to have changed by 1°, in a convergent or divergent direction as appropriate.

Sudden onset random-dot target (target position unpredictable)

Table 4.0 Calibration figures for sudden onset random-dot target trials

Sudden onset random-dot targets					
Subject name	Eye	Direction of looking	Pre-trial calibration dpv	Post-trial calibration dpv	% change
SM	Left	Left	0.00873	0.00892	-2.1
		Right	0.00856	0.00892	-4.2
	Right	Left	0.00815	0.00853	-4.6
		Right	0.00782	0.00817	-4.6
VB	Left	Left	0.00871	0.00841	3.4
		Right	0.00800	0.00840	-5.0
	Right	Left	0.00818	0.00841	-2.8
		Right	0.00803	0.00839	-4.5
KF	Left	Left	0.00783	0.00810	-3.5
		Right	0.00749	0.00773	-3.3
	Right	Left	0.00825	0.00865	-4.9
		Right	0.00756	0.00795	-5.1
BY	Left	Left	0.00967	0.00973	-0.6
		Right	0.01001	0.01040	-3.1
	Right	Left	0.00966	0.00973	-0.6
		Right	0.00903	0.00947	-4.9

Key:- dpv = degrees per volt (i.e. the number of degrees represented by the basic measuring unit of the eye movement equipment). % change was calculated as ((post-trial dpv – pre-trial dpv) / pre-trial dpv) * 100.

Inspection of table 4.0 shows that the percentage change between pre- and post-trial calibrations did not exceed 5%, the criteria set for analysing a set of trials.

Saccade disconjugacy

Table 4.1 shows that, at the end of each primary saccade, saccade disconjugacy was typically divergent for leftward saccades and convergent for rightward saccades. Exceptions to this trend are as follows:- subject SM, leftward movements; subject VB, leftward movements to near target positions; subject KF, rightward movements to far target positions and subject VB, rightward movements to near target positions. Figure 4.9 shows an example "vergence" eye movement response (left eye position - right eye position) to a single target, for each subject, for each target position. In general, each subject showed transient divergence during leftward primary saccades and small amounts of transient convergence during rightward primary saccades, for all target positions

Figure 4.8 shows the range of disconjugacy difference. For subject KF the disconjugacy difference was between 0.3° and 0.6° in size and was in the appropriate direction for both left and right targets. A Paired t-test (two tail) comparing disconjugacy to crossed and uncrossed disparity targets (Table 4.1) showed that the effect was significant ($t_8 = 2.56$, $P<0.05$) for rightward saccades but not for leftward ones. Subject BY showed just under 0.5° of disconjugacy difference for left targets in the wrong direction. The difference was significant ($t_8 = -2.65$, $P<0.05$). She showed no difference for right targets. Subject SM showed just under 0.5° of disconjugacy difference, in the appropriate direction, for right targets ($t_8 = 3.02$, $P<0.05$) but no differences for left targets. Subject VB showed 0.3° of disconjugacy difference for left targets in the appropriate direction. However, this difference was not significant. She showed no disconjugacy differences for right targets.

None of the subjects made any secondary saccades.

Table 4.1 Mean disconjugacy and disconjugacy difference in degrees.

Leftward Saccades	Subj BY	Subj KF	Subj SM	Subj VB
crossed disparity	-0.86±0.54 (9, 0.18)	-1.76±0.45 (10, 0.14)	0.13±0.15 (10, 0.05)	0.27±0.50 (10, 0.16)
uncrossed disparity	-0.44±0.44 (9, 0.15)	-2.09±0.48 (10, 0.15)	0.18±0.25 (10, 0.08)	-0.06±0.45 (10, 0.14)
crossed - uncrossed	-0.42 $P<0.05$ $t_8 = -2.65$	0.33^* NS	-0.05 NS	0.33^* NS
Rightward Saccades				
crossed disparity	0.35±0.22 (10, 0.07)	0.26±0.38 (9, 0.13)	0.61±0.31 (10, 0.10)	-0.08±0.43 (10, 0.14)
uncrossed disparity	0.35±0.51 (9, 0.17)	-0.28±0.34 (10, 0.11)	0.21±0.15 (9, 0.05)	0.03±0.41 (9, 0.14)
crossed - uncrossed	-0.01 NS	0.56^* $P<0.05$ $t_8 = 2.56$	0.41^* $P<0.05$ $t_8 = 3.02$	-0.18 NS

Key:- mean ± s.d. (n, s.e.). *P* values and t values for paired t-test (two tail) comparing disconjugacy between crossed and uncrossed disparity targets (NS: not significant).
* Disconjugacy difference in the appropriate direction.

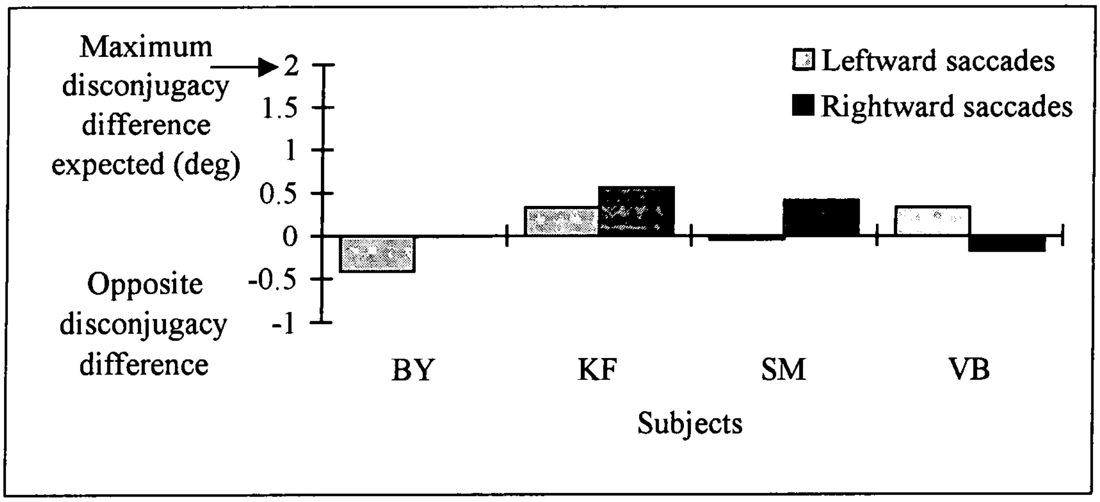


Figure 4.8 Disconjugacy difference for leftward and rightward saccades for four subjects

On-target vergence change

Subject KF showed appropriate vergence changes one second after the saccade end in all conditions except for right targets with uncrossed disparity (i.e. far targets) where only 0.03° of vergence change was effected (Figure 4.9 & Table 4.2). A paired t-test (two tail) between no vergence (i.e. zero) and vergence for each target position showed that the differences were significant (right near $t_8 = 8.67$, left near $t_9 = 3.51$, left far $t_9 = -5.74$, $P<0.01$). Interestingly, for left near targets, the eyes seem to achieve an appropriate convergence level after one or more seconds by a "hunting" movement, having started from an initial transient and inappropriate divergent position. Subject VB showed appropriate vergence changes for far targets in both directions (left $t_9 = -2.86$, $P<0.05$, right $t_9 = -3.80$, $P<0.01$). She showed an inappropriate vergence change for the right near target ($t_9 = -2.96$, $P<0.05$). Subject SM showed appropriate vergence changes for right far targets ($t_8 = -10.94$, $P<0.01$). Subject BY showed appropriate vergence changes for right near targets ($t_9 = 6.56$, $P<0.01$). She showed an inappropriate vergence change for right far targets ($t_9 = 3.07$, $P<0.01$) and left near targets ($t_8 = -2.58$, $P<0.05$).

Table 4.2 Mean vergence values in degrees.

Leftward Saccades	Subj BY	Subj KF	Subj SM	Subj VB
crossed	-0.42 ± 0.54 (9, 0.18) $P<0.05$ $t_8 = -2.58$	$0.86^{*}\pm0.77$ (10,0.24) $P<0.01$ $t_9 = 3.51$	$0.12^{*}\pm0.18$ (10, 0.06) NS	$0.13^{*}\pm0.72$ (10, 0.23) NS
uncrossed	$-0.03^{*}\pm0.37$ (9, 0.12) NS	$-1.01^{*}\pm0.56$ (10, 0.18) $P<0.01$ $t_9 = -5.74$	0.09 ± 0.19 (10, 0.06) NS	$-0.51^{*}\pm0.56$ (10, 0.18) $P<0.05$ $t_9 = -2.86$
Rightward Saccades				
crossed	$0.46^{*}\pm0.22$ 10, 0.07) $P<0.01$ $t_9 = 6.56$	$2.10^{*}\pm0.73$ (9, 0.24) $P<0.01$ $t_8 = 8.67$	-0.08 ± 0.43 (10, 0.13) NS	-0.37 ± 0.40 (10, 0.13) $P<0.05$ $t_9 = -2.96$
uncrossed	0.48 ± 0.53 (9, 0.18) $P<0.01$ $t_9 = 3.07$	0.03 ± 0.58 (10, 0.18) NS	$-0.59^{*}\pm0.16$ 9, 0.05) $P<0.01$ $t_8 = -10.94$	$-0.55^{*}\pm0.29$ (10, 0.09) $P<0.01$ $t_9 = -3.80$

Key:- mean ± s.d. (n, s.e.). *P* values and t values for paired t-test (two tail) comparing 'on-target vergence change' between crossed and uncrossed disparity targets (NS: not significant). * Vergence change was in the appropriate direction.

Subject KF

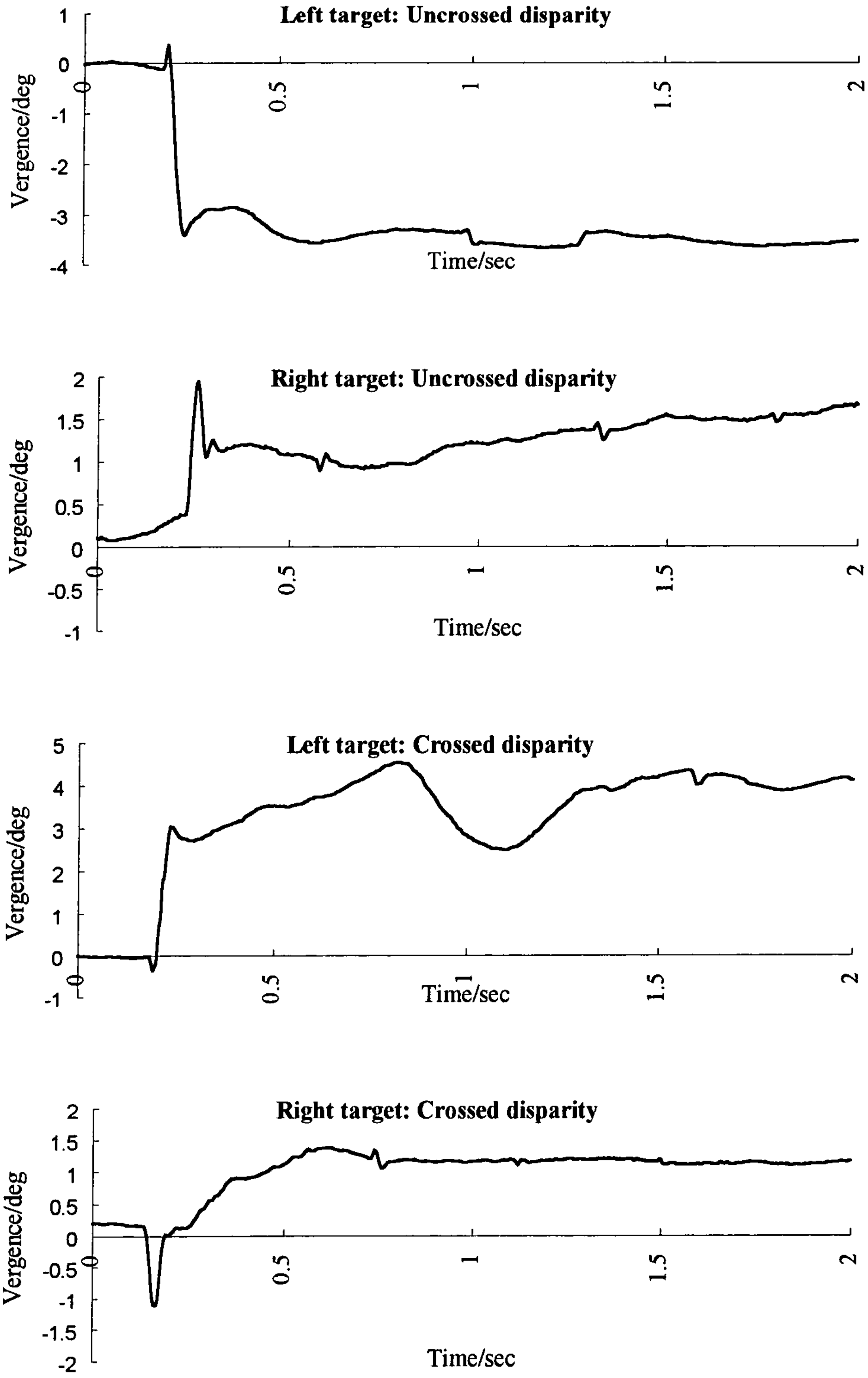


Figure 4.9 Example of vergence eye movement responses to sudden-onset "random dot" targets (left - right eye position)

Subject BY

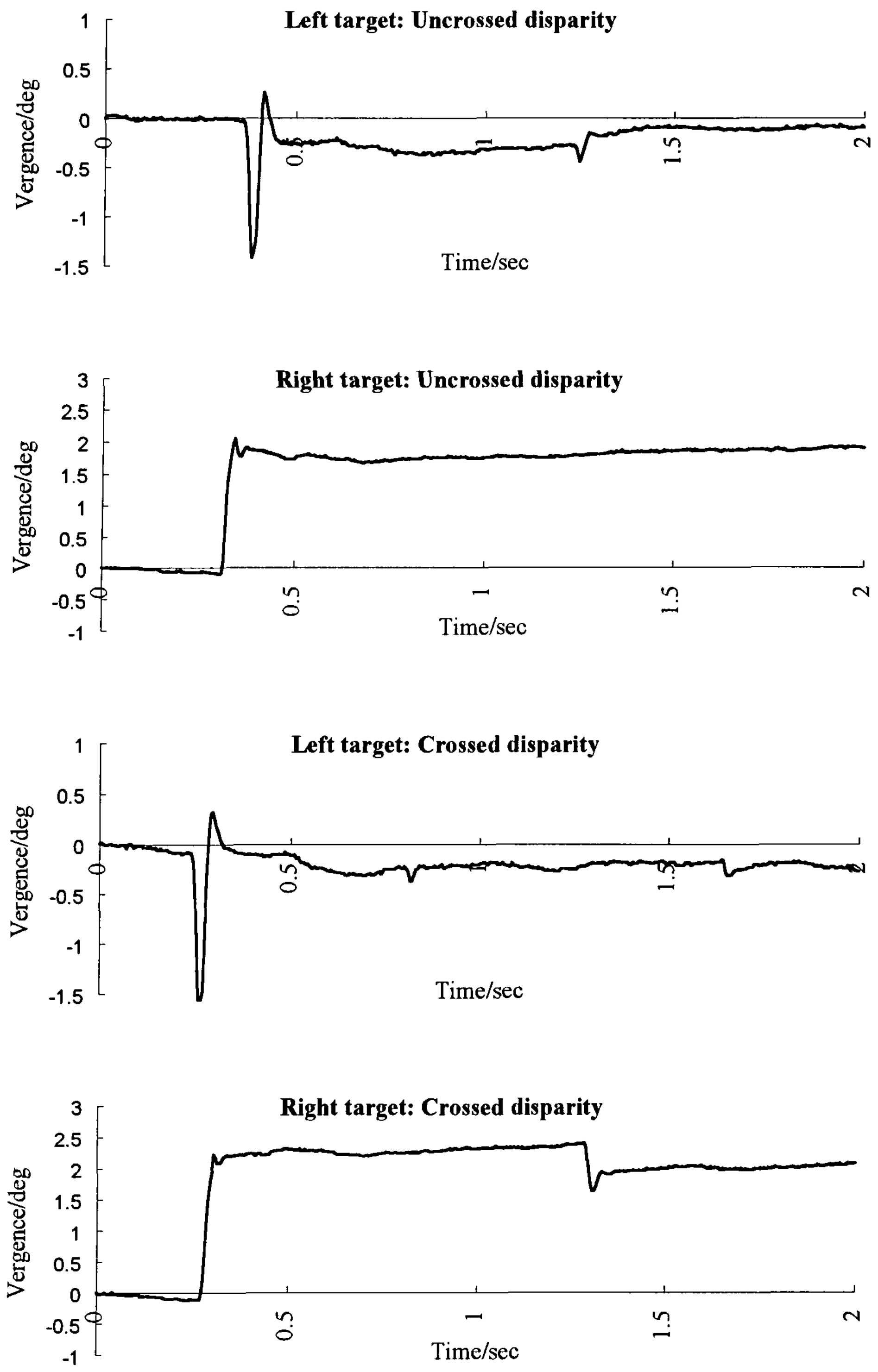


Figure 4.9 cont.

Subject SM

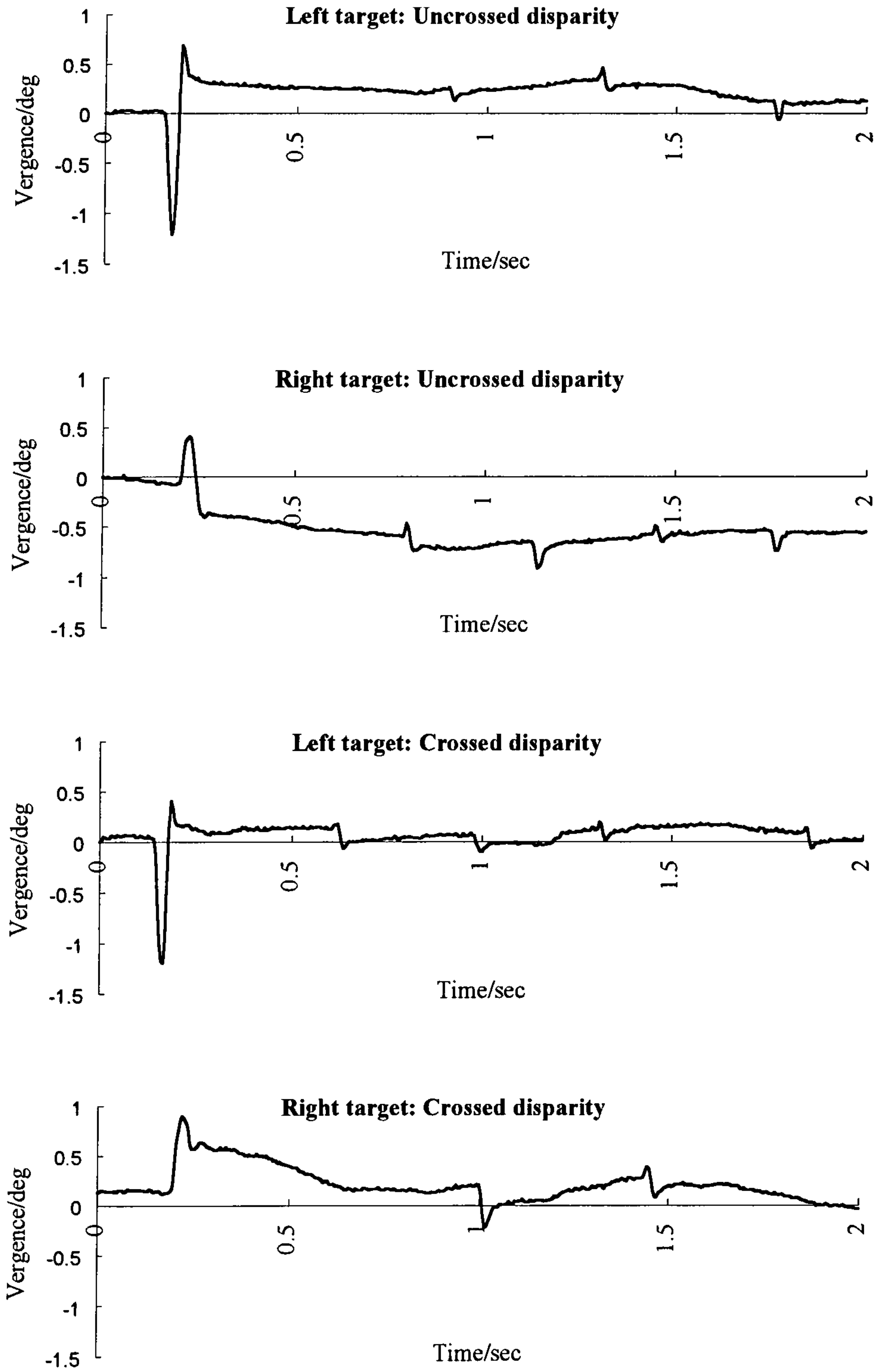
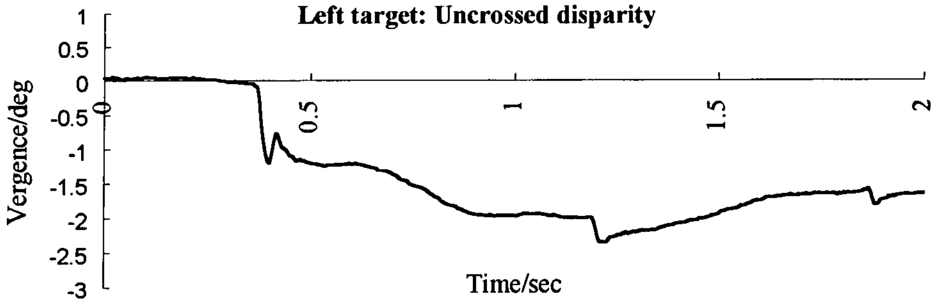
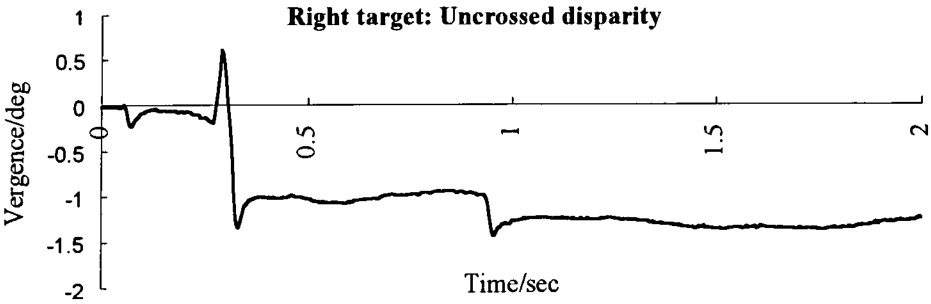
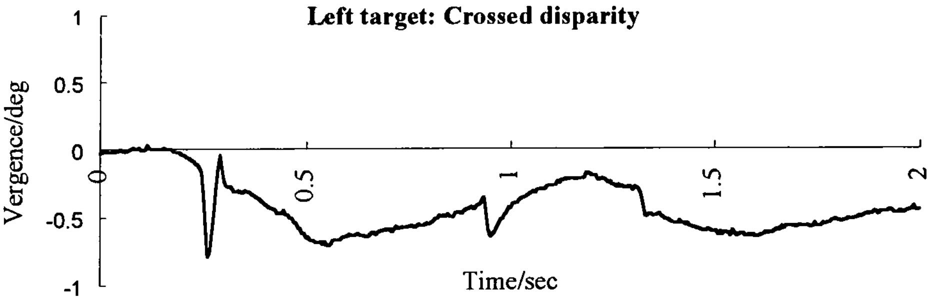


Figure 4.9 cont.

Subject VB







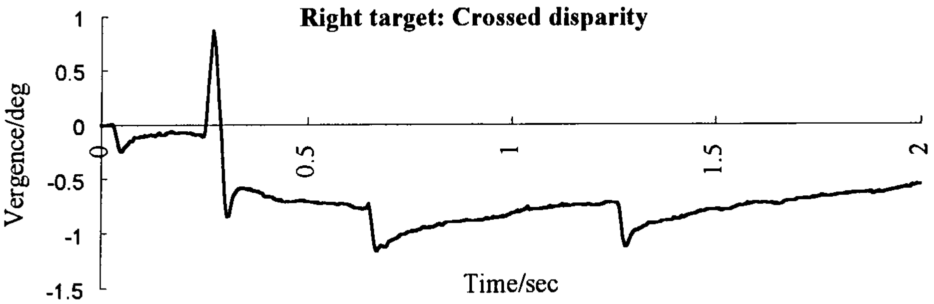


Figure 4.9 cont.

Sudden onset solid square (target position unpredictable)

Table 4.3 Calibration figures for sudden onset solid target trials

Sudden onset random-dot targets					
Subject name	Eye	Direction of looking	Pre-trial calibration dpv	Post-trial calibration dpv	% change
VB	Left	Left	0.00834	0.00870	-4.3
		Right	0.00851	0.00810	4.9
	Right	Left	0.00750	0.00711	5.1
		Right	0.00712	0.00682	4.2
KF	Left	Left	0.01018	0.01018	0.0
		Right	0.00967	0.00919	4.9
	Right	Left	0.00852	0.00889	-4.4
		Right	0.01052	0.01102	-4.8

Key:- dpv = degrees per volt (i.e. the number of degrees represented by the basic measuring unit of the eye movement equipment). % change was calculated as ((post-trial dpv – pre-trial dpv) / pre-trial dpv) * 100.

Inspection of table 4.3 shows that the percentage change between pre- and post-trial calibrations did not exceed 5%, the criteria set for analysing a set of trials.

Saccade disconjugacy

Table 4.4 shows that both subject KF & VB showed divergent disconjugacy, at the end of each primary saccade, for all target positions. Figure 4.9 shows an example of a "vergence" eye movement response (left eye position - right eye position) to a single target, for each subject, for each target position. During the rightward primary saccades, the ultimately divergent disconjugacy was preceded by a transient convergent eye movement.

Figure 4.10 shows that for subject KF, the disconjugacy difference was in the appropriate direction, between 1° and 1.3° in size, for each target position. A Paired t-test (two tail) comparing disconjugacy between crossed and uncrossed disparity targets showed that the effect was significant ($t_5 = 7.20$, $P<0.01$) for leftward saccades but not for rightward ones. Subject VB showed small differences, in the wrong direction, for each target position. These differences were not significant.

Neither subject made any secondary saccades.

Table 4.4 Mean disconjugacy and disconjugacy difference in degrees.

Leftward Saccades	Subj KF	Subj VB
crossed disparity	-0.73±0.35 (8, 0.12)	-0.52±0.47 (8, 0.17)
uncrossed disparity	-1.77±0.47 (6, 0.19)	-0.51±0.39 (9, 0.13)
crossed - uncrossed	1.04* $P<0.01$ $t_5 = 7.20$	-0.08 NS
Rightward Saccades		
crossed disparity	-1.39±0.98 (10, 0.31)	-1.29±1.29 (8, 0.46)
uncrossed disparity	-2.07±1.18 (9, 0.39)	-0.81±0.69 (10, 0.22)
crossed - uncrossed	1.28* NS	-0.46 NS

Key:- mean ± s.d. (n, s.e.). *P* values and t values for paired t-test (two tail) comparing disconjugacy between crossed and uncrossed disparity targets (NS: not significant).
* Disconjugacy difference in the appropriate direction.

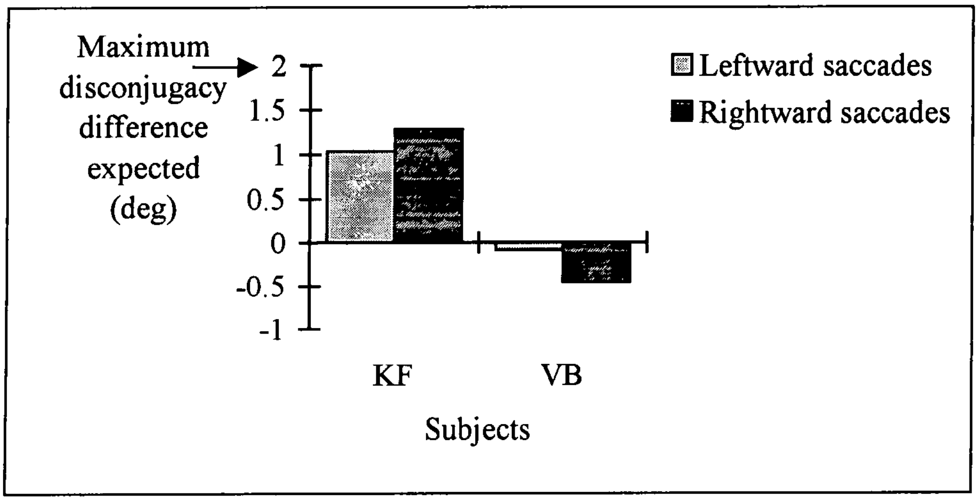


Figure 4.10 Disconjugacy difference, for each subject, for leftward and rightward saccades

On-target vergence change

Figure 4.11 and Table 4.5 show that subject KF made appropriate vergence changes at fixation for all the target positions. A paired t-test (two tail) between no vergence and vergence for each target position showed that the differences were significant for the near target positions but not for the far positions (left near $t_7 = 6.20$, $P<0.01$, right near $t_9 = 2.70$, $P<0.05$). Note that for left near targets, the eyes achieve an appropriate convergence level having started from an initial transient divergent position. However, in contrast to responses to the random dot stereogram target, no "hunting" movements were shown during this process. Subject VB showed appropriate vergence changes for left near targets and right far targets. These changes were significant for the left near position only ($t_7 = -2.35$, $P<0.05$). She showed an inappropriate vergence change for the left far target ($t_8 = -4.76$, $P<0.01$) and the right near target (NS).

Table 4.5 Mean vergence value in degrees.

Leftward Saccades	Subj KF	Subj VB
crossed disparity	$1.67^* \pm 0.76$ (8, 0.27) $P<0.01$ $t_7 = 6.20$	$0.49^* \pm 0.46$ (8, 0.16) $P<0.05$ $t_7 = -2.35$
uncrossed disparity	$-0.34^* \pm 0.61$ (6, 0.25) NS	0.27 ± 0.17 (9, 0.06) $P<0.01$ $t_8 = -4.76$
Rightward Saccades		
crossed disparity	$0.73^* \pm 0.85$ (10, 0.27) $P<0.05$ $t_9 = 2.70$	-1.02 ± 1.56 (8, 0.55) NS
uncrossed disparity	$-0.63^* \pm 1.27$ (9, 0.42) NS	$-0.38^* \pm 0.75$ (10, 0.24) NS

Key:- mean ± s.d. (n, s.e.). *P* values and t values for paired t-test (two tail) comparing 'on-target vergence change' between crossed and uncrossed disparity targets (NS: not significant). * Vergence change was in the appropriate direction.

Subject KF

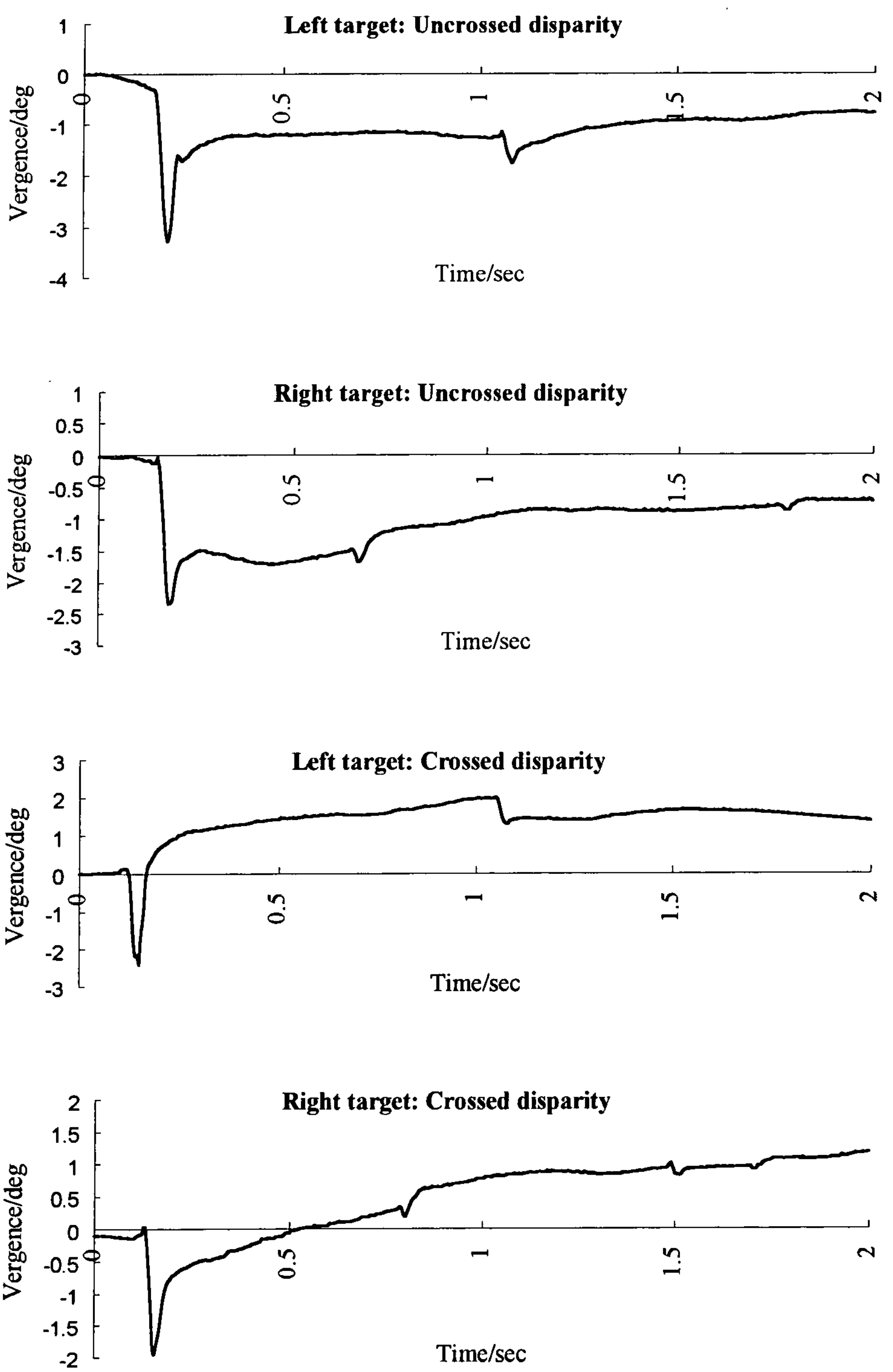


Figure 4.11 Example of vergence eye movement responses to solid targets (left - right eye position)

Subject VB

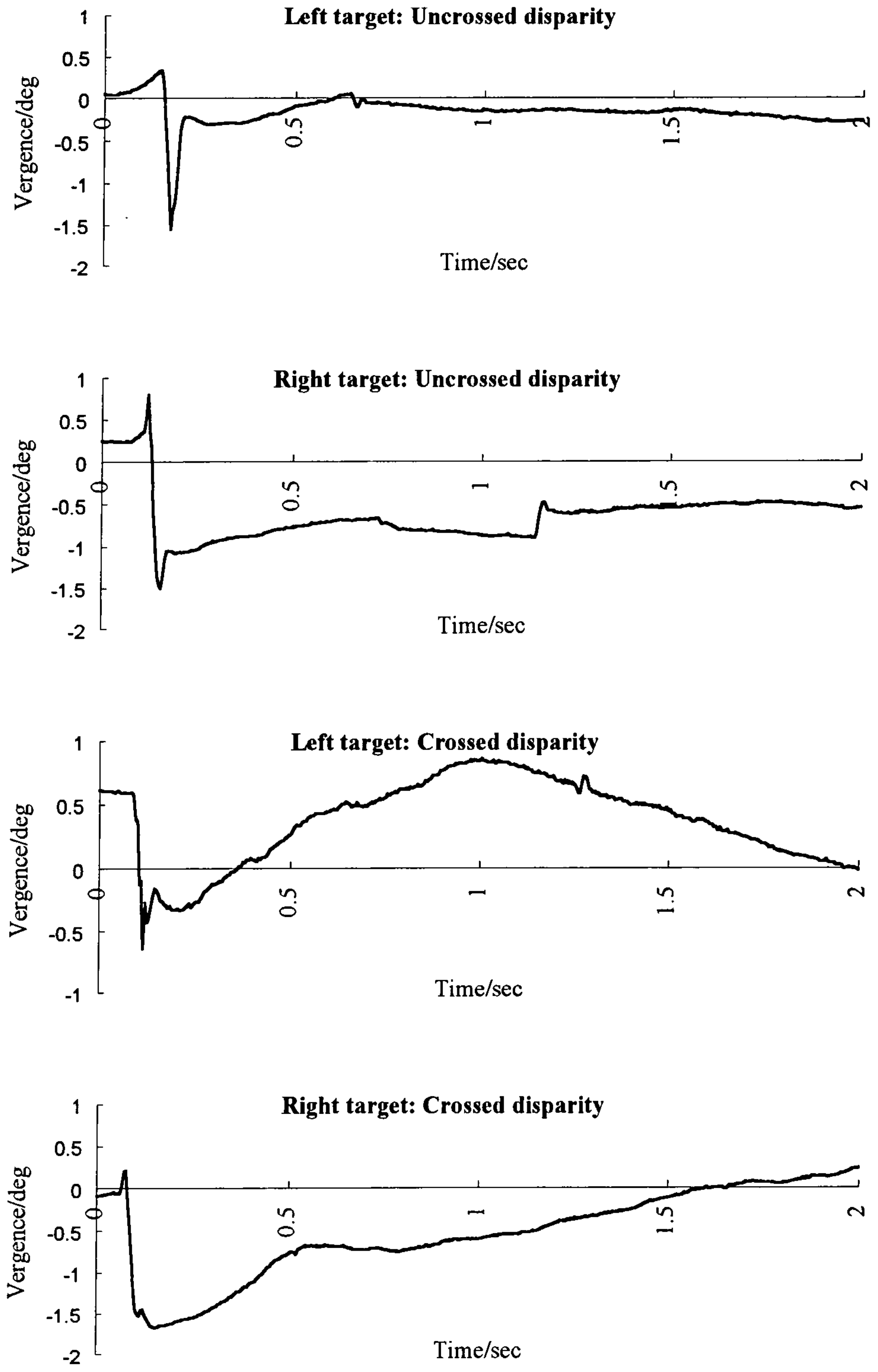


Figure 4.11 cont.

Stationary random-dot square (target position predictable)

Table 4.6 Calibration figures for stationary random-dot square trials

Stationary random-dot square targets					
Subject name	Eye	Direction of looking	Pre-trial calibration dpv	Post-trial calibration dpv	% change
SM	Left	Left	0.01067	0.01039	2.6
		Right	0.00986	0.01015	-3.0
	Right	Left	0.00974	0.00962	1.2
		Right	0.00890	0.00891	-0.1
VB	Left	Left	0.00866	0.00891	-2.8
		Right	0.00892	0.00919	-2.9
	Right	Left	0.00770	0.00804	-4.4
		Right	0.00847	0.00888	-4.7
KF	Left	Left	0.00770	0.00800	-3.9
		Right	0.00941	0.00987	-4.9
	Right	Left	0.00871	0.00905	-3.8
		Right	0.00898	0.00942	-4.9
BY	Left	Left	0.00995	0.01015	-2.0
		Right	0.01114	0.01157	-3.8
	Right	Left	0.00975	0.01022	-4.8
		Right	0.00885	0.00886	-0.1

Key:- dpv = degrees per volt (i.e. the number of degrees represented by the basic measuring unit of the eye movement equipment). % change was calculated as ((post-trial dpv – pre-trial dpv) / pre-trial dpv) * 100.

Inspection of table 4.6 shows that the percentage change between pre- and post-trial calibrations did not exceed 5%, the criteria set for analysing a set of trials.

Saccade disconjugacy

Table 4.7 shows that, in general, at the end of each primary saccade, saccade disconjugacy was divergent, for each target position. Exceptions to this are as follows:- Subjects BY and SM, rightward saccades. Figure 4.13 shows an example of a “vergence” eye movement response (left eye position - right eye position) for a single trial, for each subject, for each target position. During each primary saccade, there is transient divergence for each target position except for subjects BY and SM who show transient convergence during rightward saccades.

The disconjugacy difference, although generally small, was in the appropriate direction for all subjects (Figure 4.12), except for the leftward saccades of subject KF and VB. A Paired t-test (two tail) comparing disconjugacy between crossed and uncrossed disparity targets was not significant for any of the subjects, except for the rightward saccades made by subject SM ($t_{11} = -2.88$, $P<0.01$).

Table 4.7 Mean disconjugacy and disconjugacy difference in degrees.

Leftward saccades	Subj BY	Subj KF	Subj SM	Subj VB
crossed disparity	-0.51±0.30 (10, 0.09)	-0.74±0.81 (10, 0.26)	-0.43±0.29 (11, 0.09)	-0.32±0.17 (11, 0.05)
uncrossed disparity	-0.60±0.23 (9, 0.08)	-0.61±0.68 (12, 0.20)	-0.54±0.26 (12, 0.07)	-0.30±0.20 (12, 0.06)
crossed - uncrossed	0.11* NS	-0.08 NS	0.13* NS	-0.03 NS
Rightward saccades				
crossed disparity	1.57±0.24 (11, 0.07)	-2.61±0.80 (11, 0.24)	0.35±0.16 (12, 0.04)	-1.44±0.24 (10, 0.08)
uncrossed disparity	1.24±0.67 (10, 0.21)	-3.39±0.53 (7, 0.20)	0.21±0.09 (12, 0.03)	-1.87±0.51 (12, 0.15)
crossed - uncrossed	0.35* NS	0.63* NS	0.13* $P<0.01$ $t_{11} = -2.88$	0.43* NS

Key:- mean ± s.d. (n, s.e.). *P* values and t values for paired t-test (two tail) comparing disconjugacy between crossed and uncrossed disparity targets (NS: not significant). * Disconjugacy difference in the appropriate direction.

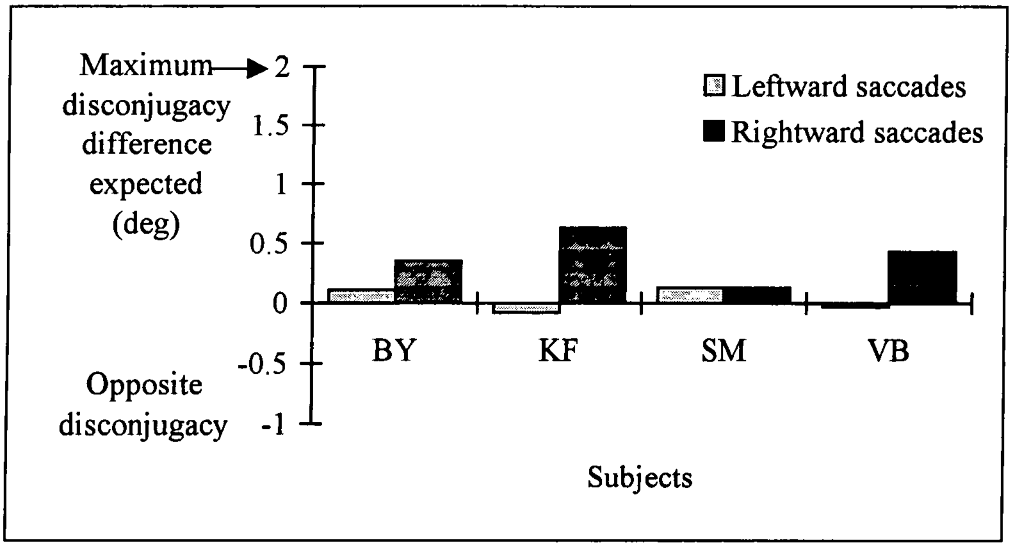


Figure 4.12 Disconjugacy difference, for each subject, for leftward and rightward saccades

None of the subjects made any secondary saccades.

On-target vergence change

Figure 4.13 and Table 4.8 show that subject KF showed appropriate and significant levels of vergence change at fixation, for left near (t_9 = 12.14, P<0.01) and right far (t_5 = -5.55, P<0.01) targets. Subject BY showed appropriate and significant (t_7 = -15.97, P<0.01) changes in vergence level for left far targets as did subject SM (t_{10} = -14.89, P<0.01) . Subject VB showed appropriate and significant (t_{10} = -8.14, P<0.01) levels of vergence change for right far targets. Subject BY and SM showed inappropriate but significant levels of vergence change at fixation for left near targets (t_7 = -7.37, t_{10} = -3.90, P<0.01). Subject VB showed inappropriate but significant levels of vergence change at fixation for right near targets (t_9 = -5.12, P<0.01).

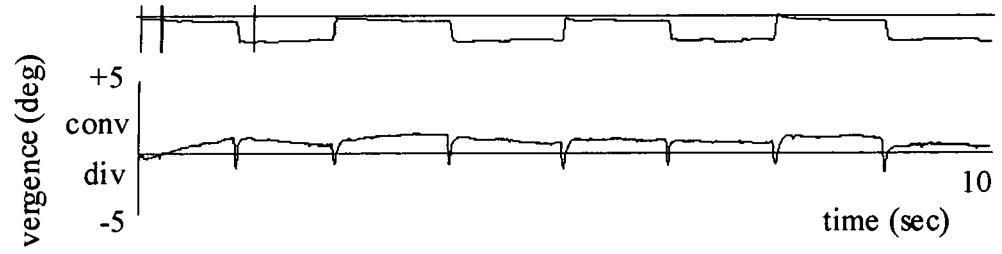
Table 4.8 Mean vergence in degrees.

Leftward saccades	Subj BY	Subj KF	Subj SM	Subj VB
crossed disparity	-0.95±0.36 (8, 0.13) P<0.01 t_7 = -7.37	1.48*±0.39 (10, 0.12) P<0.01 t_9 = 12.14	-0.22±0.19 (11, 0.06) P<0.01 t_{10} = -3.90	0.13*±0.53 (10, 0.17) NS
uncrossed disparity	-1.15*±0.20 (8, 0.07) P<0.01 t_7 = -15.97	0.20±0.63 (12, 0.18) NS	-0.53*±0.12 (11, 0.03) P<0.01 t_{10} = -14.89	0.06±0.16 (10, 0.05) NS
Rightward saccades				
crossed disparity	0.03*±0.19 (9, 0.06) NS	-0.41±0.63 (10, 0.20) NS	0.12*±0.21 (12, 0.06) NS	-0.58±0.36 (10, 0.11) P<0.01 t_9 = -5.12
uncrossed disparity	-0.10*±0.27 (8, 0.10) NS	-1.58*±0.25 (6, 0.10) p<0.01 t_5 = -15.55	-0.02*±0.16 (12, 0.05) NS	-0.97*±0.39 (11, 0.12) P<0.01 t_{10} = -8.14

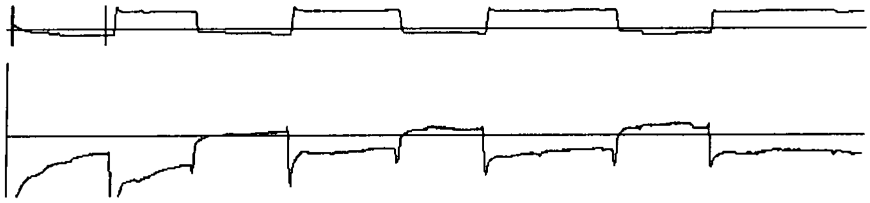
Key:- mean ± s.d. (n, s.e.). P values and t values for paired t-test (two tail) comparing 'on-target vergence change' between crossed and uncrossed disparity targets (NS: not significant). * Vergence change was in the appropriate direction.

Subject KF

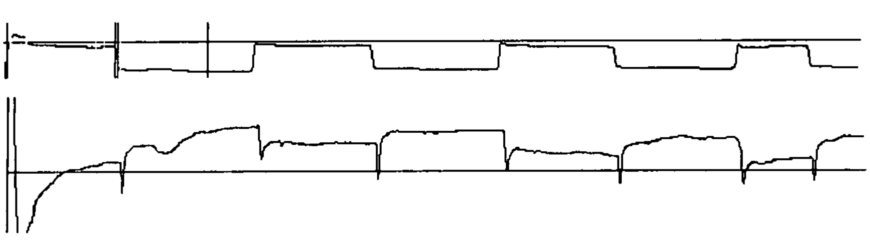
Left target: Uncrossed target[1]



Right target: Uncrossed disparity



Left target: Crossed disparity



Right target: Crossed disparity

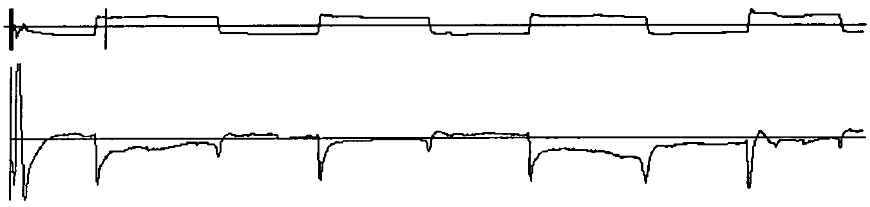


Figure 4.13 Example right eye responses (top trace) and "vergence" eye movement responses (left eye position - right eye position) for each subject looking between the central fixation cross and the target approximately four times.

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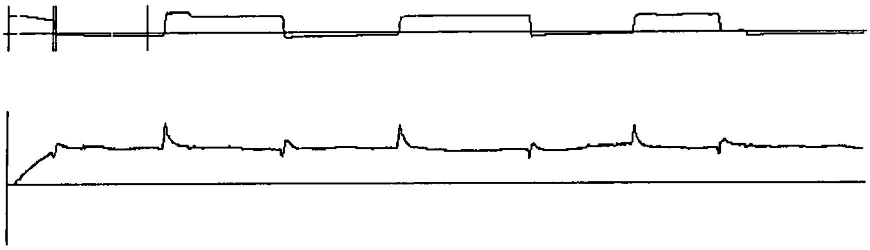
[1] Note that the same scale is used in all the following eye movement traces.

Subject BY

Left target: Uncrossed disparity

Right target: Uncrossed disparity



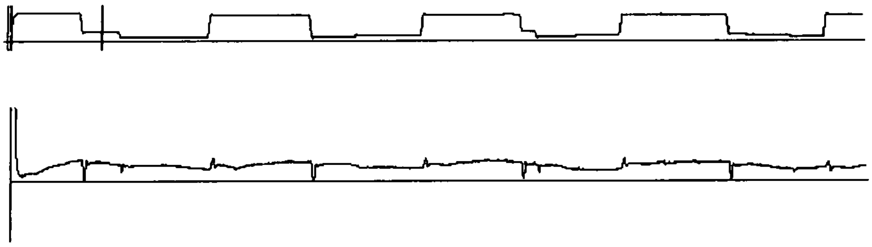
Left target: Crossed disparity

Right target: Crossed disparity

Figure 4.13 cont.

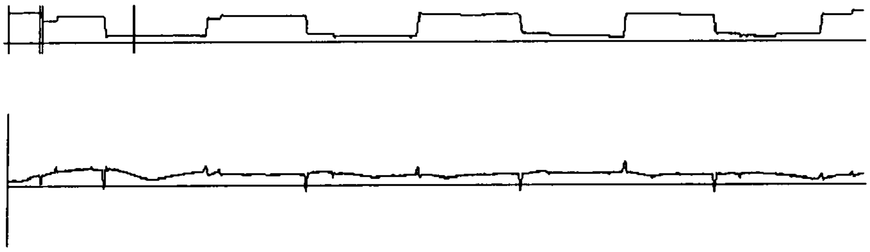
Subject SM

Left target: Uncrossed disparity



Right target: Uncrossed disparity

Left target: Crossed disparity



Right target: Crossed disparity

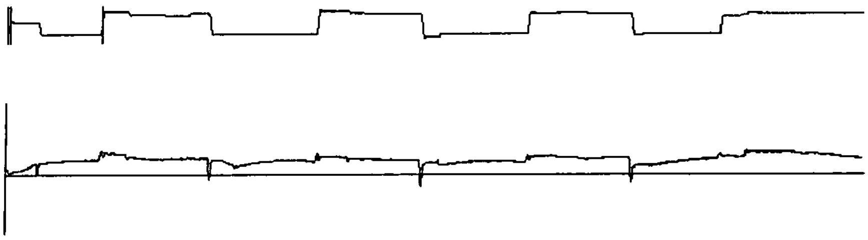
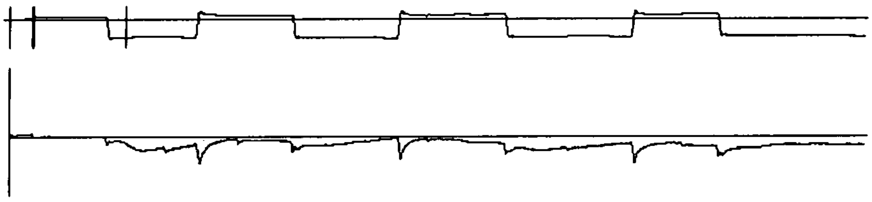


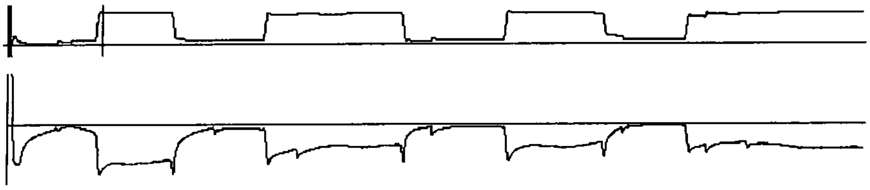
Figure 4.13 cont.

Subject VB

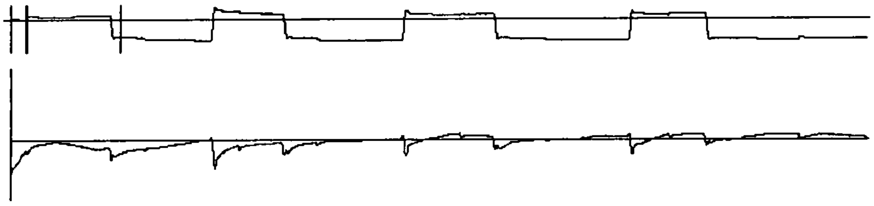
Left target: Uncrossed disparity



Right target: Uncrossed disparity



Left target: Crossed disparity



Right target: Crossed disparity

Figure 4.13 cont.

Saccade accuracy

Table 4.9 shows a comparison of the accuracy of the subjects' primary saccades in their left and right eye to a sudden onset target (position unpredictable) as against a stationary target (predictable position). In each case, the accuracy of the primary saccade in the left or right eye was compared with the ideal left and right eye movement which would have to be made if the entire depth shift, from the fixation cross to the target, was covered by a disconjugate saccade rather than vergence eye movements. The data are plotted in Figure 4.14.

The offset between primary saccade and ideal saccade for each eye ranged from -3.89° to +5.23°. Subject KF showed a mean undershoot of 20% of target eccentricity. The remaining three subjects showed no consistent tendency towards either undershooting or overshooting the target. Mean offset was 8% of target eccentricity for subjects SM and BY and 16% for subject VB. There were no differences between the accuracy of the primary saccades in the two different presentation paradigms (based on examination of figure 4.14).

Table 4.9 Comparison between the accuracy of subjects' primary saccades to a sudden onset target and a stationary target

	Uncrossed disparity			
	Leftward saccade		Rightward saccade	
	θ_L	θ_R	θ_L	θ_R
Ideal amplitude of primary saccade	**-8.9**	**-7.9**	**7.9**	**8.9**
Subj BY **Sudd.Onset**	-8.02 ± 0.49, *-0.88 (10%)*	-7.59 ± 0.72, *-0.31 (4%)*	8.87 ± 1.04, *-0.97 (12%)*	8.52 ± 0.86, *0.38 (4%)*
Stationary	-9.23 ± 0.89, *0.33 (4%)*	-8.62 ± 0.92, *0.72 (9%)*	10.09 ± 1.75, *-2.19 (28%)*	8.84 ± 1.20, *0.06 (1%)*
Subj KF **Sudd.Onset**	-8.53 ± 0.58, *-0.37 (4%)*	-6.45 ± 0.93, *-1.45 (18%)*	7.40 ± 0.70, *0.50 (6%)*	7.68 ± 0.75, *1.22 (14%)*
Stationary	-6.63 ± 0.98, *-2.27 (25%)*	-6.02 ± 0.72, *-1.88 (24%)*	5.34 ± 0.41, *2.56 (32%)*	8.73 ± 0.64, *0.17 (2%)*
Subj SM **Sudd.Onset**	-8.31 ± 0.65, *-0.59 (7%)*	-8.49 ± 0.80, *0.59(7%)*	8.62 ± 0.62, *-0.72 (9%)*	8.41 ± 0.59, *0.49 (5%)*
Stationary	-9.33 ± 0.96, *0.43 (5%)*	-8.79 ± 0.85, *0.89 (11%)*	9.32 ± 0.85, *-1.42 (18%)*	9.11 ± 0.84, *-0.21 (2%)*
Subj VB **Sudd.Onset**	-9.45 ± 0.72, *0.55 (6%)*	-9.39 ± 0.74, *1.49 (19%)*	9.56 ± 0.95, *-1.66 (21%)*	9.53 ± 0.64, *-0.63 (7%)*
Stationary	-7.76 ± 1.17, *-1.14 (13%)*	-7.52 ± 2.06, *-0.38 (5%)*	7.32 ± 0.82, *0.58 (7%)*	6.44 ± 1.23, *2.46 (28%)*

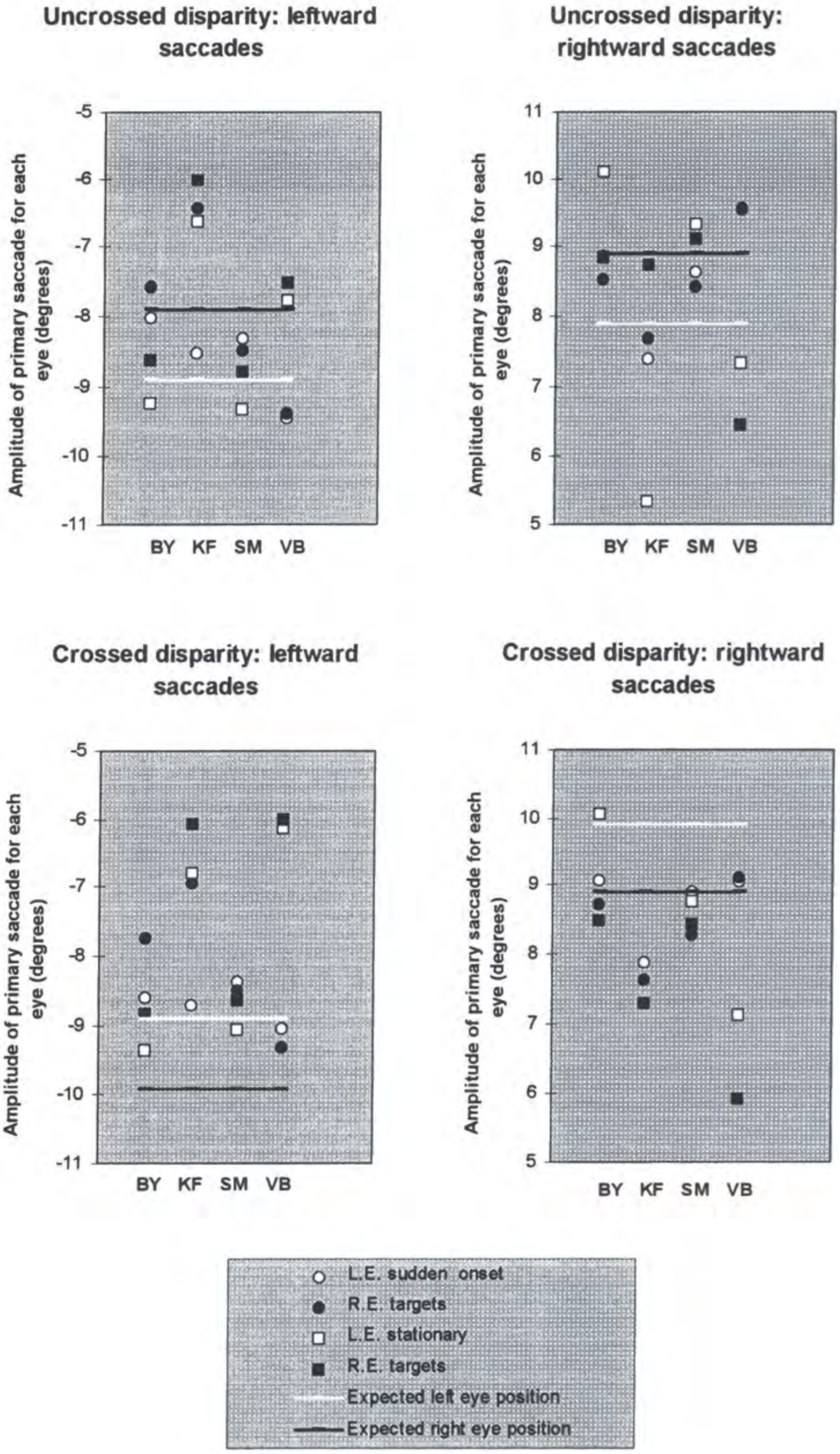
Key:- mean ± s.d., offset (= amplitude of ideal saccade - amplitude of primary saccade (mean of ≈ 10 saccades)), offset as a percentage of target eccentricity (ideal primary saccade amplitude).

Table 4.9 cont.

	Crossed disparity			
	Leftward saccade		Rightward saccade	
	θ_L	θ_R	θ_L	θ_R
Ideal amplitude of primary saccade	**-8.9**	**-9.9**	**9.9**	**8.9**
Subj BY **Sudd.Onset**	-8.61 ± 0.86, *-0.29 (3%)*	-7.75 ± 0.82, *-2.15 (22%)*	9.07 ± 0.49, *0.83 (8%)*	8.72 ± 0.62, *0.18 (2%)*
Subj BY **Stationary**	-9.36 ± 2.25, *0.46 (5%)*	-8.84 ± 2.14, *1.06 (11%)*	10.06 ± 0.95, *-0.16 (2%)*	8.48 ± 0.93, *0.42 (5%)*
Subj KF **Sudd.Onset**	-8.72 ± 0.76, *-0.18 (2%)*	-6.96 ± 0.88, *-2.94 (30%)*	7.88 ± 0.92, *2.02 (20%)*	7.62 ± 1.08, *1.25 (14%)*
Subj KF **Stationary**	-6.80 ± 0.97, *-2.10 (24%)*	-6.06 ± 0.82, *-3.84 (39%)*	4.67 ± 0.77, *5.23 (53%)*	7.28 ± 0.99, *1.62 (18%)*
Subj SM **Sudd.Onset**	-8.38 ± 0.54, *-0.52 (6%)*	-8.51 ± 0.53, *-1.39 (14%)*	8.90 ± 0.99, *1.00 (10%)*	8.28 ± 0.83, *0.62 (7%)*
Stationary	-9.08 ± 0.63, *0.18 (2%)*	-8.65 ± 0.50, *-1.25 (13%)*	8.76 ± 1.03, *1.14 (11%)*	8.41 ± 0.95, *0.49 (5%)*
Subj VB **Sudd.Onset**	-9.05 ± 0.78, *0.15 (2%)*	-9.32 ± 0.86, *-0.58 (6%)*	9.04 ± 0.82, *0.86 (9%)*	9.12 ± 0.71, *-0.22 (2%)*
Stationary	-6.14 ± 1.25, *-2.76 (31%)*	-6.01 ± 1.68, *-3.89 (39%)*	7.11 ± 1.15, *2.79 (28%)*	5.93 ± 1.09, *2.97 (33%)*

Key:- mean ± s.d., offset (= amplitude of ideal saccade - amplitude of primary saccade (mean of ≈ 10 saccades)), offset as a percentage of target eccentricity (ideal primary saccade amplitude).

Figure 4.14 Graph showing comparison between subjects' primary saccade landing positions in the sudden onset target and the stationary target conditions.



Discussion

Subjects showed some disconjugate saccades when moving to a sudden onset or stationary target in a differing direction and depth. However, unexpectedly, the direction of this disconjugacy (convergent or divergent) showed more correspondence to the horizontal direction of the target rather than its depth.

For leftward saccades, vergence during the primary saccades, to both near and far targets, was divergent for all subjects. At the end of the primary saccade the disconjugacy remained divergent for all target positions with two exceptions, both during the sudden-onset condition. Subject VB showed disconjugacy appropriate to the depth of the target. Subject SM showed convergent disconjugacy for both near and far left targets.

Rightward saccades were more variable. In the sudden-onset condition, all subjects showed transient convergence during the primary saccade to both near and far targets. At saccade offset, the disconjugacy remained convergent with two exceptions. Subject VB showed 0.08° of divergent disconjugacy to the near target and subject KF showed 0.28° of divergent disconjugacy to the far target. When subjects KF and VB repeated this condition, with a solid target, they showed similar levels of convergence during the saccade. However, at saccade offset they showed divergent disconjugacy for both target positions. In the constant target condition subjects KF and VB showed divergent vergence during the saccade and divergent disconjugacy at saccade offset. Subject BY and SM showed convergent vergence during the saccade and convergent disconjugacy at saccade offset.

The finding that the direction of disconjugacy showed more correspondence to the horizontal direction of the target than to its depth has not been previously reported in the literature for subjects with normal vision. Collewijn *et al.* (1988a) investigated the binocular co-ordination of human horizontal eye movements in detail (targets in the same depth plane). They found that a saccadic movement is typically accompanied by a transient divergence of several degrees, which begins to be corrected for during the saccade resulting in a net divergence of approximately 0.3° at saccade offset. This transient divergence resulted from the temporal saccades of one eye being larger than the corresponding nasal saccades of the other eye. They suggested various reasons why this might be the case. For example, mechanical asymmetries in the ocular muscles and ligaments may result in stiffness of the eyes when rotated nasally. Alternatively, an inhibitory interaction between the saccade and vergence subsystems may cause a transient loss of the vergence command during the saccade. Collewijn *et al.* (1988a) did not report any leftward or rightward asymmetries. Leftward and rightward asymmetries have been reported in strabismic subjects. De Faber *et al.* (1993) reported large saccade amplitude inequality that was direction specific in subjects with long standing strabismus and varying degrees of amblyopia. They found no correlation between strabismus type or the degree of amblyopia. More recently, Kapoula *et al.* (1996) have also reported direction specific saccade disconjugacy in microstrabismic subjects. Neither author could find any explanation of how such asymmetry could occur or what its function, if any, could be. The subjects in this experiment all had normal muscle balance and good visual acuities. One interesting point to note is that, for each subject, the direction of saccade disconjugacy was consistent within a stimulus presentation condition but varied slightly between stimulus conditions. This suggests that the asymmetry is likely to be centrally mediated and not the result of, for example, mechanical asymmetries in the eye musculature.

A comparison between eye movement responses to crossed and uncrossed disparity targets showed that in some cases the disconjugacy was target-directed. This means that the subject would be "on target" more quickly than would have been predicted using the traditional picture of eye movements. They would, for example, be much quicker to move around switches at differing depths on a stereoscopic display.

Some target-directed vergence eye movement was observed following the saccadic movement. Subjects may have had some difficulty assessing whether they were seeing a random dot target as being double or not. The target, for example, may have appeared "speckled". This may provide an explanation for the small vergence responses at fixation. Consequently, two of the subjects were re-run using solid targets on a plain background. They did not report seeing the targets double. No differences were found between subjects' eye movement responses to random dot targets compared with solid targets.

Only one of the four subjects showed a consistent tendency to undershoot the targets. Saccade offsets ranged from 8-20% of target eccentricities. Precision in terms of one standard deviation was about 10% of target eccentricity, broadly comparable with the precision obtained by Kowler & Blaser (1995). They used conditions designed to promote very accurate saccades (e.g. long latencies) and found a much higher level of accuracy than in the current experiment. Their average difference between mean saccade size and target eccentricity was about 1% of eccentricity (target eccentricity up to 4.2°). They found no evidence of saccade undershoot. Lemij & Collewijn (1989) reported undershoots of 10-15% of target eccentricity (target eccentricity 10°) for 'jumping' targets and of 3-6% for 'stationary' targets. The former value is more comparable with the current findings.

Subjects did not show appreciably more target-directed disconjugate saccades when the targets were continually visible. Indeed, no evidence was found of a difference in accuracy between saccades to stationary targets and sudden onset targets in contrast to the findings of Lemij & Collewijn (1989), who used targets in the same depth plane. However, there are a number of other factors which may have contributed to this difference in findings. In the first place, Lemij & Collewijn (1989) specifically emphasised only accuracy, and not speed, in their subject instructions. In the second place, they used the more accurate binocular search coil technique. These differences may have served to obscure the measurement of the effect during the current experiment. Finally, the fact that their target size was considerably smaller (1° in diameter) might also have contributed to the differences (see later discussion of Panum's area). However, this seems unlikely since recently Kowler & Blaser (1995) have found no difference in the accuracy and precision of saccades between small and large targets (largest target 4° diameter), which were presented at eccentricities of up to 4.2°.

A fourth difference might have been expected to increase the size of the effect. During the Lemij & Collewijn (1989) experiment, the location of their target was known in both conditions. The crucial difference between their two conditions was that in one the subject was asked to fixate and follow the target as it jumped between two fixed locations. In the other, they were asked to saccade between two continuously present targets in time to a metronome. During the present experiment a further factor was included, namely the location of the target in the sudden onset condition was unpredictable. This unpredictability might be expected to increase the size of the effect. It also provided an additional benefit. It enabled the relative measure of the offset of the primary saccade amplitude from the target position to be used to assess saccade accuracy for the following reason. During Lemij & Collewijn's sudden onset condition, the subject's eyes sometimes started to drift towards the target before it appeared (a well documented phenomenon called expectation drift (Kowler & Steinman 1979a, 1979b, 1981)). Hence, they could not directly compare saccade accuracy between the two conditions, by using the relative measure of the offset of the primary saccade amplitude from the target position. Rather, they had to compare the offset of absolute eye position at the end of each primary saccade from the target position. They were able to use absolute eye position reliably since they were using the binocular search coil measurement technique. Due to small slippages of the IRIS sensors relative to the subject's head measures of absolute eye position, using the IRIS system, are not reliable. By using a target, which appeared suddenly in an unpredictable position, expectation drift was eliminated. Hence, the relative measure of offset of primary saccade amplitude from target position could be used.

In conclusion, the existence of target-directed saccade disconjugacy has been confirmed in some cases. However, in general the direction of the saccade disconjugacy was better predicted by the horizontal direction of the target. We expected a higher proportion of the subjects to show target-directed disconjugate saccades. Two reasons why they may not have done so are as follows:-

- Using a red and green filter over each eye respectively gives a slightly different accommodation stimulus to each eye. Given the link between a person's accommodation level and vergence level this may have affected the alignment of the visual axis of each eye.

- On the whole, subjects fused the stimuli to each eye, thereby seeing a square. However, during binocular fixation small vergence errors can occur without causing diplopia as long as they do not exceed Panum's area. The size of Panum's area varies according to the size of the stimulus and according to the degree of eccentricity of the stimulus. For a stimulus, which subtends 3° of visual angle at the fovea, Panum's area is ≈ 1/2° (Tyler & Julesz 1980). Hence, for a disparity of 1°, for fusion to occur only 1/2° of vergence is necessary.

Lastly, the effect may have been obscured somewhat by the measurement inaccuracies of the Skalar eye movement measuring device. This device is considered to have a resolution of 2 min of arc (Reulen *et al.* 1988). However, the level of horizontal accuracy which can be achieved is considerably less, even when the head is stabilised with a mouth bite. This is because even a slight head movement relative to the Iris detectors will be interpreted as appreciable eye rotation. For example, taking the rotational radius of the eye to be 13mm, a displacement of the head of only 1mm will be misread as an eye movement of nearly 4.8°.

5

Oculomotor responses to perspective grid line drawings

Introduction

As mentioned previously in chapter one, one potential use of an eye pointing system in the aircraft cockpit, is to use the pilot's line-of-sight (one eye), or the intersection of the line-of-sights from both eyes, as a technique for activating various 'switches' displayed within a three dimensional HUD or HMD, e.g. by fixating a switch for a certain period of time. These switches may be located at different apparent depths on the flat screen of the HUD/HMD. The depth information may be available by virtue of the stereoscopic presentation of the display or by monocular depth cues such as linear perspective. Linear perspective depth cues are a particularly useful method of creating the illusion of depth in a HUD/HMD since the display information is often presented in a geometrical format, for example, two grids at right angles to represent the potential space in which the aircraft may be positioned. Consequently, we decided to investigate the effectiveness of linear perspective depth cues in eliciting eye movements to change the eye line-of-sight of both the subject's eyes appropriate to the perception of depth. From a practical stand point it is necessary to ascertain both the precision with which the eye's line-of-sight can be directed to a particular location in space and the speed with which it can be directed there.

Typically, the binocular point of foveation is moved between depth planes by vergence eye movements. These are slow eye movements (compared with saccadic eye movements) requiring up to one second to complete. It has been established that the primary visual cue for vergence is disparity, a binocular cue. Image blur (monocular cue) is another important visual stimulus to vergence acting through the accommodation-vergence cross link. More recently, various investigators have shown that several monocular depth cues can also elicit vergence primarily under monocular viewing conditions. These are the changing size of a stimulus (looming) (Erkelens & Regan 1986; McLin *et al.* 1988), the kinetic depth effect (Ringach *et al.* 1996) and linear perspective cues (discussed subsequently, Enright 1987a, 1987b). Erkelens & Regan (1986) found that changing size elicited transient vergence eye movements under binocular viewing conditions. This is interesting because it might be expected that the disparity induced by the vergence eye movements would feedback and cancel the vergence response. Further, they found that the vergence response obtained under monocular viewing conditions was less stable. The occluded eye tended to drift and blinks caused changes in the subjects vergence levels which persisted for several seconds. Indeed, Enright (1987a), who found that perspective cues could elicit vergence, commented that "much of the total vergence change usually occurred in conjunction with the initial change in fixation ("2.5° vertical saccades")" and that the ensuing ocular response, which often led to a further vergence change, was essentially the result of drift only in the occluded eye. He removed the progressive effect of this drift, over a number of fixations, by calculating the change in vergence between consecutive fixations. Enright (1987a) did not test if the vergence changes occurred under binocular conditions. Ringach *et al.* (1996) found that the kinetic depth effect did not elicit vergence eye movements under binocular viewing conditions.

As discussed in previous chapters, more recently, it has been found that where a change in the direction of gaze accompanies a change in the depth plane fixated, part of the "vergence response" may occur during the saccade i.e. saccades of unequal amplitude (disconjugate). To date it has been shown that disconjugate saccades may be elicited by real targets (all depth cues present) (Enright 1986, 1992; Erkelens *et al.* 1989a; Collewijn *et al.* 1995) and disparity only targets (Findlay & Harris 1993). The hypothesis tested by this experiment was whether "disconjugate eye movements (fast changes in the binocular point of foveation) and/or vergence eye movements could be triggered by perspective depth cues under monocular or binocular viewing conditions?".

Right eye movement responses were measured using a Purkinje tracker as subjects shifted their gaze from a central fixation point to a suddenly appearing target in a different direction and at a different perceived depth on a perspective background. Indirect measures of vergence and direct measures of saccade amplitudes and final fixation position were collected.

Prior to the main experiment, it was demonstrated, in a separate pilot experiment, that it was possible to identify vergence changes by measuring the eye movements of just one eye using the Purkinje tracker. The procedure and results of the pilot experiment are reported prior to the main experimental procedure and results.

Pilot experiment

Method

Subjects

Two subjects participated in the experiment. Both subjects had Snellen visual acuity (near and far) of, or better than, 6/6 (20/20) in each eye (normally or after correction). The muscle balance (Maddox Wing test) of each subject was normal. Both subjects had stereo acuity of better than 40 seconds of arc (Titmus).

Apparatus

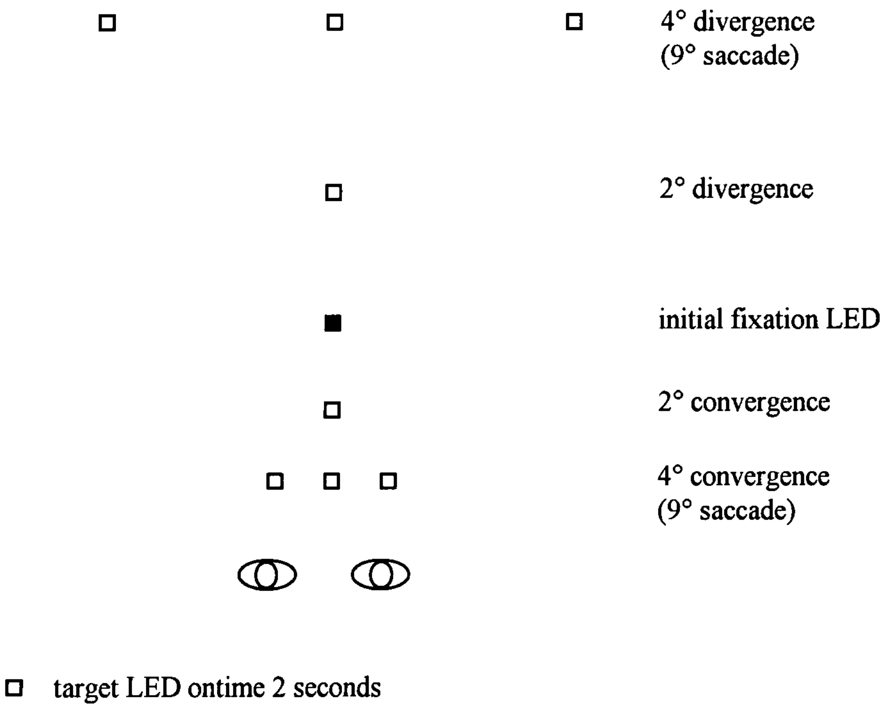


Figure 5.0 Plan view of experimental apparatus

The visual targets consisted of nine LED's (figure 5.0). The initial fixation target LED was situated 53.1 cm from the subject along the midline. Assuming an interpupillary distance of 6.5cm this would require 7° of vergence. Four other target LEDs were also placed along the midline so as to require a change in divergence or convergence of 2° or 4°. A further four LED targets were placed to require a direction change of 4° together with a convergent or divergent change in vergence level of 4°. Both subjects viewed the targets binocularly under dim lighting conditions. Hence, background features were visible.

Procedure

The subjects' task was to move their gaze, as quickly and accurately as possible, from the initial fixation LED to the target LED and to remain looking at the target LED until it extinguished. The fixation LED was illuminated for 2 seconds. At fixation offset the target was illuminated for 2 seconds. This procedure was repeated, the order in which the target LEDs lit being random, until the subject had looked at each target LED fifteen times. Eye movement recording commenced each time the target LED lit and finished two seconds later when the target LED extinguished. Hence, for each subject 120 measurement records were collected for subsequent off-line analysis.

Eye movement recording and analysis

Right eye movement responses were measured using a Purkinje tracker. Subjects' heads were stabilised using chin and forehead rests. Subjects' eye movements were sampled at 100Hz during the calibration procedure and at 200Hz during the trials. Subjects were asked to refrain from blinking during the trials since blinking causes eye movements

Results

Figure 5.1 shows a representative eye movement measurement record for one subject's horizontal right eye movement response to each of the midline LEDs (centripetal eye movement positive).

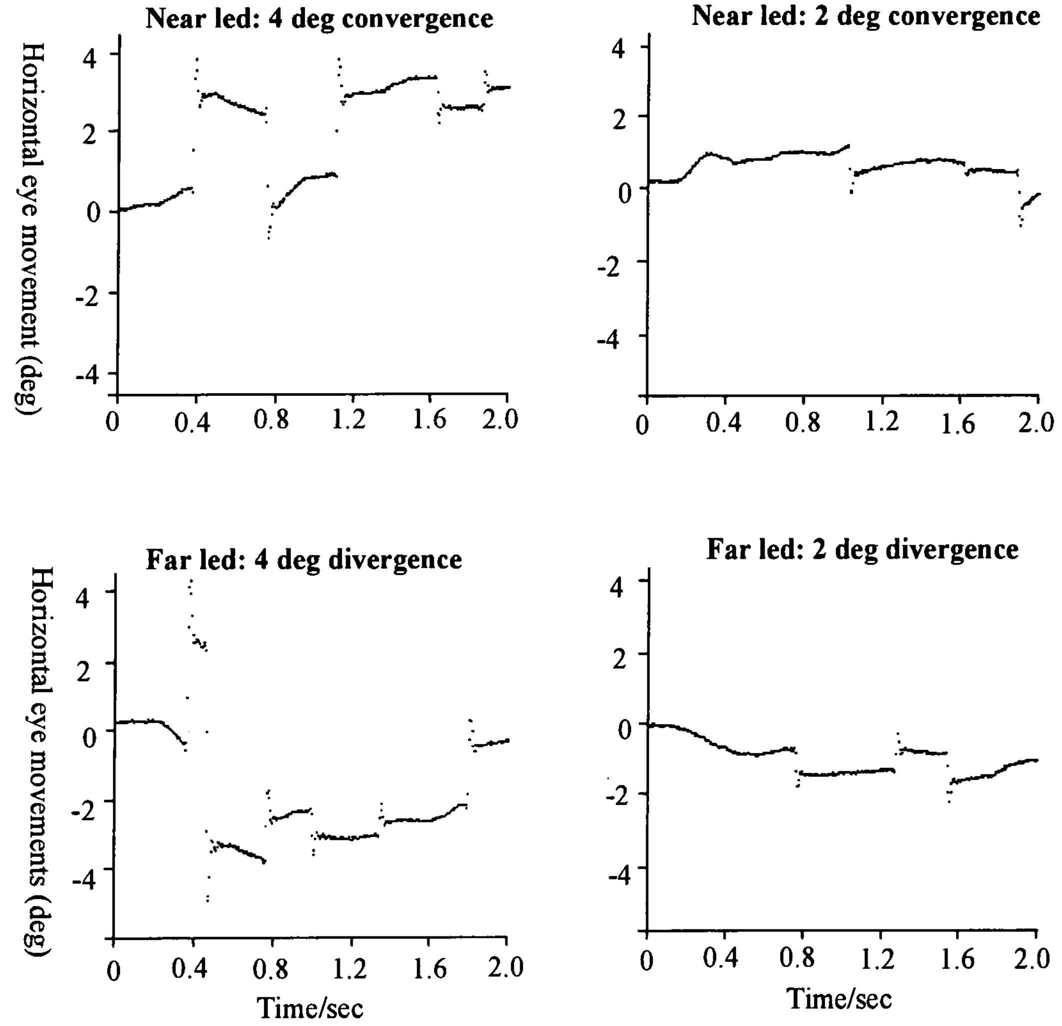


Figure 5.1 Eye movement position profiles for subject KB

The right eye's response to each of the midline LEDs can be clearly differentiated and is appropriate to the new level of vergence required.

Main Experiment

Method

Nine subjects with an age range of 19-28, were recruited from Durham University, to participate in the experiment. All subjects had Snellen visual acuity (near and far) of, or better than, 6/6 (20/20) in each eye (normally or after correction). The muscle balance (Maddox Wing test) of each subject was normal. All subjects had stereo acuity of better than 40 seconds of arc (Titmus). The majority of the subjects had not participated in eye movement experiments before and were naive as to the purpose of the study. The dominant eye of each subject was ascertained in the following manner. Subjects looked through an aperture (diameter ~3cm) held a few centimeters infront of them so that they were able to see a distant object (such as a light switch) with both eyes open. They then shut their left eye. If they could still see the object they were classed as left eye dominant, otherwise they were classed as right eye dominant.

Stimuli

The background consisted of a grid superimposed on two inner surfaces of a cube, one directly ahead of the subject and the other appearing to come towards the subject (Figure 5.2). The central fixation point was superimposed on the square grid, which appeared to be straight ahead of the subject. The target was superimposed on the perspective grid, which appeared to form a surface towards the subject. For each target direction there was a perspective grid background and two control conditions: a square grid (i.e. no perspective cues) and a blank background (figure 5.3). The geometry of the perspective display was calculated according to the method in appendix II.

The target, a small square (0.5° of visual angle), could appear in one of four directions, up, down, left or right, 10° from an initial central fixation point. Large saccades were chosen to try to promote saccade disconjugacy. Each display was presented for 2.5 seconds with a 2 second "rest" period in between each presentation. The subjects were seated so that they viewed the perspective display from its vanishing point. This was at a distance of 60 cm from the display in the horizontal

Main Experiment

Method

Nine subjects with an age range of 19-28, were recruited from Durham University, to participate in the experiment. All subjects had Snellen visual acuity (near and far) of, or better than, 6/6 (20/20) in each eye (normally or after correction). The muscle balance (Maddox Wing test) of each subject was normal. All subjects had stereo acuity of better than 40 seconds of arc (Titmus). The majority of the subjects had not participated in eye movement experiments before and were naive as to the purpose of the study. The dominant eye of each subject was ascertained in the following manner. Subjects looked through an aperture (diameter ~3cm) held a few centimeters infront of them so that they were able to see a distant object (such as a light switch) with both eyes open. They then shut their left eye. If they could still see the object they were classed as left eye dominant, otherwise they were classed as right eye dominant.

Stimuli

The background consisted of a grid superimposed on two inner surfaces of a cube, one directly ahead of the subject and the other appearing to come towards the subject (Figure 5.2). The central fixation point was superimposed on the square grid, which appeared to be straight ahead of the subject. The target was superimposed on the perspective grid, which appeared to form a surface towards the subject. For each target direction there was a perspective grid background and two control conditions: a square grid (i.e. no perspective cues) and a blank background (figure 5.3). The geometry of the perspective display was calculated according to the method in appendix II.

The target, a small square (0.5° of visual angle), could appear in one of four directions, up, down, left or right, 10° from an initial central fixation point. Large saccades were chosen to try to promote saccade disconjugacy. Each display was presented for 2.5 seconds with a 2 second "rest" period in between each presentation. The subjects were seated so that they viewed the perspective display from its vanishing point. This was at a distance of 60 cm from the display in the horizontal plane of (and directly perpendicular to) the fixation point. Three subjects viewed the display binocularly whereas six subjects viewed the display monocularly to remove conflicting disparity cues. Since, only right eye movements were being measured, three of the subjects who viewed the display monocularly did so with their left eye covered whereas three had the view of their right eye occluded (by placement of a cover a few centimeters in front of the eye). This was to allow for the possibility that only the covered eye would participate in any ocular response. Subjects were asked to look, as quickly and as accurately as possible, from the initial, central fixation point (a cross) to the white dot in the centre of the target square (eccentric position) and to continue to look at the target square until it disappeared. Verbatum instructions to subjects are in appendix IV.

For each target direction, the target was presented 15 times with each background. Again eye movement recording began when the target and background appeared and stopped 2.5 seconds later when the central fixation point appeared. Consequently, for each subject 180 measurement records were collected and stored for off-line analysis. The stimuli were presented to the subject, in random order of conditions and target direction, across two separate experimental sessions i.e. 90 trials in each experimental block.

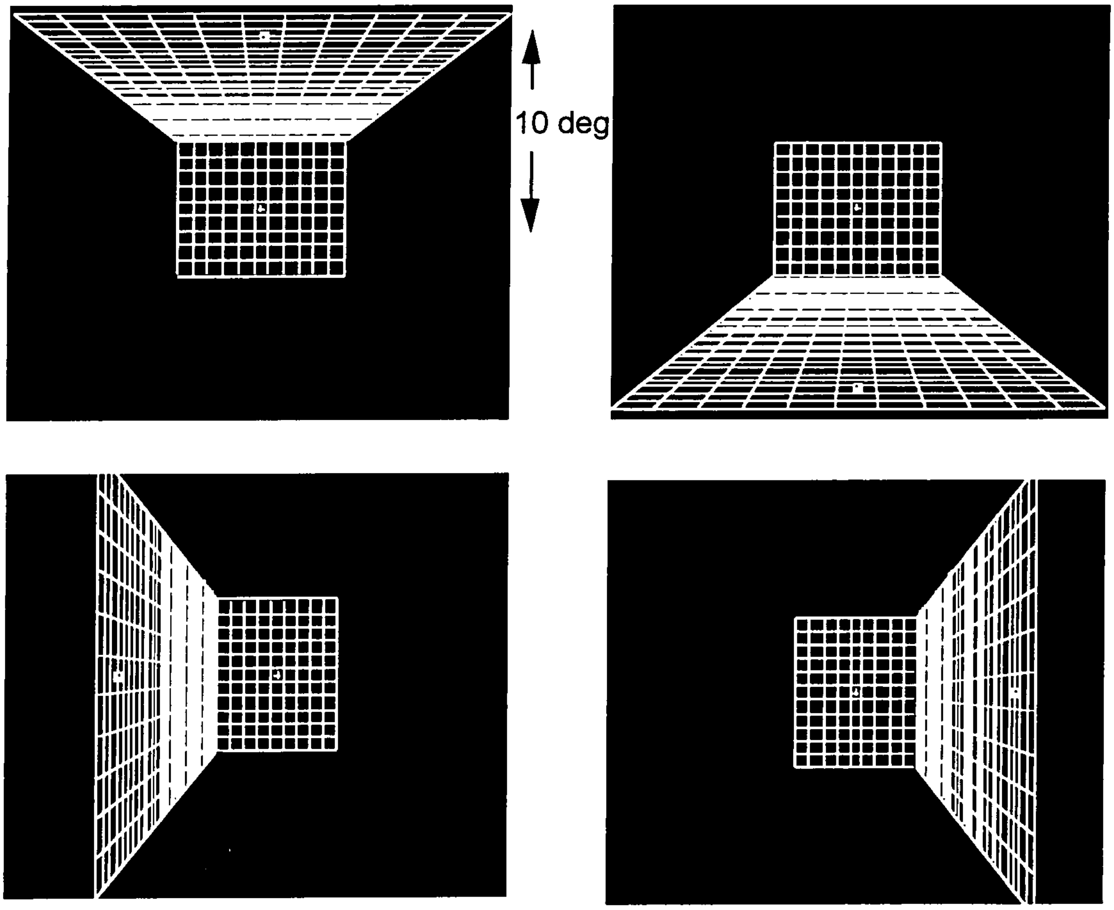


Figure 5.2 Layout of perspective displays (entire display not shown, some line detail lost and distorted in printing)

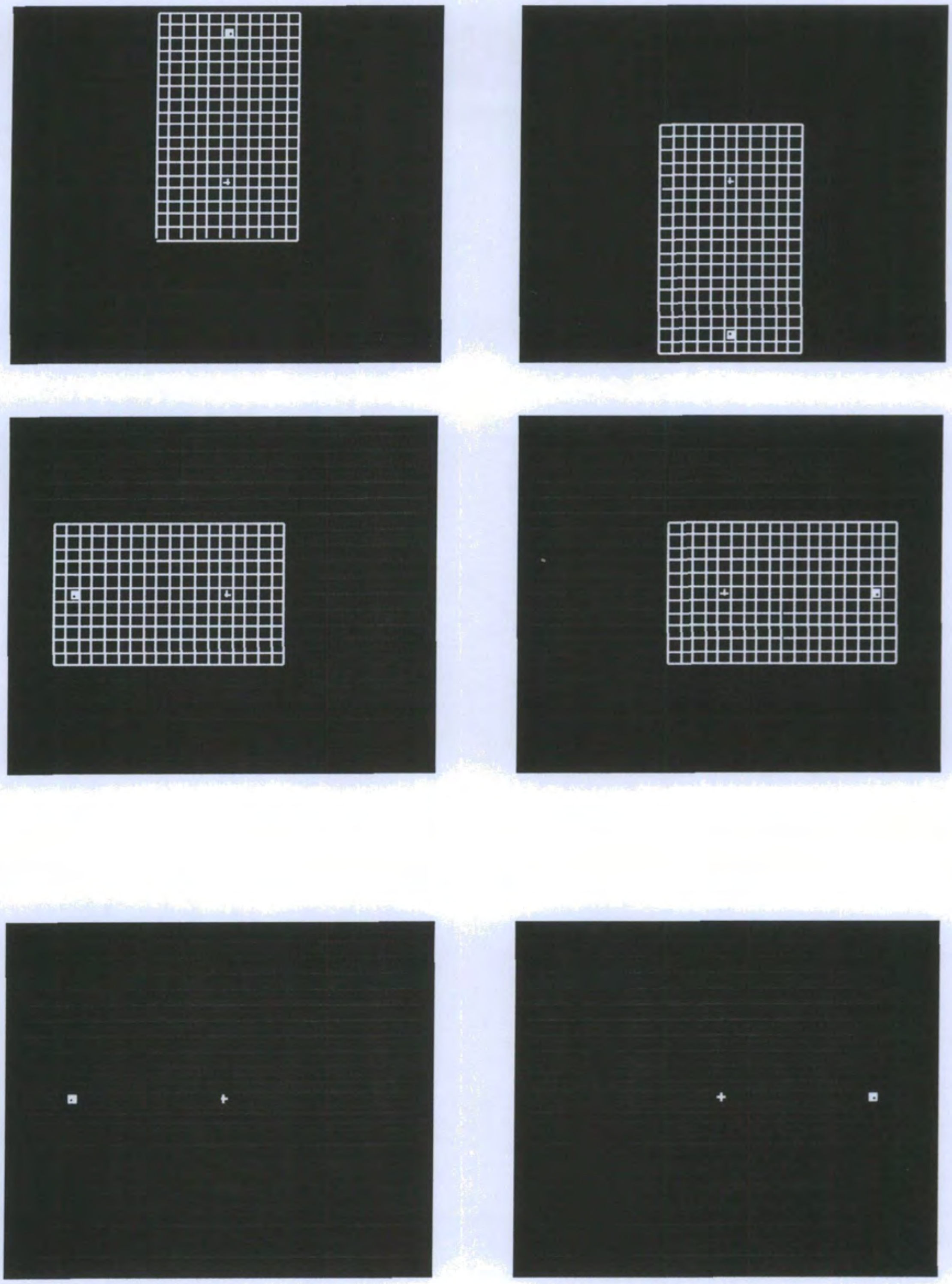


Figure 5.3 Layout of grid and no background (left & right target directions only shown) displays (entire displays not shown).

Eye movement recording and analysis

Figure 5.4 shows an example of the ocular measures calculated for each measurement record using an automated procedure. The subject's eye movements were sampled at 100Hz during the calibration procedure and at 200Hz during the trials. Subjects were asked to refrain from blinking during the trials since blinking causes eye movements. Data were stored off-line for subsequent analysis. The raw data were calibrated (linear), i.e. the eye movement units were converted to degrees of eye movement (Appendix III for the calibration procedure and calculation), the centre fixation cross being defined as 0°. The left calibration target was at +10° and the right calibration target was at -10°. All trials which met the following criteria were analysed:-

- Less than 5% change between initial and final calibrations.
- Subjects did not look away during the trial or shut their eyes.
- A blink had not occurred.

Where data met the previous criteria, the following measures were computed using a semi-automated software package (Figure 5.4). This graphically plotted out the raw data for each eye, on a computer screen, with time along the x-axis and eye movement units along the y-axis:-

- For each eye, the amplitude and direction of the primary saccade from the fixation cross to the target was measured in degrees. Both these measures were a conversion of the horizontal and vertical eye movement raw data. For example, the amplitude was calculated as $[(\text{horizontal amplitude})^2 + (\text{vertical amplitude})^2]^{½}$. The start of the saccade was defined as the point where the velocity of the eye movement exceeded 15°/sec. The saccade's end was calculated as the point where the velocity of the eye movement decreased below 15°/sec. The software automatically picked out and placed a line cursor at each of these points so that its selection could be checked[1].

- Amplitude (relative to eye position at the start of the primary saccade) and direction of eye movement 1 second after the end of the primary saccade. This will be termed 'fixation'.

Note that the upwards direction is defined as 0°, right as 90°, downwards as 180° etc.

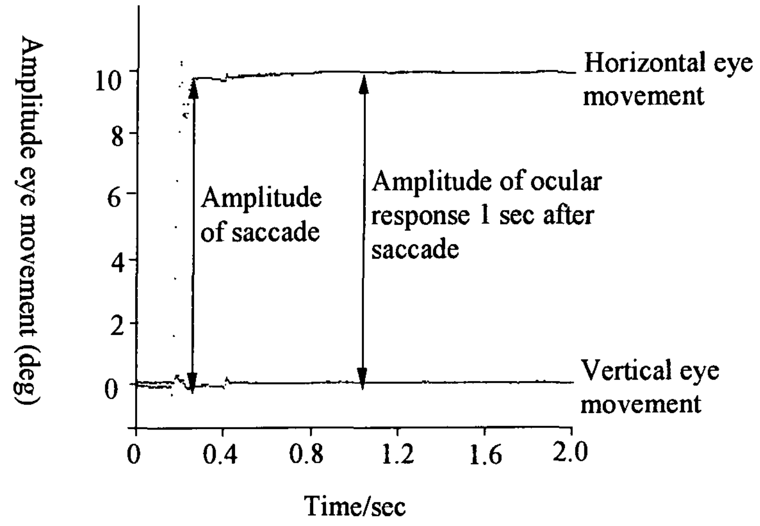


Figure 5.4 Eye movement measures computed.

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[1] A primary saccade was deemed to be one whose amplitude was greater than or equal to 30% of the target amplitude. The velocity of this saccade must be greater than 15 degrees/second and its latency greater than 60 msec, i.e. the target was not anticipated.

Results

Assuming an interpupillary distance of 6.5 cm, fixation in the plane of the display would require 6.2° of vergence. During a perspective trial the subject's level of vergence would be expected to change by ≈ 2° (convergence), as they looked from the initial fixation point to the target, if the subject responded to the apparent depth portrayed in the display. Hence, the maximum expected values for the direction or amplitude of the ocular response (right eye) for each condition would be as follows (assuming vergence change to be equally distributed between the two eyes):-

Table 5.0 Maximum expected eye movement responses for each condition.

	No background & grid conditions		Perspective condition	
	Expected direction or amplitude of ocular response	Expected change in direction or amplitude	Expected direction or amplitude of ocular response	Expected change in direction or amplitude
Down saccades (direction)	180°	0°	182.8°	+2.8°
Up saccades (direction)	0°	0°	-2.8° (i.e. 357.2°)	-2.8°
Left saccades (amplitude)	10°	0°	≈ 11°	+1°
Right saccades (amplitude)	10°	0°	≈ 9°	-1°

Subjects reported that in the perspective condition the target wall did appear "to come towards them".

In line with previous findings (Collewijn *et al.* 1988a), subjects' primary saccade endpoints tended to undershoot the left, right and up targets and overshoot the down targets. Figures 5.5 and 5.6 show the primary saccade and fixation endpoints for subject ANP (viewing eye recorded) and subject MV (covered eye recorded).

Tables 5.1 - 5.9 show means for the direction or amplitude of the ocular response at the end of the primary saccade and at fixation, for each target direction, for each condition, for each subject. Each mean is based on 12-15 trials. The change in direction or amplitude of the ocular response between these two "events" is also given. The results are also plotted in figures 5.7 - 5.9.

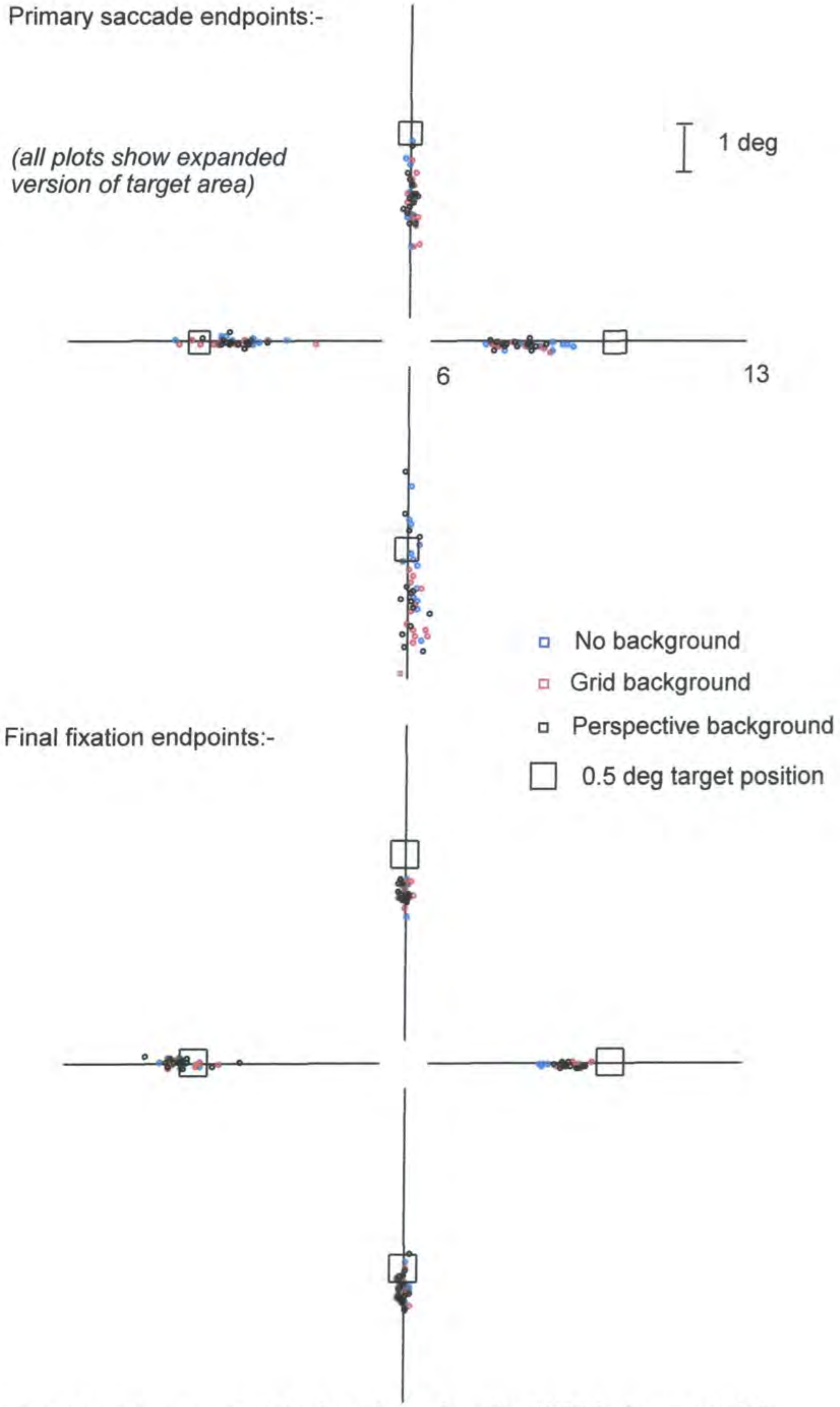

Figure 5.5 Primary saccade & fixation endpoints for subject ANP (viewing eye recorded)

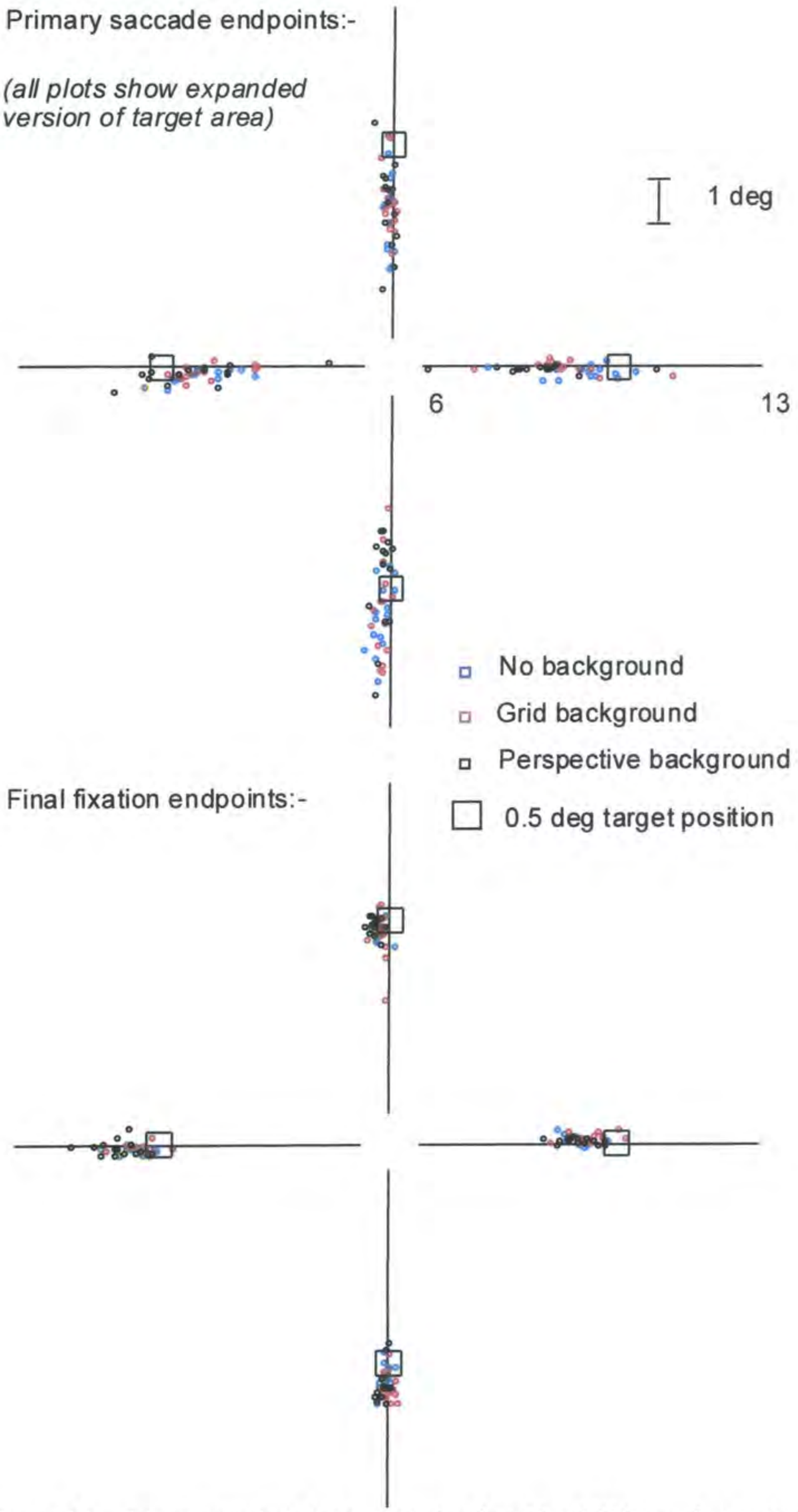

Figure 5.6 Primary saccade & fixation endpoints for subject MV (covered eye recorded)

Subject AU

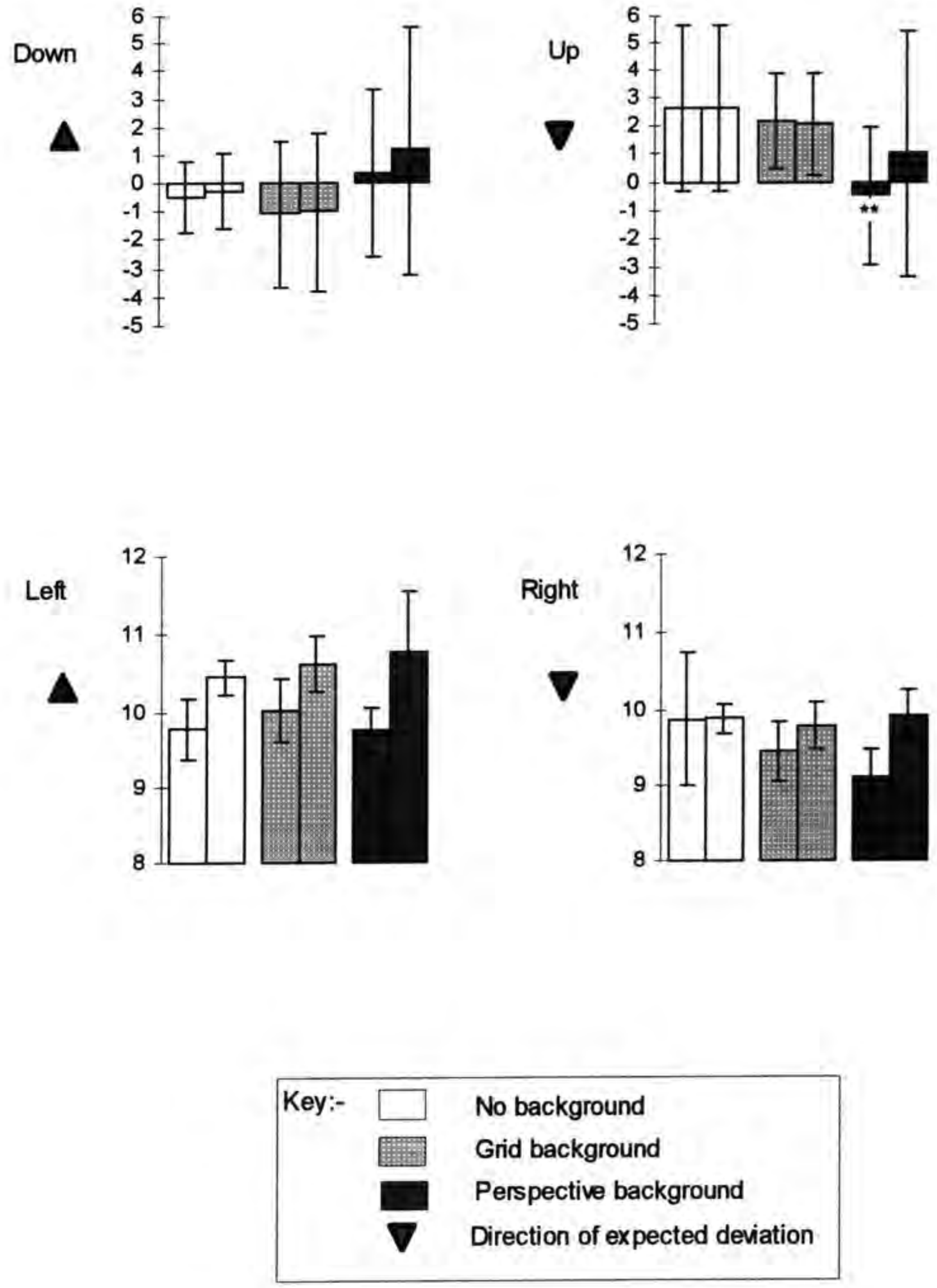

Figure 5.7 Mean primary saccade (first column) and fixation (second column) direction/amplitude (degrees ± s.d.), binocular viewing

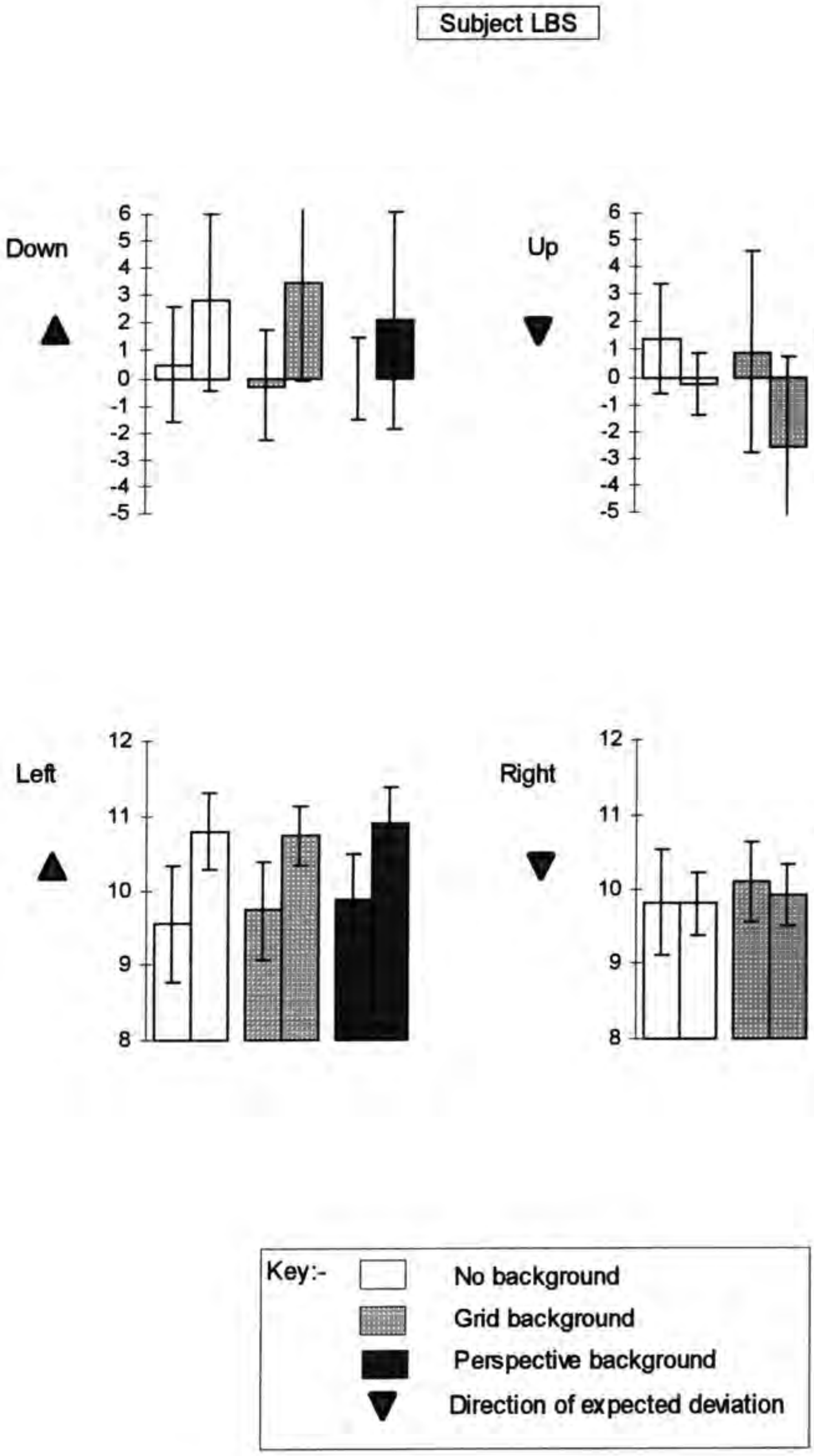

Figure 5.7 cont Mean primary saccade (first column) and fixation (second column) direction/amplitude (degrees ± s.d.), binocular viewing

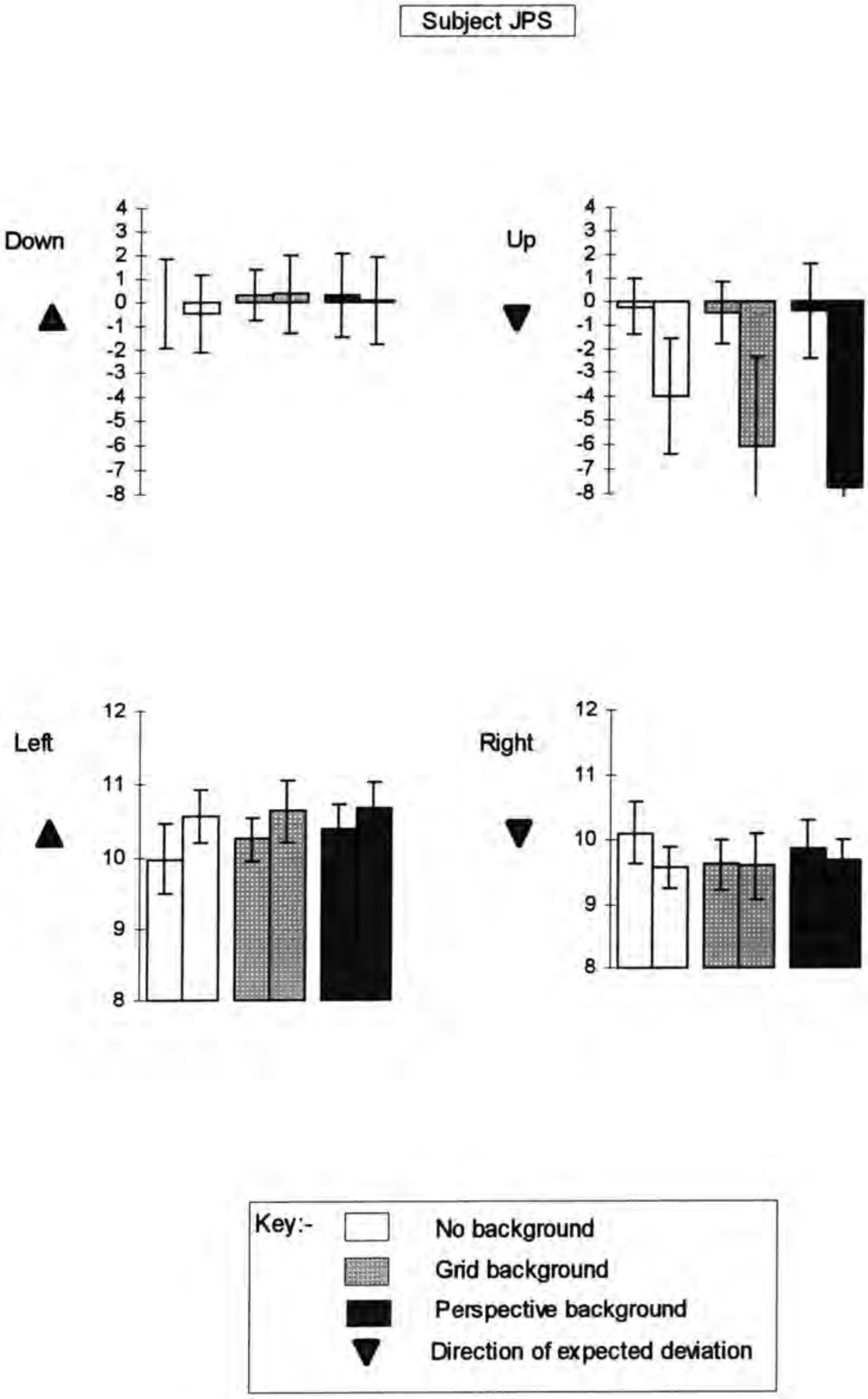

Figure 5.7 cont Mean primary saccade (first column) and fixation (second column) direction/amplitude (degrees ± s.d.), binocular viewing

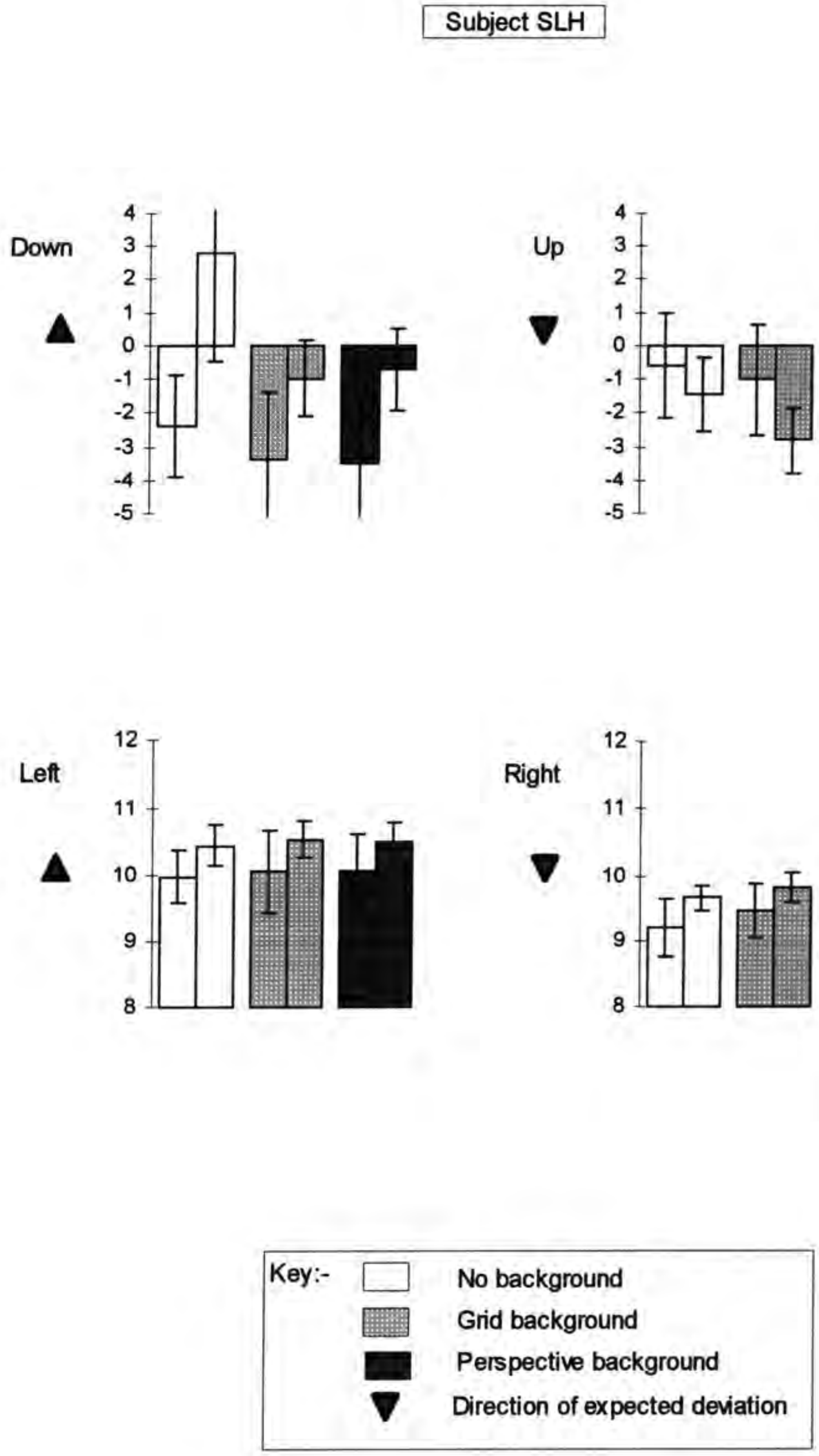

Figure 5.8 Mean primary saccade (first column) and fixation (second column) direction/amplitude (degrees ± s.d.), viewing eye recorded

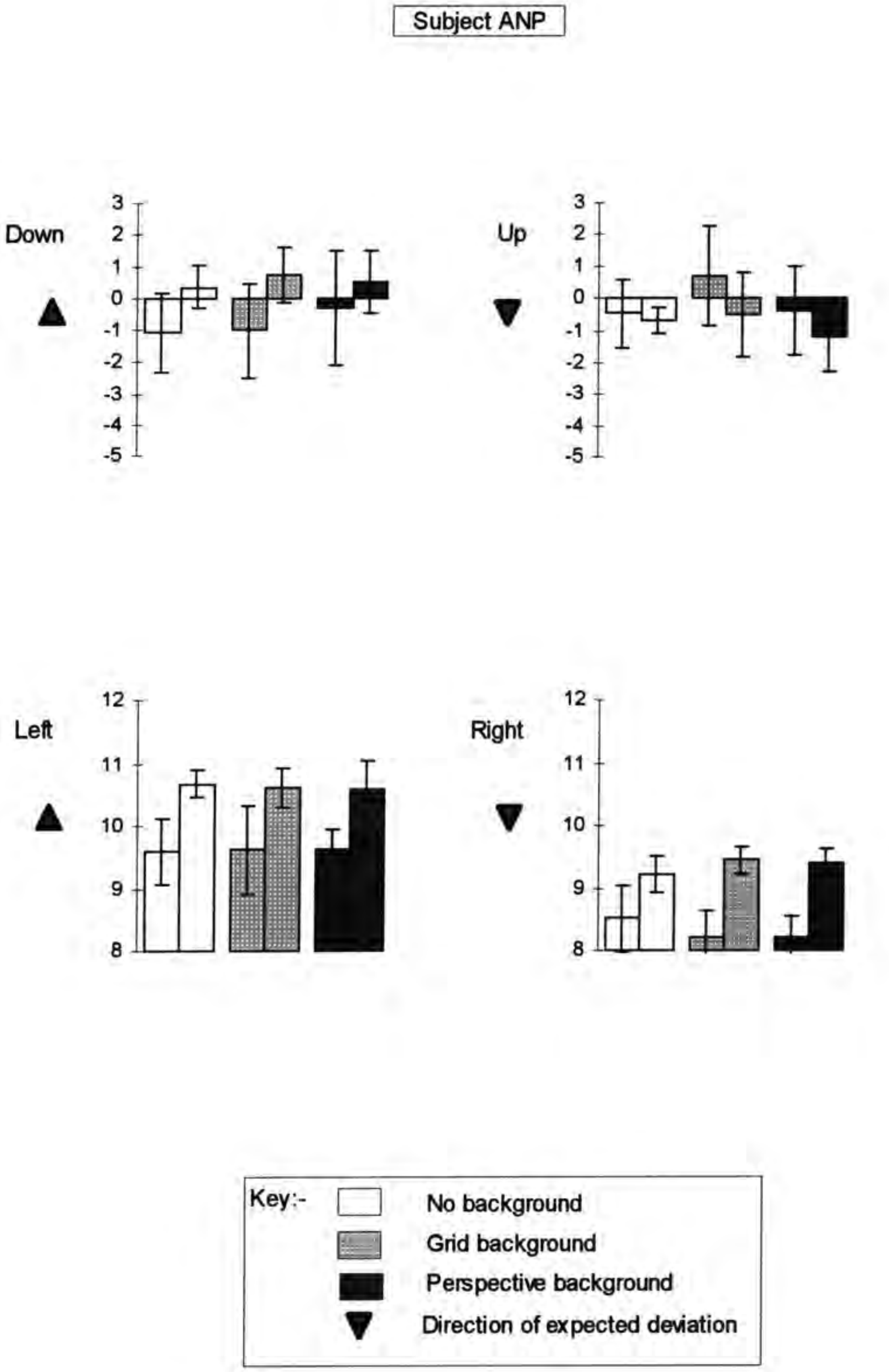

Figure 5.8 cont. Mean primary saccade (first column) and fixation (second column) direction/amplitude (degrees ± s.d.), viewing eye recorded

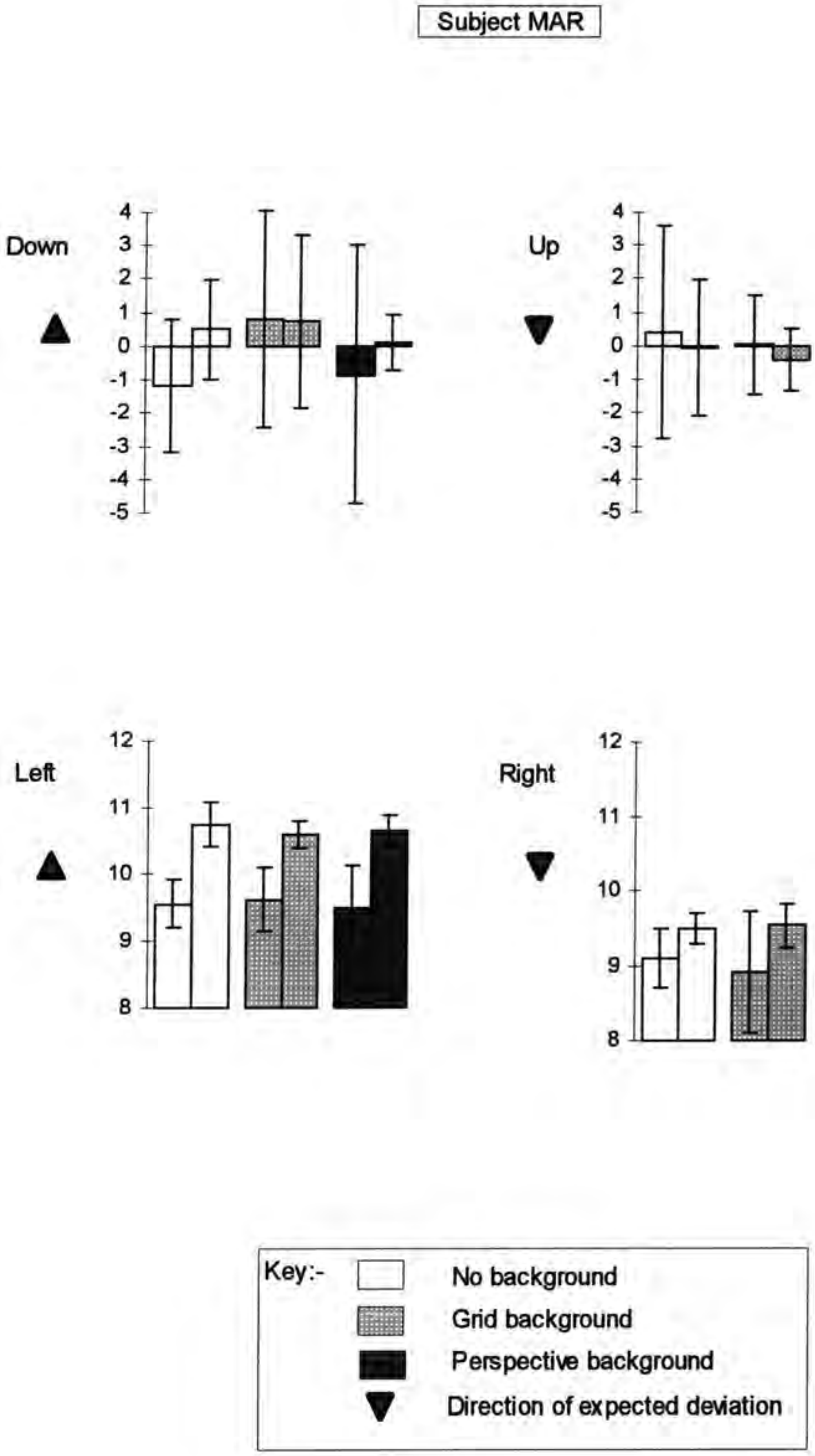

Figure 5.8 cont. Mean primary saccade (first column) and fixation (second column) direction/amplitude (degrees ± s.d.), viewing eye recorded

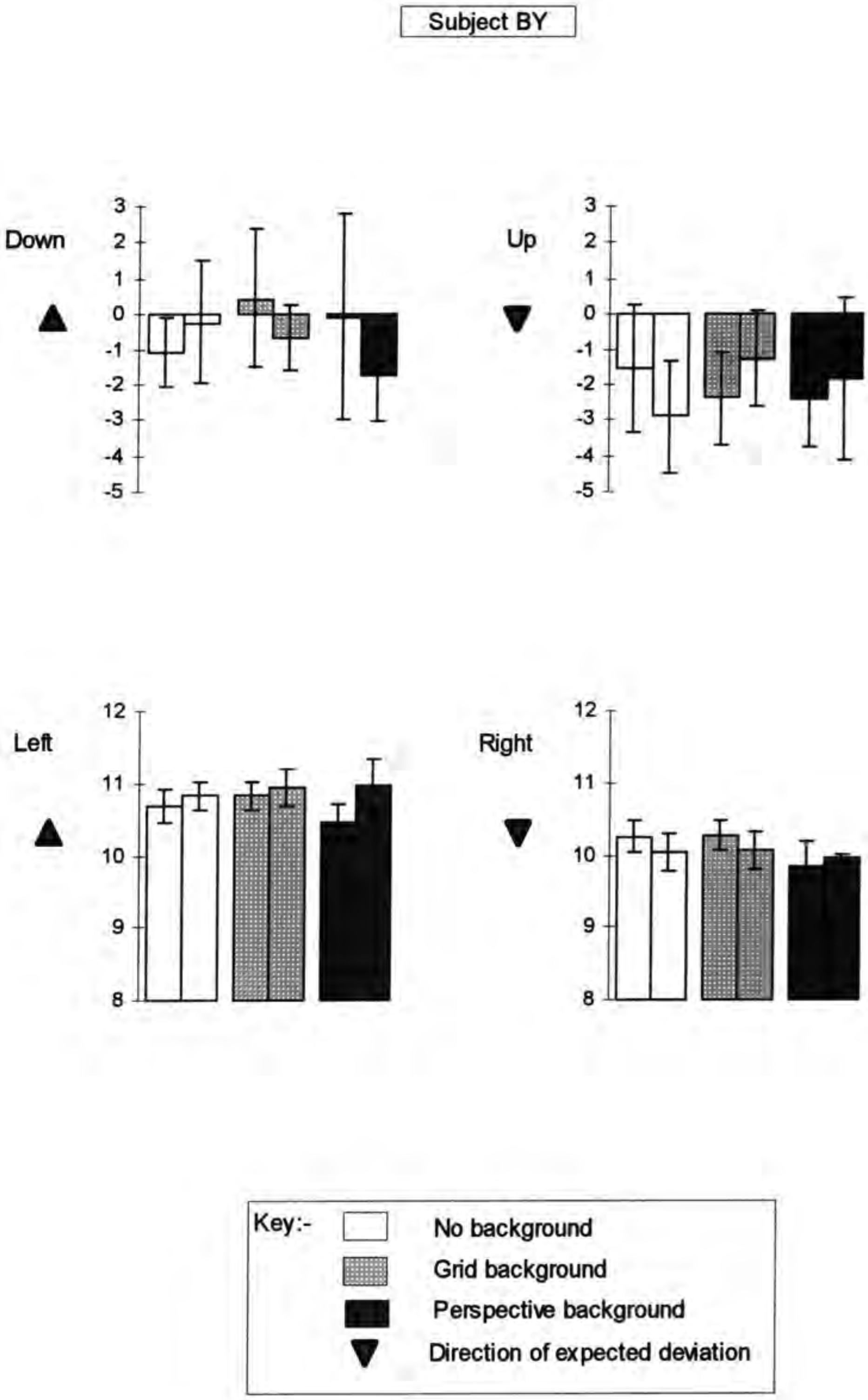

Figure 5.9 Mean primary saccade (first column) and fixation (second column) direction/amplitude (degrees ± s.d.), covered eye recorded

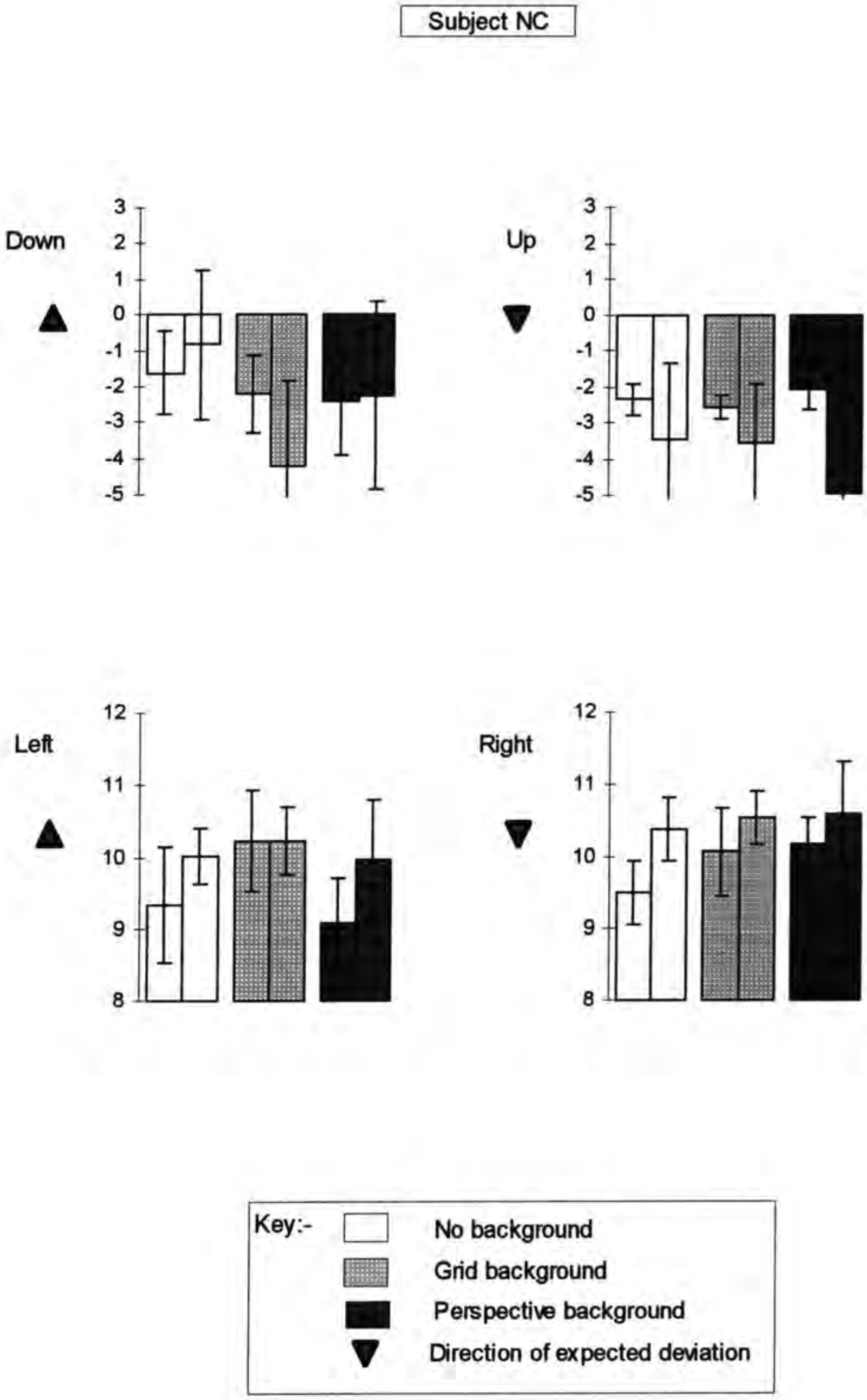

Figure 5.9 cont. Mean primary saccade (first column) and fixation (second column) direction/amplitude (degrees ± s.d.), covered eye recorded

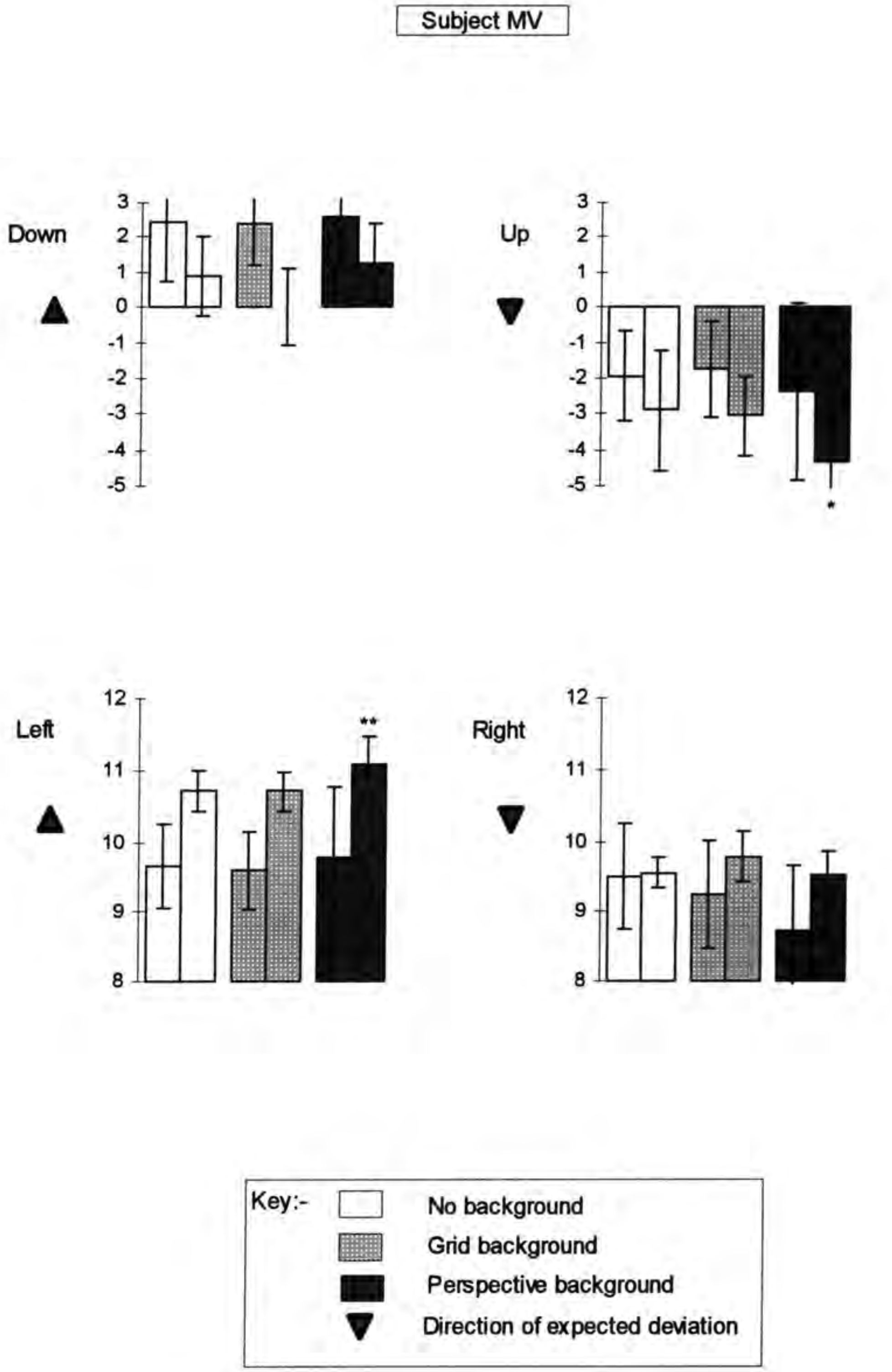

Figure 5.9 cont. Mean primary saccade (first column) and fixation (second column) direction/amplitude (degrees ± s.d.), covered eye recorded

Speed with which the eye's line-of-sight is directed to a particular location

Overall, the hypothesis that disconjugate or vergence eye movements are triggered by perspective depth cues was not supported by the results of this experiment. However, some effects did occur with individual subjects. Subjects AU (binocular viewing) and SLH (viewing eye recorded) showed evidence of disconjugate saccades towards upward and rightward perspective targets respectively and subject MV (covered eye recorded) showed evidence of vergence eye movements towards upward and leftward perspective targets. The results for each target direction are presented in the following section.

Downward targets

Saccade disconjugacy

For each subject, the separate one-way ANOVA (repeated measures) showed no significant differences, in primary saccade direction, between the background conditions i.e. no evidence of saccade disconjugacy movements was found in response to the perspective depth cues for downward targets.

Vergence

Similarly, at fixation, a one-way ANOVA (repeated measures), for each subject, showed no significant differences in ocular direction between the background conditions with the exception of two subjects NC and MV (both covered eye recorded, $F_{2,13} = 8.52$, $F_{2,14} = 6.81$, $P<0.01$) (Table 5.8, 5.9). Fisher's Protected Least Significant Difference (PLSD) post-hoc test showed that both subjects made a significantly more divergent ocular response in the grid condition compared with the perspective and no background conditions (subject NC: $F=1.79$ $P<0.05$, subject MV: $F=0.74$ $P<0.05$) but showed no significant differences in ocular direction between the no background and perspective condition were found. Hence, no evidence of convergent eye movements was found in response to the perspective depth cues for downward targets.

Upward targets

Saccade disconjugacy

For each subject, a one-way ANOVA (repeated measures) found no significant differences in ocular direction between the background conditions during the primary saccade except for subject AU (binocular viewing, $F_{2,12} = 6.67$, $P<0.01$, Table 5.1). A post-hoc Fisher PLSD test indicated that subject AU made a significantly greater convergent response during the perspective condition compared with either the grid or no background condition i.e. demonstrated an effect of perspective (F=1.97, $P<0.05$). Hence, in response to the perspective depth cues, one subject (AU) showed evidence of disconjugate saccades towards the target.

Vergence

At fixation, subjects LBS, SLH and MV showed significant differences between the conditions ($F_{2,13} = 5.98$, $P<0.01$; $F_{2,11} = 4.63$, $P<0.05$ & $F_{2,14} = 4.29$, $P<0.05$ respectively). The results are shown in tables 5.2, 5.4 and 5.9. Subject LBS (binocular viewing) showed significantly greater convergence during the perspective condition compared with the no background condition (Fisher PLSD F=1.77, $P<0.05$). Subject SLH (viewing eye recorded) showed significantly greater convergence during the perspective and grid conditions, compared with the no background condition (Fisher PLSD F=4.63, $P<0.05$) i.e. an effect of background was found. Furthermore, subject MV (covered eye recorded) showed a significantly greater convergent response in the perspective condition compared with the no background and grid conditions (Fisher PLSD F=1.06, $P<0.05$) i.e. an effect of perspective. Subjects AU, JPS (binocular viewing), ANP, MAR (viewing eye recorded) and BY (covered eye recorded) showed no significant differences in ocular direction between the conditions. Hence, in response to the perspective depth cues, one subject (MV) showed evidence of vergence eye movements.

Leftward targets

Saccade disconjugacy

For each subject, a one-way ANOVA (repeated measures) showed that there were no significant differences in primary saccade amplitude between the background conditions. Hence, no evidence was found of saccade disconjugacy in response to the perspective depth cues.

Vergence

At fixation, none of the subjects showed a significant difference in fixation amplitude between the conditions except for subject MV ($F_{2,14} = 6.53$, *P*<0.01, Table 5.9). A post-hoc Fisher PLSD test showed subject MV made a significantly greater convergent response in the perspective condition (F=0.26, *P*<0.05) compared with the grid and no background conditions i.e. an effect of perspective.

Rightward targets

Saccade disconjugacy

For each subject, a one-way ANOVA (repeated measures) showed that for subjects AU, SLH (viewing eye recorded) and NC (covered eye recorded) there were significant differences in primary saccade amplitude between the background conditions ($F_{2,14} = 9.33$, $F_{2,11} = 7.26$, $F_{2,13} = 9.40$, *P*<0.01, Tables 5.1, 5.4 and 5.8). A post-hoc Fisher LSD test showed that the ocular response was in a more convergent direction for AU (F=0.41, *P*<0.05) and a more divergent direction for NC (F=0.35, *P*<0.05) during the perspective and grid conditions compared with the no background condition i.e. an effect of background was found. For subject SLH the ocular response was in a more convergent direction during the perspective condition compared with the control conditions (F=0.36, *P*<0.05) i.e. an effect of perspective was found. No such differences were found for the remaining subjects. Hence, one subject (SLH) showed evidence of disconjugate saccades towards the target in response to the perspective depth cues. Two subjects (AU and NC) showed evidence of disconjugate saccades towards the target in response to the presence of a background.

Vergence

At fixation, with the exception of subject ANP (viewing eye recorded, $F_{2,13} = 5.74$, $P<0.01$, Table 5.5), none of the subjects showed evidence of a vergence response. Subject ANP showed a more divergent response during the perspective and grid conditions compared with the no background condition i.e. an effect of background was found, F=0.17, $P<0.05$.

Change in direction/amplitude between the end of the primary saccade and fixation for all conditions

Overall, most subjects showed a predominantly convergent change in direction or amplitude, toward the target, between the end of the primary saccade and fixation, for both control and perspective background conditions. Exceptions were as follows. Firstly, the three covered eye recorded subjects who showed a predominantly divergent 'change in direction' toward downward targets in both control and perspective background conditions. Secondly, subjects SLH, ANP & MAR (viewing eye recorded), MV, BY & NC (covered eye recorded) and AU (binocular viewing) showed a divergent 'change in amplitude' to rightward targets. Thirdly, subjects AU (binocular viewing) and BY (covered eye recorded) showed a divergent 'change in direction' to upward targets in the perspective background condition and in the case of BY also in the grid control background condition.

Figure 5.10 shows a representative subset of the data from the eye movement responses of subject AU (binocular viewing) for targets appearing in the leftward direction. For the purposes of clarity only two measurement records are shown for each condition.

It can be seen that there are no appreciable differences between the individual measurement records for the perspective background condition and the two control conditions.

Figure 5.11 shows the eye movement traces for the leftward saccades on separate graphs. Some small differences are apparent such as the step like movement of the horizontal eye movement trace when the subject is looking to the target in the left wall (perspective) condition. This is similar to the vergence response shown to midline real LED targets (Figure 5.1).

Table 5.1 Eye movement measures for subject AU (binocular viewing, right eye dominant).

Down saccades	Direction of primary saccade	Direction of ocular response at fixation	Change in Direction
Perspective	180.38 ± 2.96 (179.38)	181.18 ± 4.40 (179.50)	0.80
Grid	178.92 ± 2.56 (179.14)	178.99 ± 2.81 (179.29)	0.07
No background	179.51 ± 1.30 (179.90)	179.72 ± 1.32 (180.12)	0.21
	NS	NS	
Up saccades			
Perspective	-0.47 ± 2.45 (-0.96)	1.0 ± 4.40 (0.22)	1.47
Grid	2.17 ± 1.68 (1.93)	2.07 ± 1.81 (1.49)	-0.10
No background	2.67 ± 2.97 (3.11)	2.66 ± 2.96 (3.10)	-0.01
	P<0.01 $F_{2,11} = 6.67$ N:P G:P $P<0.05$ F=1.97 i.e. effect of perspective	NS	
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation	Change in amplitude
Perspective	9.76 ± 0.29 (9.77)	10.77 ± 0.77 (10.58)	1.01
Grid	10.01 ± 0.42 (10.09)	10.61 ± 0.36 (10.58)	0.60
No background	9.77 ± 0.40 (9.80)	10.44 ± 0.21 (10.51)	0.67
	NS	NS	
Right saccades			
Perspective	9.10 ± 0.36 (9.16)	9.92 ± 0.33 (9.92)	0.82
Grid	9.44 ± 0.39 (9.44)	9.78 ± 0.30 (9.83)	0.34
No background	9.87 ± 0.87 (9.84)	9.88 ± 0.19 (9.92)	0.01
	P<0.01 $F_{2,13} = 9.33$ N:P N:G $P<0.05$ F=0.41	NS	

Key:- mean ± s.d. (median). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 5.2 Eye movement measures for subject LBS (binocular viewing, left eye dominant).

Down saccades	Direction of primary saccade	Direction of ocular response at fixation	Change in direction
Perspective	179.96 ± 1.48 (180.11)	182.09 ± 3.98 (181.20)	2.13
Grid	179.71 ± 2.03 (179.56)	183.43 ± 3.53 (183.07)	3.72
No background	180.48 ± 2.10 (180.99)	182.79 ± 3.24 (181.55)	2.31
	NS	NS	
Up saccades			
Perspective	1.74 ± 3.23 (2.26)	-3.21 ± 2.30 (-3.17)	-4.95
Grid	0.89 ± 3.69 (1.03)	-2.61 ± 3.36 (-1.52)	-3.50
No background	1.37 ± 1.97 (1.78)	-0.24 ± 1.13 (-0.29)	-1.61
	NS	$P<0.01$ $F_{2,12} = 5.98$ N:P $P<0.05$ F=1.77	
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation	Change in amplitude
Perspective	9.86 ± 0.61 (9.97)	10.90 ± 0.47 (10.86)	1.04
Grid	9.72 ± 0.65 (9.64)	10.73 ± 0.40 (10.57)	1.01
No background	9.55 ± 0.78 (9.47)	10.78 ± 0.52 (10.81)	1.23
	NS	NS	
Right saccades			
Perspective	9.97 ± 0.82 (9.97)	9.88 ± 0.49 (9.89)	-0.09
Grid	10.09 ± 0.54 (10.00)	9.90 ± 0.41 (9.86)	-0.19
No background	9.81 ± 0.71 (9.75)	9.80 ± 0.42 (9.86)	-0.01
	NS	NS	

Key:- mean ± s.d. (median). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 5.3 Eye movement measures for subject JPS (binocular viewing, left eye dominant).

Down saccades	Direction of primary saccade	Direction of ocular response at fixation	Change in direction
Perspective	180.31 ± 1.77 (180.12)	180.06 ± 1.86 (180.12)	-0.25
Grid	180.28 ± 1.10 (180.46)	180.34 ± 1.68 (180.35)	0.06
No background	179.94 ± 1.91 (180.01)	179.49 ± 1.61 (179.28)	-0.45
	NS	NS	
Up saccades			
Perspective	-0.42 ± 2.01 (-0.91)	-7.73 ± 2.29 (-7.76)	-7.31
Grid	-0.50 ± 1.33 (-0.89)	-6.09 ± 3.71 (-6.15)	-5.59
No background	-0.22 ± 1.17 (0.03)	-3.99 ± 2.42 (-3.65)	-3.77
	NS	NS	
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation	Change in amplitude
Perspective	10.37 ± 0.35 (10.37)	10.67 ± 0.35 (10.60)	0.30
Grid	10.24 ± 0.30 (10.24)	10.62 ± 0.43 (10.75)	0.38
No background	9.97 ± 0.47 (9.91)	10.56 ± 0.36 (10.62)	0.59
	NS	NS	
Right saccades			
Perspective	9.86 ± 0.43 (9.85)	9.68 ± 0.31 (9.75)	-0.18
Grid	9.61 ± 0.40 (9.62)	9.58 ± 0.52 (9.60)	-0.03
No background	10.09 ± 0.48 (10.12)	9.57 ± 0.32 (9.55)	-0.52
	NS	NS	

Key:- mean ± s.d. (median). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 5.4 Eye movement measures for subject SLH (monocular viewing, viewing eye recorded. right eye dominant).

Down saccades	Direction of primary saccade	Direction of ocular response at fixation	Change in direction
Perspective	176.50 ± 2.02 (176.76)	179.28 ± 1.23 (178.91)	2.78
Grid	176.61 ± 1.98 (176.02)	179.02 ± 1.12 (178.92)	2.41
No background	177.60 ± 1.50 (177.54)	182.79 ± 3.24 (181.55)	5.19
	NS	NS	
Up saccades			
Perspective	-1.04 ± 4.41 (-2.84)	-2.66 ± 1.22 (-2.51)	-1.62
Grid	-1.01 ± 1.66 (-0.93)	-2.82 ± 0.98 (-2.48)	-1.81
No background	-0.59 ± 1.58 (-0.89)	-1.44 ± 1.11 (-1.76)	-0.85
	NS	$P<0.05$ $F_{2,10} = 4.63$ N:G N:P $P<0.05$ F=1.00	
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation	Change in amplitude
Perspective	10.07 ± 0.54 (10.02)	10.49 ± 0.30 (10.56)	0.42
Grid	10.05 ± 0.63 (10.03)	10.53 ± 0.28 (10.49)	0.48
No background	9.97 ± 0.41 (9.90)	10.44 ± 0.30 (10.45)	0.47
	NS	NS	
Right saccades			
Perspective	8.80 ± 0.36 (8.87)	9.71 ± 0.30 (9.76)	0.91
Grid	9.45 ± 0.41 (9.40)	9.81 ± 0.22 (9.81)	0.36
No background	9.20 ± 0.43 (9.29)	9.65 ± 0.19 (9.62)	0.45
	$P<0.01$ $F_{2,10} = 7.26$ N:P G:P $P<0.05$ F=0.36 i.e. effect of perspective	NS	

Key:- mean ± s.d. (median). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 5.5 Eye movement measures for subject ANP (monocular viewing, viewing eye recorded, left eye dominant).

Down saccades	Direction of primary saccade	Direction of ocular response at fixation	Change in direction
Perspective	179.69 ± 1.80 (179.82)	180.52 ± 0.99 (180.67)	0.83
Grid	178.99 ± 1.48 (179.28)	180.74 ± 0.85 (180.74)	1.75
No background	178.92 ± 1.24 (178.93)	180.35 ± 0.66 (180.38)	1.43
	NS	NS	
Up saccades			
Perspective	-0.41 ± 1.38 (-0.38)	-1.22 ± 1.06 (-1.53)	-0.81
Grid	0.70 ± 1.57 (0.84)	-0.49 ± 1.32 (-0.59)	-1.19
No background	-0.46 ± 1.07 (-0.50)	-0.68 ± 0.41 (-0.62)	-0.22
	NS	NS	
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation	Change in amplitude
Perspective	9.62 ± 0.33 (9.69)	10.58 ± 0.45 (10.63)	0.96
Grid	9.61 ± 0.70 (9.58)	10.61 ± 0.31 (10.77)	1.00
No background	9.59 ± 0.52 (9.58)	10.68 ± 0.22 (10.67)	1.09
	NS	NS	
Right saccades			
Perspective	8.20 ± 0.36 (8.22)	9.40 ± 0.21 (9.33)	1.20
Grid	8.20 ± 0.44 (8.14)	9.44 ± 0.21 (9.45)	1.24
No background	8.51 ± 0.53 (8.45)	9.21 ± 0.29 (9.27)	0.70
	NS	$P<0.01$ $F_{2,12} = 5.74$ N:G N:P $P<0.05$ F=0.17	

Key:- mean ± s.d. (median). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 5.6 Eye movement measures for subject MAR (monocular viewing, viewing eye recorded, right eye dominant).

Down saccades	Direction of primary saccade	Direction of ocular response at fixation	Change in direction
Perspective	178.81 ± 3.86 (179.57)	180.10 ± 0.83 (180.64)	1.29
Grid	180.79 ± 3.26 (180.37)	180.74 ± 2.58 (180.26)	-0.05
No background	179.13 ± 1.99 (179.61)	180.49 ± 1.50 (180.33)	1.36
	NS	NS	
Up saccades			
Perspective	0.19 ± 1.50 (0.14)	-0.77 ± 1.16 (-0.94)	-0.96
Grid	0.03 ± 1.50 (-0.04)	-0.41 ± 0.93 (-0.45)	-0.44
No background	0.41 ± 3.20 (0.54)	-0.07 ± 2.02 (0.25)	-0.48
	NS	NS	
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation	Change in amplitude
Perspective	9.47 ± 0.64 (9.49)	10.64 ± 0.22 (10.68)	1.17
Grid	9.60 ± 0.48 (9.59)	10.58 ± 0.21 (10.62)	0.98
No background	9.55 ± 0.36 (9.58)	10.73 ± 0.33 (10.63)	1.18
	NS	NS	
Right saccades			
Perspective	8.82 ± 0.53 (8.88)	9.36 ± 0.41 (9.33)	0.54
Grid	8.91 ± 0.80 (8.80)	9.52 ± 0.30 (9.45)	0.61
No background	9.10 ± 0.39 (8.95)	9.48 ± 0.21 (9.49)	0.38
	NS	NS	

Key:- mean ± s.d. (median). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 5.7 Eye movement measures for subject BY (monocular viewing, covered eye recorded, right eye dominant).

Down saccades	Direction of primary saccade	Direction of ocular response at fixation	Change in direction
Perspective	179.90 ± 2.90 (0.87, 11)	178.24 ± 1.26 (0.38, 11)	-1.66
Grid	180.43 ± 1.94 (0.54, 13)	179.34 ± 0.93 (0.26, 13)	-1.09
No background	178.92 ± 0.97 (0.25, 12)	179.77 ± 1.71 (0.49, 12)	0.85
	NS	NS	
Up saccades			
Perspective	-2.40 ± 1.34 (0.35, 15)	-1.84 ± 2.29 (0.59, 15)	0.56
Grid	-2.38 ± 1.32 (0.38, 12)	-1.28 ± 1.37 (0.40, 12)	1.10
No background	-1.55 ± 1.81 (0.50, 13)	-2.90 ± 1.57 (0.43, 13)	-1.35
	NS	NS	
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation	Change in amplitude
Perspective	10.45 ± 1.03 (0.26, 15)	10.98 ± 0.34 (0.09, 15)	0.53
Grid	10.83 ± 0.66 (0.19, 12)	10.94 ± 0.26 (0.08, 12)	0.11
No background	10.69 ± 0.77 (0.23, 11)	10.83 ± 0.20 (0.06, 11)	0.14
	NS	NS	
Right saccades			
Perspective	9.83 ± 1.23 (0.37, 11)	9.95 ± 0.07 (0.25, 11)	0.12
Grid	10.27 ± 0.68 (0.21, 10)	10.06 ± 0.25 (0.08, 10)	-0.21
No background	10.25 ± 0.81 (0.22, 13)	10.03 ± 0.26 (0.07, 13)	-0.22
	NS	NS	

Key:- mean ± s.d. (s.e., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 5.8 Eye movement measures for subject NC (monocular viewing, covered eye recorded, left eye dominant).

Down saccades	Direction of primary saccade	Direction of ocular response at fixation	Change in direction
Perspective	177.60 ± 1.53 (0.42, 13)	177.76 ± 2.59 (0.72, 13)	0.16
Grid	177.77 ± 1.08 (0.28, 15)	175.75 ± 2.40 (0.62, 15)	-2.02
No background	178.36 ± 1.16 (0.32, 13)	179.16 ± 2.07 (0.57, 13)	0.80
	NS	$P<0.002$ $F_{2,12} = 8.52$ N:G G:P $P<0.05$ F=1.79	
Up saccades			
Perspective	-2.09 ± 2.01 (0.54, 14)	-4.93 ± 2.61 (0.70, 14)	-2.84
Grid	-2.57 ± 1.32 (0.34, 15)	-3.54 ± 1.64 (0.42, 15)	-0.97
No background	-2.34 ± 1.61 (0.43, 14)	-3.48 ± 2.12 (0.57, 14)	-1.14
	NS	NS	
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation	Change in amplitude
Perspective	9.09 ± 0.62 (0.16, 14)	9.96 ± 0.83 (0.22, 14)	0.87
Grid	10.22 ± 0.69 (0.18, 15)	10.22 ± 0.47 (0.12, 15)	0.00
No background	9.34 ± 0.79 (0.21, 14)	10.02 ± 0.39 (0.10, 14)	0.68
	NS	NS	
Right saccades			
Perspective	10.17 ± 0.36 (0.10, 13)	10.59 ± 0.71 (0.20, 13)	0.42
Grid	10.06 ± 0.61 (0.16, 15)	10.54 ± 0.36 (0.10, 14)	0.48
No background	9.50 ± 0.43 (0.12, 13)	10.37 ± 0.44 (0.12, 13)	0.87
	$P<0.01$ $F_{2,12} = 9.40$ N:P N:G $P<0.05$ F=0.35	NS	

Key:- mean ± s.d. (s.e., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 5.9 Eye movement measures for subject MV (monocular viewing, covered eye recorded, right eye dominant).

Down saccades	Direction of primary saccade	Direction of ocular response at fixation	Change in direction
Perspective	182.61 ± 1.60 (0.43, 14)	181.26 ± 1.10 (0.29, 14)	-1.35
Grid	182.37 ± 1.20 (0.31, 15)	180.02 ± 1.09 (0.28, 15)	-2.35
No background	182.45 ± 1.71 (0.44, 15)	180.89 ± 1.12 (0.29, 15)	-1.56
	NS	$P<0.01$ $F_{2,13} = 6.81$ N:G G:P $P<0.05$ F=0.74	
Up saccades			
Perspective	-2.37 ± 2.49 (0.67, 14)	-4.31 ± 1.26 (0.34, 14)	-1.94
Grid	-1.75 ± 1.36 (0.35, 15)	-3.06 ± 1.12 (0.29, 15)	-1.31
No background	-1.93 ± 1.24 (0.32, 15)	-2.90 ± 1.69 (0.43, 15)	-0.97
	NS	$P<0.05$ $F_{2,13} = 4.29$ N:P G:P $P<0.05$ F=1.06 i.e. effect of perspective	
Left saccades	Amplitude of primary saccade	Amplitude of ocular response 1 at fixation	Change in amplitude
Perspective	9.79 ± 0.97 (0.25, 15)	11.08 ± 0.39 (0.10, 15)	1.29
Grid	9.59 ± 0.56 (0.14, 15)	10.70 ± 0.27 (0.07, 15)	1.11
No background	9.66 ± 0.59 (0.16, 14)	10.71 ± 0.29 (0.08, 14)	1.05
	NS	$P<0.01$ $F_{2,13} = 6.53$ N:P G:P $P<0.05$ F=0.26 i.e. effect of perspective	
Right saccades			
Perspective	8.73 ± 0.91 (0.23, 15)	9.53 ± 0.33 (0.09, 15)	0.80
Grid	9.24 ± 0.78 (0.20, 15)	9.77 ± 0.36 (0.09, 15)	0.53
No background	9.49 ± 0.75 (0.19, 15)	9.56 ± 0.23 (0.06, 15)	0.07
	NS	NS	

Key:- mean ± s.d. (s.e., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

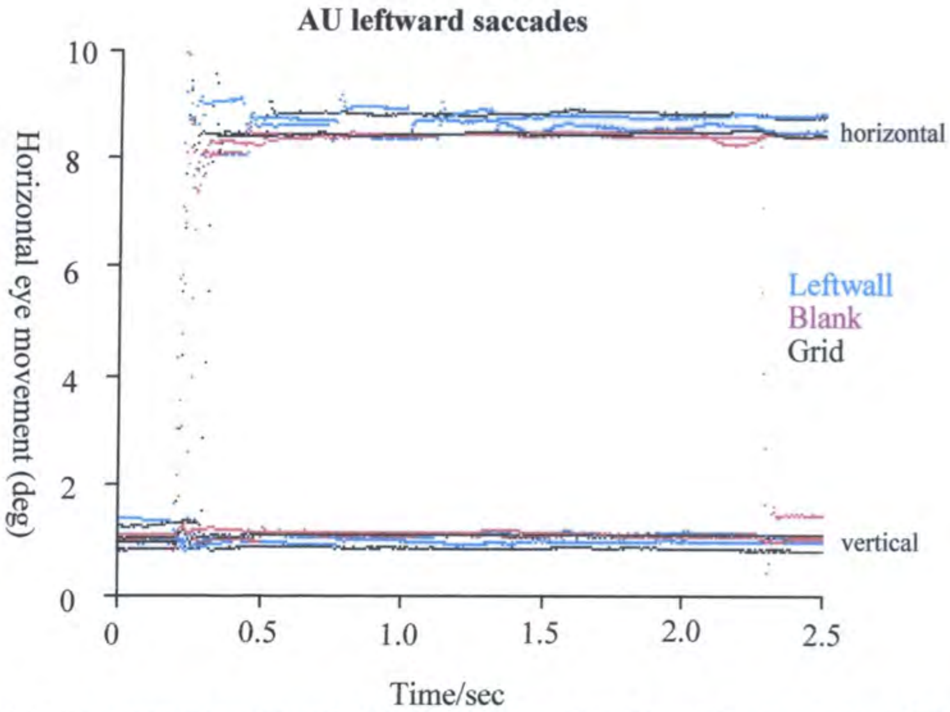

Figure 5.10 Eye movement responses for targets appearing in the leftward direction (subject AU)

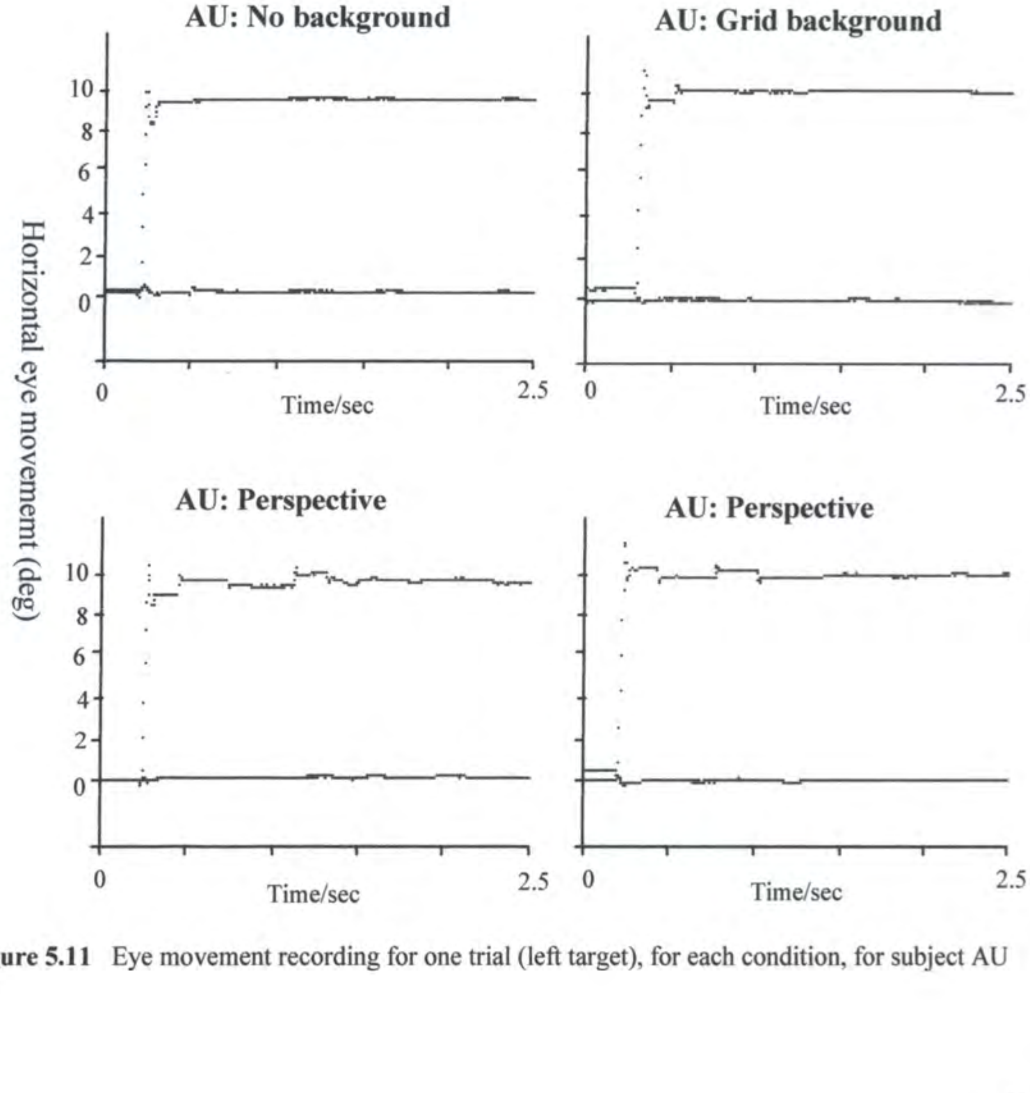

Figure 5.11 Eye movement recording for one trial (left target), for each condition, for subject AU

Precision with which the eye's line-of-sight is directed to a particular location

Table 5.10 Mean fixation offset from target and standard deviation ranges (italics) for horizontal and vertical fixation positions (13-15 repeated measures) compared across control and perspective backgrounds, for the three subjects in each viewing condition (target amplitude 10°).

	Horizontal fixation		Vertical fixation	
	No background	Perspective background	No background	Perspective background
Binocular viewing	0.44° *0.19-0.52°*	0.49° *0.31-0.77°*	1.74° *1.13-3.24°*	2.54° *1.86-4.40°*
Monocular - viewing eye	0.58° *0.19-0.33°*	0.54° *0.21-0.45°*	0.97° *0.41-3.24°*	1.00° *0.83-1.23°*
Monocular - covered eye	0.40° *0.20-0.44°*	0.53° *0.07-0.83°*	1.87° *1.12-2.12°*	2.72° *1.10-2.61°*

The above table shows the offset of the mean readings of fixation position from the actual position of the target together with the standard deviation ranges (n = 12-15) for the amplitude of the eye movement response at fixation. These values give a measure of the overall accuracy with which a target can be located by a subject's eye line-of-sight. Subjects fixated the target more accurately when it was in a horizontal compared with a vertical position. There were no consistent differences in target fixation accuracy between the three viewing conditions.

Discussion

This experiment investigated whether a sudden-onset perspective display, present for 2.5 seconds, would elicit evidence of saccade disconjugacy (and/or vergence eye movements), under monocular or binocular viewing conditions, for 4 different target directions.

No consistent evidence was found of such ocular responses, under the conditions during this experiment. However, one subject (covered eye recorded) showed approximately 0.4° and 1.4° of convergence at fixation, for left and up targets respectively, in the perspective condition compared with the control conditions. Another subject (binocular viewing) showed over 2° of convergent saccade disconjugacy for upward targets in the perspective condition compared with the control conditions. Finally, one subject (viewing eye recorded) showed 0.4° of convergent saccade disconjugacy for rightward targets in the perspective condition compared with the control conditions.

Some fine details of the post-saccadic ocular motor response during the perspective condition, although not significant in size, are different in form. Figure 5.11 showed an example of a step like pattern, which one subject (binocular viewing) made during leftward saccades. This suggests that the perspective stimuli may be effecting some very small changes in the ocular response.

The presence of a background (compared with no background) was not expected to elicit saccade disconjugacy or any vergence eye movements. However, some evidence was found for an effect of the presence of a background compared with no background, on subjects' ocular responses. Two subjects, (a) monocular viewing - covered eye recorded and (b) binocular viewing, showed some convergent saccade disconjugacy, for rightward target directions, in the presence of a background. Two subjects (both viewing eye recorded, monocular viewing) showed that the presence of a background compared with no background led to convergence at fixation, one for up targets and the other for rightward targets.

Two subjects (both covered eye recorded) showed significant evidence of convergence at fixation, for downward targets only, in the grid condition compared with the no background and perspective condition.

Lastly, the overall changes in ocular response between the end of the primary saccade and fixation are considered. Two previous studies, Collewijn *et al.* (1988a) and Enright (1989), have found that downward saccades (for example, 8° amplitude) are associated with about 1° of transient convergence followed by divergent post-saccadic changes. The results from this study partially agree with these findings. Four of the nine subjects showed a divergent change in their ocular response between the end of the primary saccade and fixation, for all target directions, for all conditions. However, five of the subjects showed a convergent change. For upward saccades, previous findings have been more variable. Collewijn *et al.* (1988b) found that their subjects showed a smaller transient divergent response when looking upwards followed by convergent post-saccadic drift whereas Enright (1989) found that subjects made very small responses which were often negligible. During this study, seven of the subjects made a convergent change after the primary saccade. Two made a divergent change.

The resolution and accuracy of the Purkinje Tracker is quoted as approximately 1 arc minute. Eyetracker calibrations were conducted before and after each block of trials (Appendix III). Comparison of the degree per unit values between before and after calibrations showed close correspondence (horizontally 0.011° ± 0.012°, vertically 0.012°± 0.084°) indicating, for example, that negligible equipment drift had occurred. Therefore, the recording technique was adequate to measure even small effects. Further, the use of relative rather than absolute measures of eye position controlled for any shifts in the centre calibration position (horizontally 0.14° ± 0.09°, vertically 0.15° ± 0.11°). Hence, it is unlikely that the lack of differences between subject's ocular responses for each of the conditions can be attributed to equipment measurement problems.

The expected change in the ocular response, when looking to the target on the perspective wall, was approximately 1°. This figure was calculated based on the geometry of a 3D model using the same size proportions as the perspective display. However, it is possible that the subject may mis-perceive the actual size of the display, for example, by imagining that they are looking into a larger room. Likewise, the subject may mis-perceive the distance to the display. These factors could possibly reduce the expected size of the ocular response. However, the subjects were able to see the display and its distance from them prior to the start of the experiment. They all reported that they saw the perspective display as two sides of a medium sized box rather than as, for example, a room. Hence, it seems unlikely that the subject's significantly mis-perceived the size of the perspective stimulus.

Two other mechanisms may have affected subjects' ocular responses. The first is the subject's knowledge of the nearness of the display. It is possible that the subject's prior knowledge that the display was flat may have curtailed any vergence response or saccade disconjugacy (proximal vergence, Hokoda & Ciuffreda, 1983). The second relates to evidence which suggests that subjects may have some volitional control over their vergence. McLin & Schor (1988) found that subjects could voluntarily produce vergence changes. The ratio of the vergence changes produced relative to the accommodative changes, suggested that the voluntary effort drove accommodation first and then vergence through the accommodation/vergence cross-link. However, given that the subjects were naive as to the purpose of the experiment and that most had not participated in eye movement experiments before it seems unlikely that they would have tried to deter any vergence changes in the perspective condition.

There is apparently no association between the form of subject's ocular responses and which of their eyes is the dominant one.

Previously, Enright (1987a) has found vergence changes of the order of 20' and even over a degree for a couple of subjects, when they looked between the corners of a 2D perspective view of a cube. One potentially pertinent difference between that experiment and this one was that the display in Enright's study was constantly present and subjects looked up and down between the two corners every 2-4 seconds. Ringach *et al.*. (1996) have suggested that the visual system may construct a 3D model of the environment based on retinal stimulation and that this 3D model may then be used to plan motor activities such as binocular eye movements. One of the inputs to this model would be monocular depth cues. The results reported here suggest that it may take time, longer than 2.5 seconds, for the visual system to construct such a model, or to be able to utilise such a model, based solely on perceptive cues.

Finally, the practical implications of this result are that perspective cues to depth alone, where used for example to display two switches at different perceived depths, are not sufficient to enable binocular eye pointing to resolve/measure their different perceived positions in depth. Hence, although the two switches were perceived at different depths the two eyes were pointing at their actual horizontal and vertical positions on the display with a similar degree of precision to the 2D eye pointing situation. It remains a possibility that perspective cues to depth may have a role in enhancing the accuracy of the oculomotor response to targets presented on a display using other depth cues, for example, a stereoscopic display.

6

Further oculomotor responses to perspective grid line drawings

Introduction

The importance of ascertaining the speed of the ocular response in moving the binocular point of foveation between two depth planes defined by perspective depth cues, was demonstrated, from a practical point of view, in the introduction to chapter five. However, it was shown that linear perspective depth cues did not consistently elicit target directed disconjugate saccade or vergence responses, under either monocular or binocular viewing conditions. Rather, the subjects' ocular responses remained in the depth plane of the display. The aim of this chapter is to examine some of the theoretical reasons (discussed below) why this was the case.

One potential explanation is that it may take a longer period of time for a depth percept to be perceived from linear perspective depth cues than was available. Hence, when the target was displayed in an unpredictable location (sudden-onset) for 2.5 seconds, insufficient time may have been available for the subject to perceive the depth relationships sufficiently to affect ocular motor behaviour. As mentioned previously, during monocular viewing, Enright (1987a) demonstrated asymmetric vergence changes (movement in the covered eye), to perspective depth cues. A principle difference between the procedure used in that experiment and the one just reported was that Enright's displays were constantly present. It may be that it takes a longer period of time than was available for a depth percept, capable of affecting oculomotor behaviour, to develop. In order to determine whether this factor might account for the disagreement in results, the monocular viewing (covered eye recorded) condition of the previous experiment was repeated using displays presented for a longer period of time. The experiment used two display paradigms. In the first, the target was presented in an unpredictable location (sudden-onset) for 2.5 seconds, whereas in the second (constant) the target was presented for 20 seconds, enabling sufficient time for the depth percept to develop and providing a predictable target location.

Experiment 1

Method

Three subjects, who had participated in the previous experiment under monocular viewing (covered eye recorded) conditions, were re-recruited.

The experimental stimuli and procedures were identical to those in the previous chapter except that each display was presented for 20 seconds with a 2 second 'rest' period in between each presentation. Subjects were asked to look back and forward between the central fixation cross and the square target on a voice command, spending approximately 2.5 seconds at each location (verbatum instructions in appendix V).

Results

Assuming an interpupillary distance of 6.5 cm, fixation in the plane of the display would require 6.2° of vergence. During a perspective trial the subject's level of vergence would be expected to change by ≈ 2° (convergence), as they looked from the initial fixation point to the target, if the subject responded to the apparent depth portrayed in the display. Hence, the maximum expected values for the direction or amplitude of the ocular response (right eye) for each condition would be as follows (assuming vergence change to be equally distributed between the two eyes):-

Table 6.0 Maximum expected eye movement responses for each condition.

	No background & grid conditions		Perspective condition	
	Expected direction or amplitude of ocular response	Expected change in direction or amplitude	Expected direction or amplitude of ocular response	Expected change in direction or amplitude
Down saccades (direction)	180°	0°	182.8°	+2.8°
Up saccades (direction)	0°	0°	-2.8° (i.e. 357.2°)	-2.8°
Left saccades (amplitude)	10°	0°	≈ 11°	+1°
Right saccades (amplitude)	10°	0°	≈ 9°	-1°

Subjects reported that in the perspective condition the target wall did appear to come towards them.

Table 6.1 Eye movement measures for subject MV (monocular viewing, covered eye recorded)

Down saccades	Direction of primary saccade	Direction of ocular response at fixation	Change in direction
Perspective	183.72 ± 0.27 (0.94, 12)	183.05 ± 0.37 (1.27, 12)	-0.67
Grid	182.08 ± 0.29 (1.08, 14)	180.65 ± 0.27 (1.00, 14)	-1.43
No background	182.73 ± 0.37 (1.33, 13)	181.43 ± 0.50 (1.73, 12)	-1.30
	$F_{2,11} = 5.95$ $P<0.01$ G:P $P<0.05$ F=0.94	$F_{2,11} = 9.31$ $P<0.01$ N:P G:P $P<0.05$ F=1.25	
Up saccades			
Perspective	-4.67 ± 0.39 (1.50, 15)	-4.61 ± 0.26 (0.96, 14)	0.06
Grid	-3.50 ± 0.43 (1.68, 15)	-2.23 ± 0.34 (1.27, 14)	1.27
No background	-1.30 ± 0.69 (2.19, 10)	-3.01 ± 0.53 (1.69, 10)	-1.71
	$F_{2,9} = 7.95$ $P<0.01$ N:G N:P $P<0.05$ F=0.94	$F_{2,9} = 5.40$ $P<0.01$ G:P $P<0.05$ F=12.27	
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation	Change in amplitude
Perspective	10.17 ± 0.12 (0.44, 14)	12.19 ± 0.12 (0.44, 14)	2.02
Grid	9.89 ± 0.20 (0.77, 14)	10.94 ± 0.06 (0.24, 14)	1.05
No background	10.00 ± 0.17 (0.61, 13)	11.14 ± 0.07 (0.24, 12)	1.14
	NS	$F_{2,11} = 41.23$ $P<0.01$ N:P G:P $P<0.05$ F=0.29	
Right saccades			
Perspective	8.41 ± 0.17 (0.62, 13)	9.08 ± 0.10 (0.35, 13)	0.67
Grid	9.06 ± 0.13 (0.40, 10)	9.72 ± 0.08 (0.24, 9)	0.66
No background	9.04 ± 0.09 (0.34, 15)	9.78 ± 0.08 (0.31, 15)	0.74
	$F_{2,9} = 4.38$ $P<0.05$ N:P P:G $P<0.05$ F=0.49	$F_{2,8} = 10.62$ $P<0.01$ N:P P:G $P<0.05$ F=0.31	

Key:- mean ± s.e. (s.d., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 6.2 Eye movement measures for subject BY (monocular viewing, covered eye recorded)

Down saccades	Direction of primary saccade	Direction of ocular response at fixation	Change in direction
Perspective	180.16 ± 0.34 (1.43, 18)	180.23 ± 0.26 (1.06, 16)	0.07
Grid	178.55 ± 0.27 (1.19, 19)	179.09 ± 0.16 (0.73, 20)	0.54
No background	179.15 ± 0.48 (2.16, 20)	179.49 ± 0.22 (0.96, 20)	0.34
	NS	$F_{2,15} = 6.16$ $P<0.01$ N:P G:P $P<0.05$ F=0.66	
Up saccades			
Perspective	-2.18 ± 0.38 (1.69, 20)	-3.50 ± 0.32 (1.45, 20)	-1.32
Grid	-1.18 ± 0.34 (1.38, 16)	-2.50 ± 0.28 (1.12, 16)	-1.32
No background	-0.26 ± 0.36 (1.52, 18)	-2.21 ± 0.47 (1.96, 17)	-1.95
	$F_{2,15} = 7.21$ $P<0.01$ N:P $P<0.05$ F=1.14	$F_{2,15} = 3.88$ $P<0.05$ N:P $P<0.05$ F=1.05	
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation	Change in amplitude
Perspective	11.29 ± 0.19 (0.84, 20)	11.57 ± 0.10 (0.44, 20)	0.28
Grid	10.91 ± 0.14 (0.60, 19)	11.29 ± 0.17 (0.76, 19)	0.38
No background	10.41 ± 0.18 (0.76, 17)	11.53 ± 0.11 (0.46, 17)	1.12
	$F_{2,16} = 8.94$ $P<0.01$ N:G N:P G:P $P<0.05$ F=0.49	NS	
Right saccades			
Perspective	9.98 ± 0.18 (0.81, 20)	9.80 ± 0.09 (0.42, 20)	-0.18
Grid	10.51 ± 0.20 (0.89, 19)	10.10 ± 0.07 (0.33, 20)	-0.41
No background	10.41 ± 0.20 (0.88, 20)	10.04 ± 0.10 (0.43, 20)	-0.37
	NS	NS	

Key:- mean ± s.e. (s.d., n). P values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 6.3 Eye movement measures for subject NC (monocular viewing, covered eye recorded)

Down saccades	Direction of primary saccade	Direction of ocular response at fixation	Change in direction
Perspective	176.38 ± 0.55 (2.28, 17)	177.75 ± 0.64 (2.86, 20)	1.37
Grid	177.03 ± 0.53 (2.39, 20)	176.07 ± 0.48 (2.16, 20)	-0.96
No background	177.51 ± 0.43 (1.94, 20)	176.32 ± 0.32 (1.43, 20)	-1.19
	NS	$F_{2,19} = 5.54$ $P<0.01$ N:P G:P P<0.05 F=1.56	
Up saccades			
Perspective	-4.78 ± 0.35 (1.53, 19)	-9.95 ± 0.36 (1.61, 20)	-5.17
Grid	-3.90 ± 0.59 (2.44, 17)	-7.12 ± 0.66 (2.88, 19)	-3.22
No background	-2.48 ± 0.60 (2.61, 19)	-5.33 ± 0.44 (1.96, 20)	-2.85
	$F_{2,16} = 4.01$ $P<0.05$ N:P $P<0.05$ F=1.65	$F_{2,18} = 16.78$ $P<0.01$ N:G N:P G:P $P<0.05$ F=1.64	
Left saccades	Amplitude of primary saccade	Amplitude of ocular response 1 at fixation	Change in amplitude
Perspective	10.18 ± 0.27 (0.91, 11)	11.26 ± 0.16 (0.56, 12)	1.08
Grid	10.69 ± 0.18 (0.72, 16)	11.07 ± 0.10 (0.39, 16)	0.38
No background	10.13 ± 0.23 (1.00, 19)	10.58 ± 0.10 (0.45, 19)	0.45
	NS	$F_{2,11} = 4.26$ $P<0.05$ N:P $P<0.05$ F=0.47	
Right saccades			
Perspective	9.70 ± 0.15 (0.65, 19)	9.96 ± 0.08 (0.38, 20)	0.26
Grid	10.54 ± 0.16 (0.71, 20)	10.71 ± 0.11 (0.48, 20)	0.17
No background	9.92 ± 0.18 (0.79, 20)	10.53 ± 0.10 (0.46, 20)	0.61
	$F_{2,18} = 8.27$ $P<0.01$ N:G G:P $P<0.05$ F=0.43	$F_{2,19} = 18.09$ $P<0.01$ G:P P:N $P<0.05$ F=0.28	

Key:- mean ± s.e. (s.d., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Tables 6.1 - 6.3 show means for the direction or amplitude of the ocular response at the end of the primary saccade and at fixation (one second after the end of the primary saccade), for each target direction, for each condition, for each subject. Each mean is based on 9-20 saccades. The change in direction or amplitude of the ocular response between these two "events" is also given. For each subject, a one-way ANOVA (repeated measures) was carried out investigating any differences between the conditions in primary saccade direction/amplitude and fixation direction/amplitude. Where differences were found the Fisher's Protected Least Significant Difference (PLSD) post-hoc test was conducted to determine between which conditions the difference originated. These statistical results are reported in tables 6.1 - 6.3. The results are also plotted in figure 6.0.

Saccade disconjugacy

Subject MV was the only subject to show evidence of target directed disconjugate saccades in the perspective condition, but this was solely towards right targets ($F_{2,9} = 4.38$, $P<0.05$). On average, subject MV made a 0.64° more convergent response in the perspective condition compared with the grid and no background conditions (PLSD: $F = 0.49$, $P<0.05$).

Various other cases of disconjugate saccades occurred which were anomalous in that, although target directed, they were not produced solely in the perspective condition compared with both control background conditions. These were as follows. Subjects BY, MV and NC produced a 1.92°, 2.30° and 3.37° more convergent response, respectively, towards up targets in the perspective compared with the no background (but not grid) conditions. Further, subject MV also produced a 2.2° more convergent response in the grid condition compared with the no background condition. Towards down targets, subject MV produced a 1.64° more convergent response in the perspective compared with the grid condition. Lastly, subject BY produced a 0.63° more convergent response towards left targets in the perspective compared with the no background and grid conditions and, also, a 0.5° more convergent response in the grid condition compared with the no background condition.

Vergence

Each subject showed evidence of target directed vergence towards the down targets. Subject MV showed the largest average convergent response of 2.10° ($F_{2,11} = 9.31$, $P<0.01$, PLSD: $F = 1.25$, $P<0.05$) while subjects BY and NC produced a 0.94° ($F_{2,15} = 6.16$, $P<0.01$, PLSD: $F = 0.66$, $P<0.05$) and a 1.5° ($F_{2,19} = 5.54$, PLSD: $F = 1.56$, $P<0.05$) more convergent response respectively. None of the subjects showed direct evidence of target directed vergence towards up targets. The ocular responses to left and right targets were idiosyncratic across the three subjects. Subject MV produced a 1.15° ($F_{2,11} = 41.23$, $P<0.01$, PLSD: $F = 0.29$, $P<0.05$) and a 0.67° ($F_{2,8} = 10.62$, $P<0.01$, PLSD: $F = 0.31$, $P<0.05$) more convergent response to left and right targets respectively whereas subject BY showed no evidence of target directed vergence to either target direction. Conversely, subject NC produced a 0.66° ($F_{2,19} = 18.09$, $P<0.01$, PLSD: $F = 0.28$, $P<0.05$) more convergent response to right targets but no direct evidence of target directed vergence toward left targets.

Various vergence responses, anomalous in that they were not elicited exclusively by the perspective display compared with both the control displays, were produced by all three subjects toward up targets (Subject MV: $F_{2,9} = 5.4$, $P<0.01$, subject NC: $F_{2,18} = 16.78$, $P<0.01$ & subject BY: $F_{2,15} = 3.88$, $P<0.05$). Subject MV produced a 2.38° more convergent response in the perspective compared with the grid condition (PLSD: $F = 12.27$, $P<0.05$) whereas subject BY produced a 1.29° more convergent response in the perspective compared with the no background but not the grid condition (PLSD: $F = 1.05$, $P<0.05$). Subject NC produced a 3.72° more convergent response in the perspective compared with the two control backgrounds but also a 1.79° more convergent response in the grid compared with the no background condition. Lastly, subject NC also produced a 0.68° more convergent response toward left targets in the perspective compared with the no background (but not grid) condition.

Change in direction/amplitude between the end of the primary saccade and fixation for all conditions

Overall, subjects NC and BY showed a predominantly convergent ocular response, between the end of the primary saccade and fixation for all conditions and target directions. Exceptions to this statement, i.e. a divergent ocular response, were produced by subject NC toward down targets in the control background conditions and right targets in all conditions. Conversely, subject MV produced a predominantly divergent ocular response, with the exception of eye movements toward the up targets in the no background condition and left targets in all conditions.

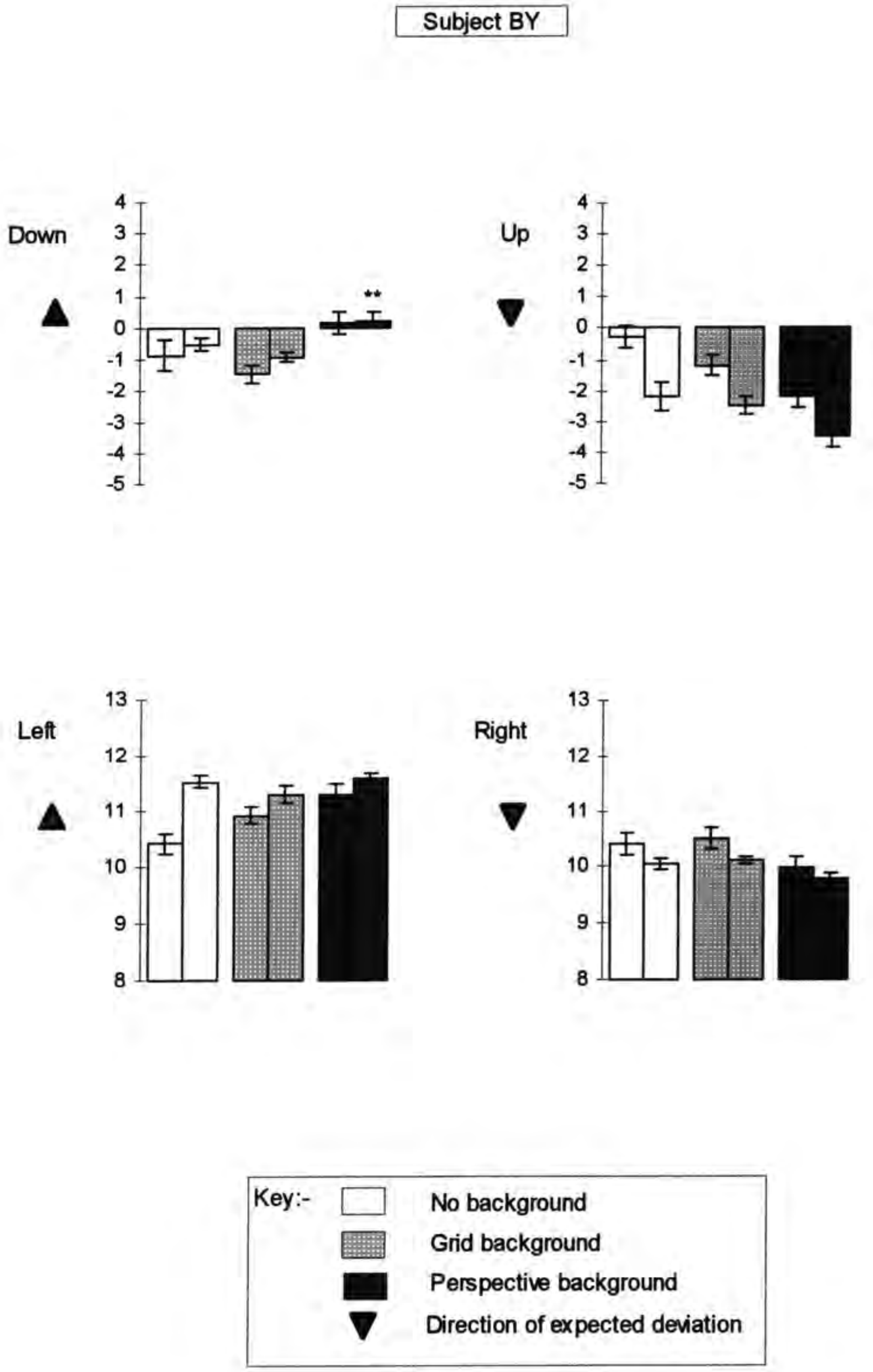

Figure 6.0 Mean primary saccade (first column) and fixation (second column) direction/amplitude (degrees ± s.d.), covered eye recorded, constant display

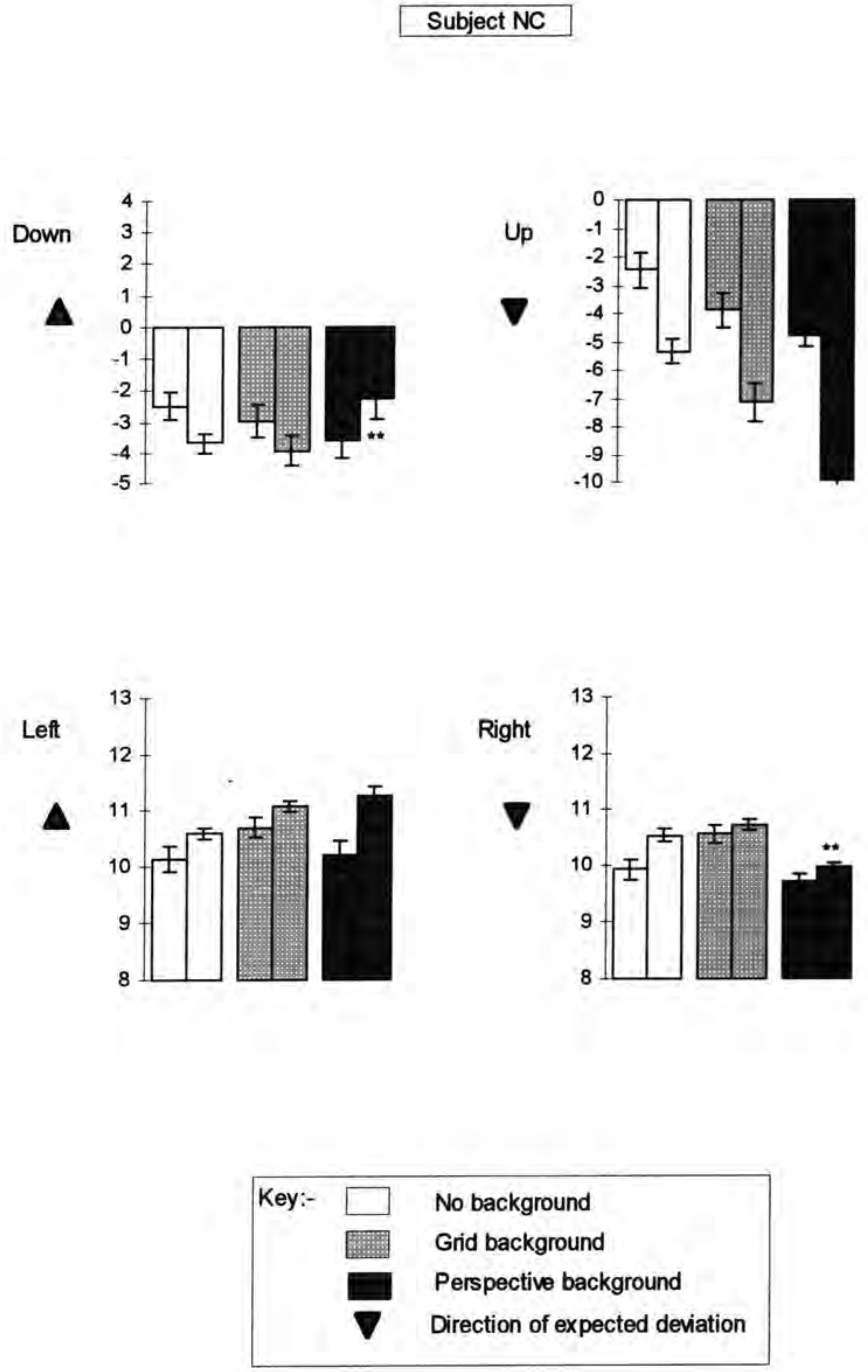

Figure 6.0 cont. Mean primary saccade (first column) and fixation (second column) direction/amplitude (degrees ± s.d.), covered eye recorded, constant display

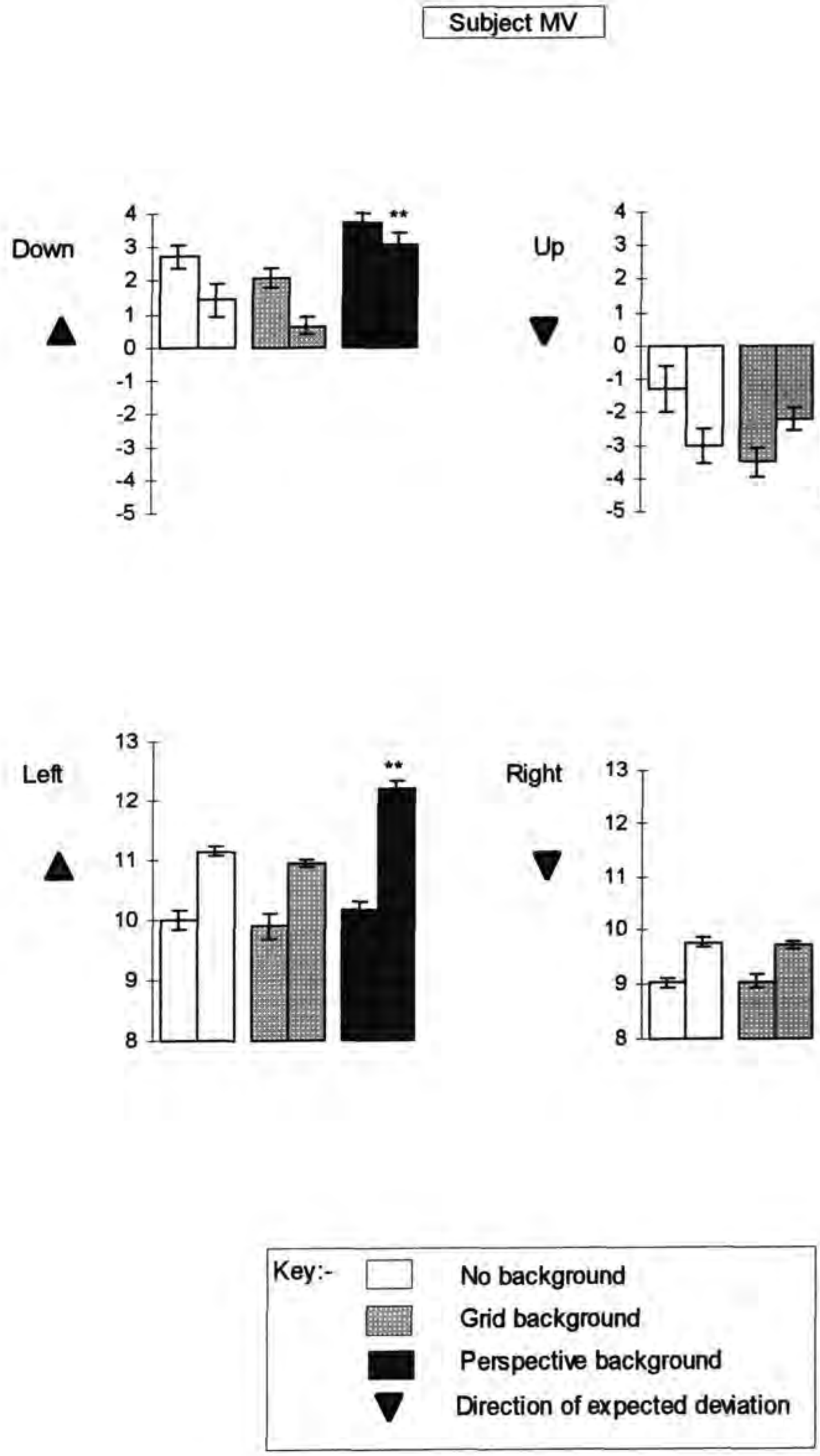

Figure 6.0 cont. Mean primary saccade (first column) and fixation (second column) direction/amplitude (degrees ± s.d.), covered eye recorded, constant display

Discussion

This experiment investigated whether a constant perspective display would elicit evidence of disconjugate saccades and/or vergence eye movements, under monocular viewing (covered eye recorded) conditions, for four different target directions.

Saccade disconjugacy

No consistent evidence of target directed disconjugate saccades was found.

Vergence

A summary of the subjects' ocular motor responses at fixation are shown below in table 6.4.

Table 6.4 Summary of vergence toward perspective targets

	Constant display, covered eye recorded			
	Down target	Up target	Left target	Right target
Subject MV	N:P G:P, 2.10°	P:G 2.38°	N:P G:P, 1.15°	N:P G:P, 0.67°
Subject BY	N:P G:P, 0.94°	N:P 1.29°		
Subject NC	N:P G:P, 1.50°	N:P G:P, 3.72° *N:G 1.79°*	N:P 0.68°	N:P G:P, 0.66°

Key:- N:P indicates that a significant difference in fixation amplitude was found between the no background and perspective conditions etc. *Italics* represent an anomalous response. Mean difference in fixation amplitude (degrees), between the perspective conditions and the grid + no background condition or no background condition only (as appropriate), shown.

More evidence of vergence, at fixation, was shown by the three subjects than under the sudden-onset conditions of the previous experiment. This provides support for the idea that it takes a longer period of time than was originally available for a 3D percept capable of affecting ocular motor behaviour to develop. However, none of the subjects produced an appropriate vergence response for all of the target directions and some evidence of an effect of a textured background (grid) was found. Hence, the results are only in partial agreement with Enright's (1987) findings that subjects made an appropriate vergence response when looking between two corners of a perspective cube separated by 2.5° vertically and 0.5° horizontally. However, it is by no means clear why the effect should only be shown for some of the target directions, particularly since each subject showed an appropriate vergence response toward a different pattern of target directions. It should also be noted that, where a vergence response was found, its magnitude was sufficiently large to argue against the equipment being of borderline sensitivity to detect the effect.

It remains a possibility that the lack of opportunity to record both eye's movements may have obscured the explanation. For example, if asymmetric vergence by the left eye was occurring for some of the target directions this would not have been observed.

Comparison of eyetracker calibrations (Appendix III) between before and after calibrations showed close correspondence between the scaling information (horizontally 0.004° ± 0.004°, vertically 0.009°± 0.008°) indicating that negligible equipment drift had occurred. Further, the use of relative rather than absolute measures of eye position controlled for shifts in the centre calibration position (horizontally 0.26° ± 0.25°, vertically 0.47° ± 0.29°). Hence, it is unlikely that the lack of differences between subject's ocular responses for each of the conditions can be attributed to equipment measurement problems.

Experiment 2

Introduction

A second potential explanation of the finding in chapter five is that concomitant with the subjects' vergence responses, their accommodation level also changed through the accommodation-vergence cross link (Semmlow & Hung 1983), thus increasing retinal blur, which then acted as a stimulus to maintain the subjects' near responses in the depth plane of the display. As a corollary to test this hypothesis the experiment in chapter five was repeated using display stimuli, modified by blurring, to remove any accommodative feedback to vergence. Similarly, subjects viewed the display monocularly to remove feedback to the vergence response from resultant changes in retinal disparity. A sudden-onset and constant display paradigm were used in order to determine the influence of the time available to develop a 3D percept capable of affecting ocular motor behaviour.

Eye movement recording of both the viewing and the covered eye (monocular viewing conditions) was conducted to allow for the possibility of the ocular movement, responsible for shifting the binocular point of foveation between two depth planes, occurring predominantly in one eye. Previous evidence (Enright 1987b) suggests that vergence eye movements, produced in response to monocular, perspective depth cues, are predominantly the result of movements in the covered eye.

In summary, this experiment investigated whether a target on a perspective background, would result in disconjugate saccades (and/or vergence eye movements), under monocular viewing conditions. Ocular responses were monitored in either the viewing or the covered eye. The accommodative vergence loop was opened and two display paradigms were used, sudden-onset and constant. Four target directions were chosen.

Method

Subjects

Two subjects with normal visual acuity (near and far) participated. The muscle balance (Maddox Wing test) of each subject was normal. Both subjects had stereo acuity of better than 40 seconds of arc (Titmus). Subject JS had not participated in eye movement experiments before and was naive as to the purpose of the study whereas subject IG was an experienced subject. Subject JS was right eye dominant and subject IG was left eye dominant.

Stimuli

The stimuli were identical to those used in the main experiment in chapter five, except that they were blurred (which we considered sufficient to open the accommodative vergence loop) using a low pass filter (Enhance 2.0, 3x3 convolution mask).

Two display paradigms were used, sudden-onset (target location unpredictable) and constant (target location predictable). In the first, each display was presented for 2.5 seconds with a 2 second "rest" period in between each presentation. Subjects were asked to look, as quickly and as accurately as possible, from the initial fixation point to the white dot in the centre of the target square and to continue to look at the target square until it disappeared (verbatum instructions in appendix IV). In the second, each display was presented for 20 seconds with a 2 second "rest" period in between each presentation. Subjects were asked to look back and forward between the central fixation cross and the square target on a voice command spending approximately 2.5 seconds at each location (verbatum instructions in appendix V).

Each subject viewed the displays monocularly under both right eye (covered eye recorded) and left eye (viewing eye recorded) covered conditions.

Eye movement recording and analysis

Techniques of eye movement recording and analysis were identical to those used in chapter five, except that a mouth bite (dental impression of subject's teeth) rather than a chin rest was used to stabilize subjects' heads.

Results

Subjects reported that in the perspective condition the target wall did appear to come towards them.

In line with previous findings (Collewijn *et al.* 1988a,b), subjects' primary saccade endpoints tended to undershoot the left, right and up targets and overshoot the down targets. Figures 6.1 and 6.2 show the primary saccade and fixation endpoints for subject JS (covered eye recorded, sudden-onset) and subject IG (covered eye recorded, constant).

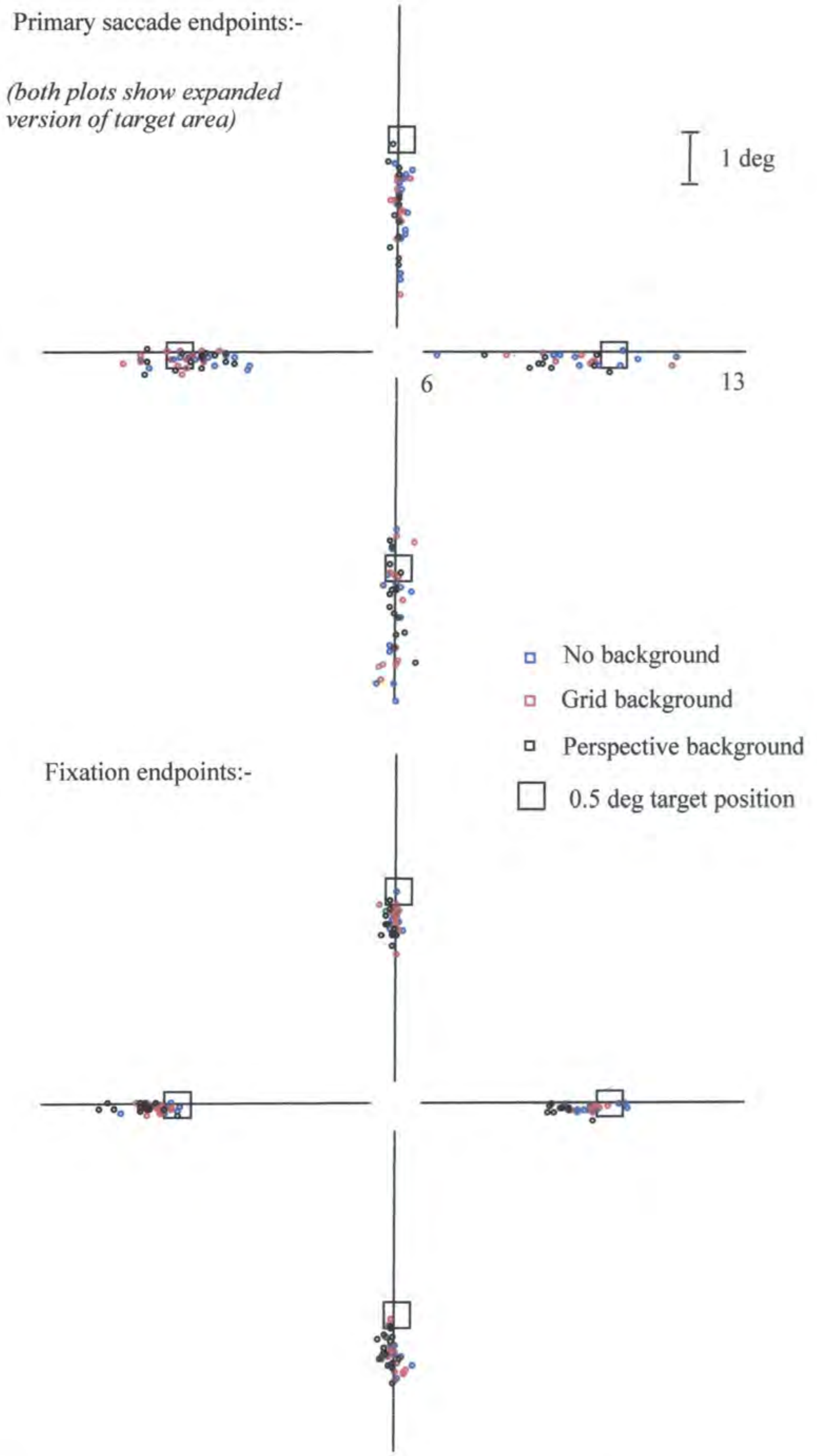

Figure 6.1 Polar plot of primary saccade and fixation endpoints for subject JS (covered eye recorded, sudden-onset).

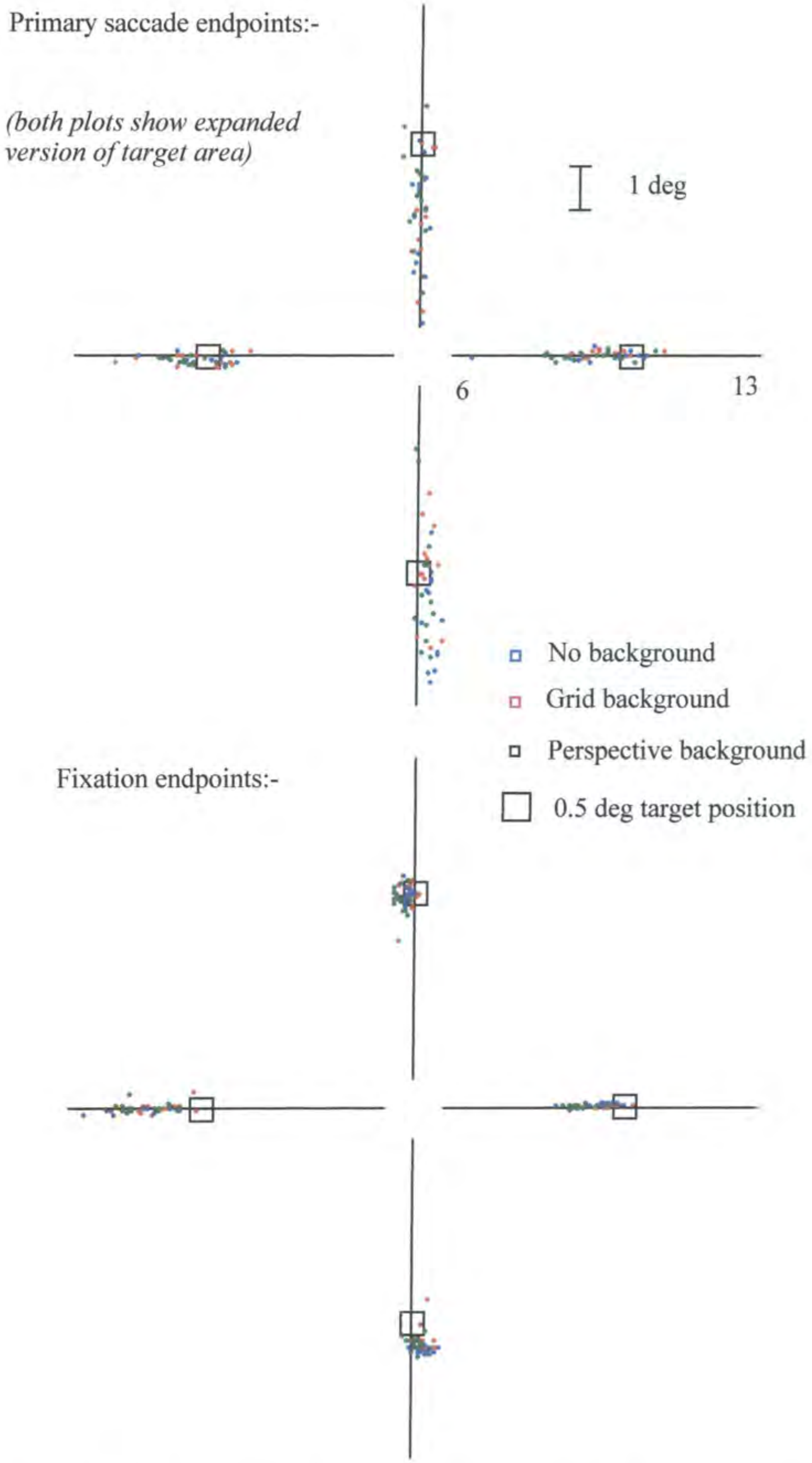

Figure 6.2 Polar plot of primary saccade and fixation endpoints for subject IG (covered eye recorded, constant).

Speed with which the eye's line-of-sight is directed to a particular location

For each subject, a separate one-way ANOVA (repeated measures), investigating differences in primary saccade and fixation direction/amplitude between the background conditions, was carried out. Where differences were found, Fisher's Protected Least Significant Difference (PLSD) post-hoc test was conducted to assess between which conditions the differences occurred. Overall, consistent evidence of convergence toward the perspective target was found under 'covered eye recorded, constant' conditions with subject JS showing the same result under 'covered eye recorded, sudden-onset' conditions. Very limited evidence of disconjugate saccades was found. The results for each display paradigm are presented in the following section.

Saccade disconjugacy

Constant display

The results are plotted in figure 6.3. No evidence of disconjugate saccades was obtained with the exception of the following four instances where significant differences in primary saccade direction/amplitude, between the background conditions, were found:-

(a) under 'viewing eye recorded' conditions for subject JS for right saccades ($F_{2,13} = 4.17$, $P<0.05$) and subject IG for up saccades ($F_{2,14} = 3.21$, $P<0.05$). Both subjects made a significantly more convergent ocular response in the perspective condition compared with the no background condition (PLSD: $F = 0.39$, $P<0.05$ & $F = 0.85$, $P<0.05$ respectively).

(b) under 'covered eye recorded' conditions for subject JS for up saccades ($F_{2,14} = 13.3$, $P<0.01$) and subject IG for down saccades ($F_{2,13} = 3.48$, $P<0.05$). Subject JS made a significantly more convergent ocular response toward up targets in the perspective condition compared with the no background or grid control conditions. Further, subject JS made a more convergent ocular response in the grid background condition compared with the no background condition (PLSD: $F = 1.16$, $P<0.05$). Subject IG made a more convergent ocular response in the perspective background condition compared with the grid control background condition (PLSD: F = 1.25, $P<0.05$).

Sudden-onset display

No significant differences in primary saccade direction/amplitude were found between the background conditions with three exceptions. The results are tabulated in tables 6.9 - 6.12 and are plotted in figure 6.3. The exceptions are as follows:-

(a) under 'viewing eye recorded' conditions, subject JS ($F_{2,21} = 13.46$, $P<0.01$) made a more divergent ocular response toward left targets in the perspective background condition compared with the grid and no background control conditions (PLSD: F = 0.42, $P<0.05$).

(b) under 'covered eye recorded' conditions, subject JS ($F_{2,13} = 5.64$, $P<0.01$) made a more convergent ocular response toward up targets in the perspective condition compared with the no background condition and in the grid condition compared with the no background condition (PLSD: F = 1.4, $P<0.05$). Subject IG ($F_{2,13} = 6.92$, $P<0.01$) made a more convergent ocular response toward right targets in the perspective condition compared with the no background and grid control background conditions (PLSD: F = 0.39, $P<0.05$).

Vergence

Constant display

The results are plotted in figure 6.5. Evidence of consistent convergence was found, in the perspective background condition compared with the grid and background control conditions, under 'covered eye recorded' conditions for both subjects (tables 6.7 & 6.8). However, under 'viewing eye recorded' conditions (tables 6.5 & 6.6), convergence was only shown by subject JS (ANOVA: $F_{2,14} = 3.54$, $P<0.05$) toward right targets in the perspective condition compared with the grid condition (PLSD: F = 0.14, $P<0.05$). In contrast, a divergent response was shown by subject JS toward up targets (ANOVA: $F_{2,14} = 5.84$, $P<0.01$) in the perspective and grid conditions compared with the no background condition (PLSD: F = 0.64, $P<0.05$) and toward left targets (ANOVA: $F_{2,14} = 17.54$, $P<0.01$) in the perspective condition compared with the grid and no background conditions (PLSD: F = 0.13, $P<0.05$). Similarly, a divergent response was shown by subject IG toward left targets (ANOVA: $F_{2,14} = 16.28$, $P<0.01$) in the perspective condition compared with the grid and no background conditions (PLSD: F = 0.15, $P<0.05$).

Sudden-onset display

The results are plotted in figure 6.6. Under 'covered eye recorded' conditions, subject JS showed consistent evidence of convergence in the perspective compared with the grid and no background conditions. Table 6.11 shows the ANOVA and PLSD values for each target direction. Conversely, subject IG made a convergent ocular response only toward the right target (ANOVA: $F_{2,13} = 10.53$, $P<0.01$) in the perspective compared with the grid and no background conditions (PLSD: F = 0.26, table 6.12). Under 'viewing eye recorded' conditions, no evidence of convergence toward the perspective target was found. However, both subjects showed a divergent response toward the left target in the perspective compared with the grid and no background conditions. Table 6.9 & 6.10 show the ANOVA and PLSD values.

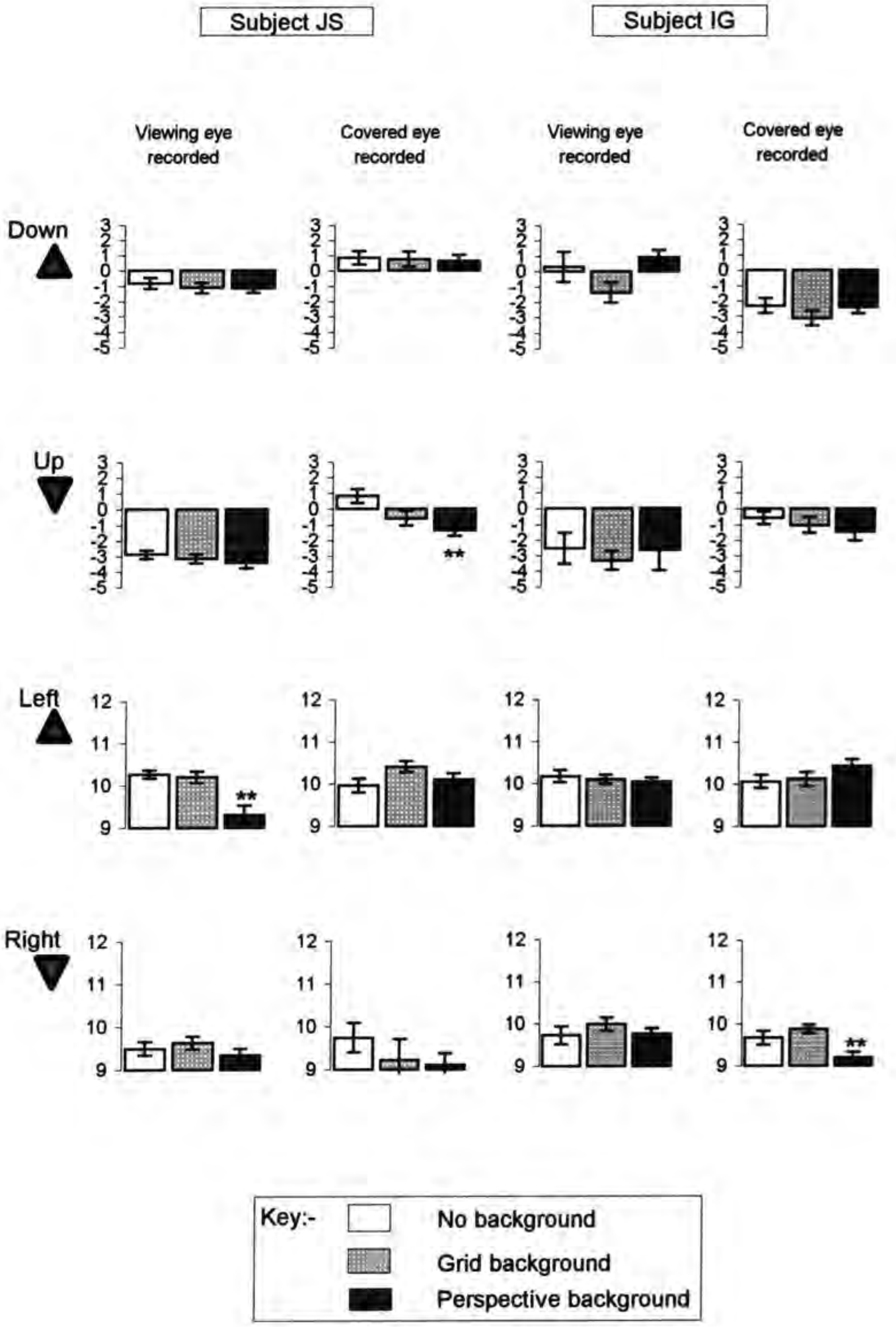

Figure 6.3 Mean primary saccade direction/amplitude (degrees ± s.d.) for sudden-onset display (* $P<0.05$, ** $P<0.01$). Arrows show direction of convergence.

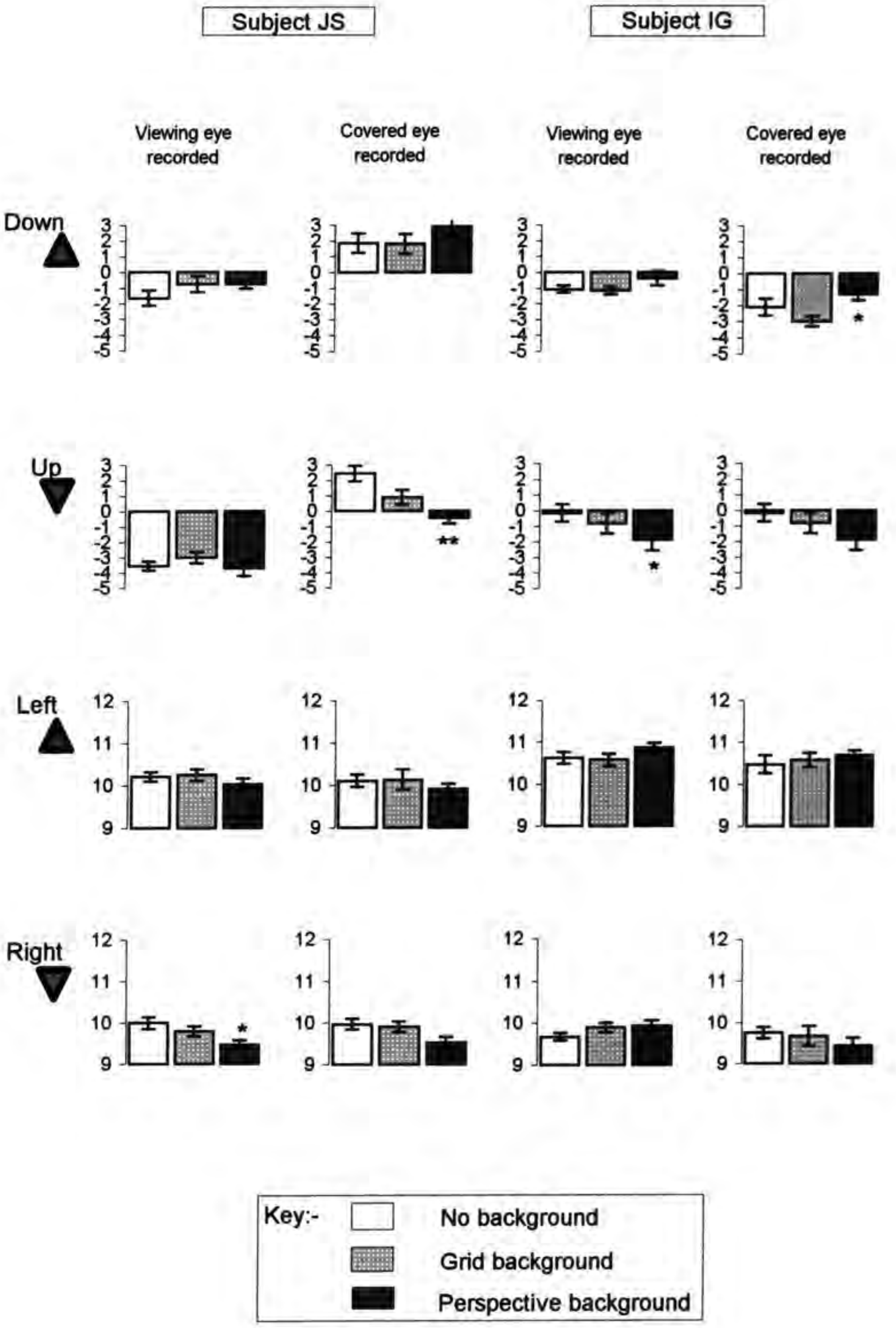

Figure 6.4 Mean primary saccade direction/amplitude (degrees ± s.d.) for constant display (* $P<0.05$, ** $P<0.01$). Arrows show direction of convergence.

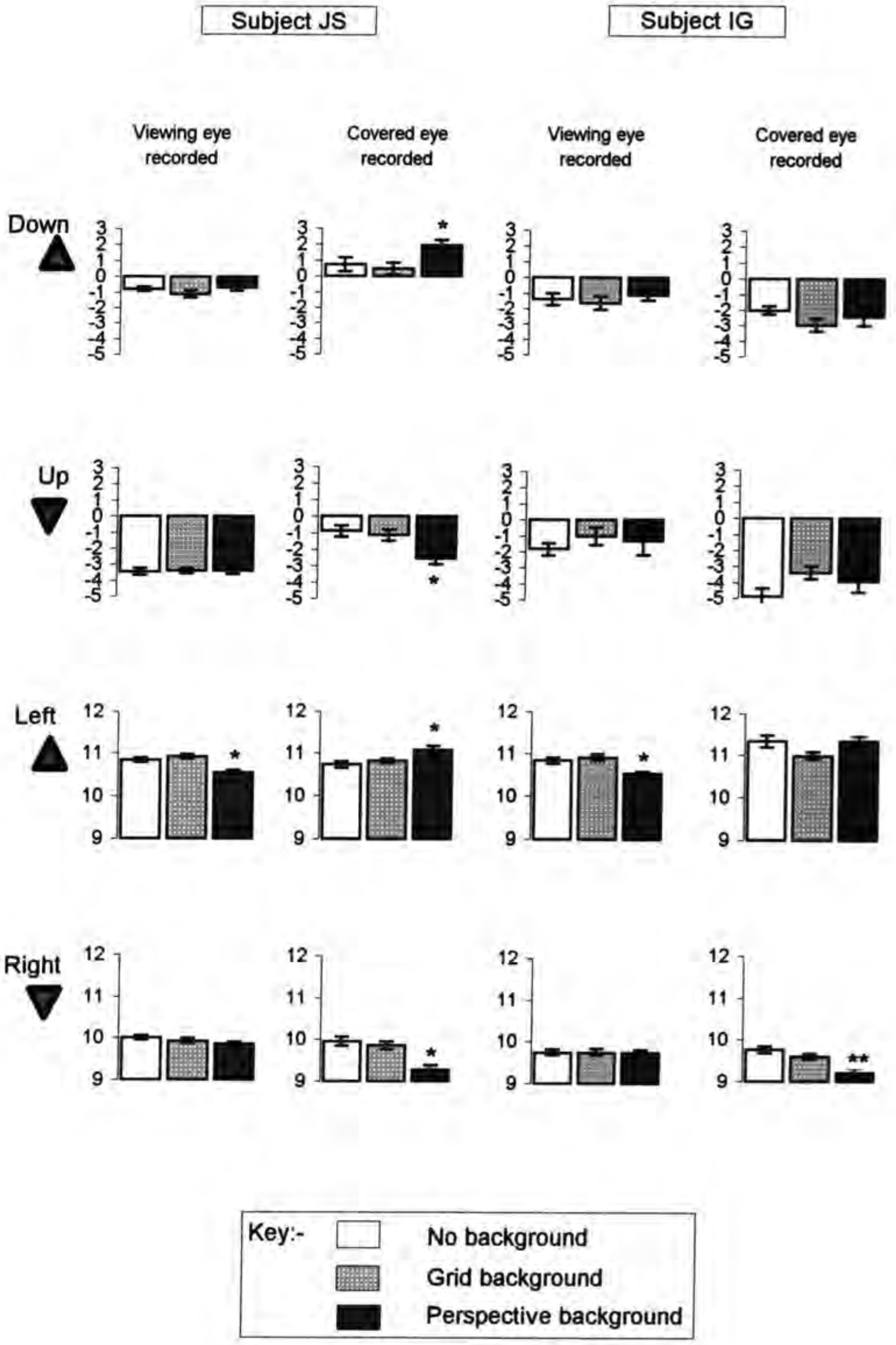

Figure 6.5 Mean fixation direction/amplitude (degrees ± s.d.) for sudden-onset display (* $P<0.05$, ** $P<0.01$). Arrows show direction of convergence.

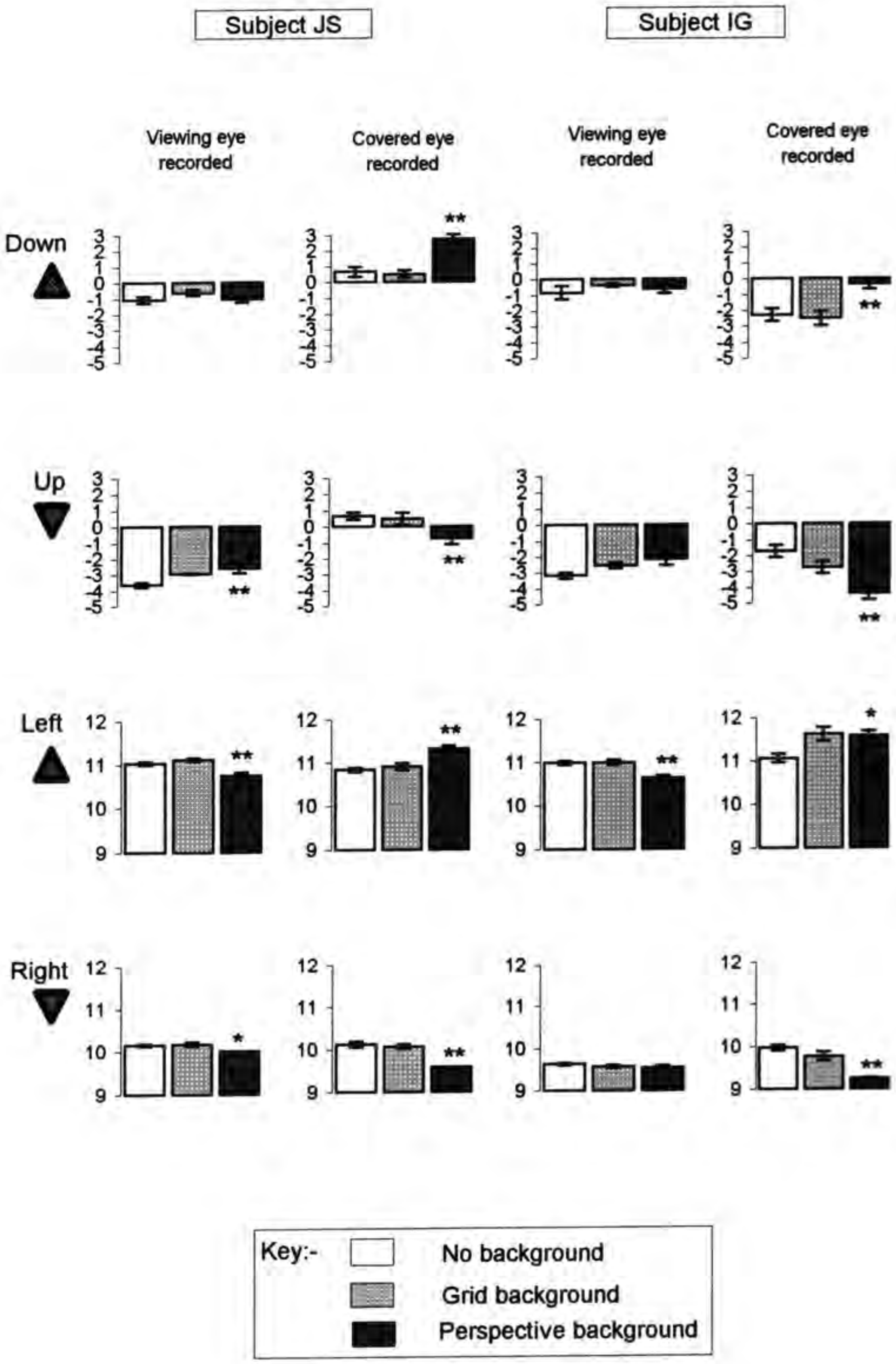

Figure 6.6 Mean fixation direction/amplitude (degrees ± s.d.) for constant display (* $P<0.05$, ** $P<0.01$). Arrows show direction of convergence.

Table 6.5 Eye movement measures for subject JS (viewing eye recorded, constant)

Down saccades	Direction of primary saccade	Direction of ocular response at fixation
No background	178.34 ± 0.48 (1.86, 15)	178.91 ± 0.21 (0.83, 15)
Grid	179.24 ± 0.52 (2.00, 15)	179.36 ± 0.21 (0.81, 15)
Perspective	179.23 ± 0.27 (1.04, 15)	178.93 ± 0.19 (0.74, 15)
	NS	NS
Up saccades		
No background	-3.56 ± 0.31 (1.21, 15)	-3.65 ± 0.16 (0.60, 15)
Grid	-3.00 ± 0.37 (1.45, 15)	-2.94 ± 0.04 (0.17, 15)
Perspective	-3.70 ± 0.52 (2.03, 15)	-2.61 ± 0.31 (1.20, 15)
	NS	$F_{2,14} = 5.84$ $P<0.01$ N:G N:P $P<0.05$ F = 0.64
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation
No background	10.20 ± 0.11 (0.43, 15)	11.02 ± 0.04 (0.17, 15)
Grid	10.25 ± 0.14 (0.53, 15)	11.11 ± 0.04 (0.16, 15)
Perspective	10.03 ± 0.14 (0.54, 15)	10.74 ± 0.06 (0.24, 15)
	NS	$F_{2,14} = 17.54$ $P<0.01$ N:P G:P $P<0.05$ F = 0.13
Right saccades		
No background	9.99 ± 0.15 (0.59, 15)	10.15 ± 0.03 (0.12, 15)
Grid	9.79 ± 0.12 (0.48, 15)	10.17 ± 0.05 (0.20, 15)
Perspective	9.45 ± 0.11 (0.43, 14)	10.01 ± 0.04 (0.15, 15)
	$F_{2,13} = 4.17$ $P<0.05$ N:P $P<0.05$ F = 0.39	$F_{2,14} = 3.54$ $P<0.05$ P:G $P<0.05$ F = 0.14

Key:- mean ± s.e. (s.d., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 6.6 Eye movement measures for subject IG (viewing eye recorded, constant)

Down saccades	Direction of primary saccade	Direction of ocular response at fixation
No background	178.92 ± 0.23 (0.91, 15)	179.14 ± 0.42 (1.61, 15)
Grid	178.84 ± 0.26 (0.96, 14)	179.61 ± 0.12 (0.45, 14)
Perspective	179.61 ± 0.45 (1.74, 15)	179.37 ± 0.26 (1.01, 15)
	NS	NS
Up saccades		
No background	-2.84 ± 0.49 (1.88, 15)	-3.19 ± 0.20 (0.77, 15)
Grid	-1.55 ± 0.33 (1.26, 15)	-2.55 ± 0.18 (0.70, 15)
Perspective	-1.55 ± 0.63 (2.45, 15)	-2.14 ± 0.43 (1.65, 15)
	$F_{2,14} = 3.21$ *P*<0.05 N:P P<0.05 F = 0.85	NS
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation
No background	10.62 ± 0.14 (0.56, 15)	10.98 ± 0.05 (0.18, 15)
Grid	10.57 ± 0.15 (0.57, 15)	10.99 ± 0.06 (0.24, 15)
Perspective	10.86 ± 0.12 (0.46, 15)	10.63 ± 0.06 (0.22, 15)
	NS	$F_{2,14} = 16.28$ *P*<0.01 N:P G:P *P*<0.05 F = 0.15
Right saccades		
No background	9.67 ± 0.09 (0.33, 14)	9.63 ± 0.04 (0.16, 14)
Grid	9.89 ± 0.11 (0.40, 14)	9.57 ± 0.04 (0.17, 14)
Perspective	9.94 ± 0.12 (0.43, 14)	9.54 ± 0.05 (0.17, 14)
	NS	NS

Key:- mean ± s.e. (s.d., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 6.7 Eye movement measures for subject JS (covered eye recorded, constant)

Down saccades	Direction of primary saccade	Direction of ocular response at fixation
No background	181.84 ± 0.62 (2.41, 15)	180.66 ± 0.30 (1.15, 15)
Grid	181.79 ± 0.62 (2.34, 14)	180.51 ± 0.23 (0.87, 14)
Perspective	182.90 ± 0.47 (1.84, 15)	182.76 ± 0.28 (1.07, 15)
	NS	$F_{2,13} = 18.56$ $P<0.01$ N:P G:P $P<0.05$ F = 0.86
Up saccades		
No background	2.43 ± 0.51 (1.97, 15)	0.66 ± 0.22 (0.87, 15)
Grid	0.90 ± 0.48 (1.85, 15)	0.48 ± 0.37 (1.43, 15)
Perspective	-0.48 ± 0.37 (1.43, 15)	-0.73 ± 0.38 (1.48, 15)
	$F_{2,14} = 13.3$ $P<0.01$ N:G N:P G:P $P<0.05$ F = 1.16	$F_{2,14} = 6.33$ $P<0.01$ N:P G:P $P<0.05$ F = 0.14
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation
No background	10.10 ± 0.14 (0.53, 15)	10.83 ± 0.05 (0.19, 15)
Grid background	10.13 ± 0.24 (0.93, 15)	10.90 ± 0.08 (0.32, 15)
Perspective background	9.90 ± 0.13 (0.49, 15)	11.32 ± 0.07 (0.28, 15)
	NS	$F_{2,14} = 15.45$ $P<0.01$ N:P G:P $P<0.05$ F = 0.20
Right saccades		
No background	9.96 ± 0.13 (0.44, 12)	10.12 ± 0.07 (0.23, 12)
Grid	9.90 ± 0.13 (0.49, 15)	10.07 ± 0.05 (0.19, 15)
Perspective	9.52 ± 0.14 (0.53, 15)	9.59 ± 0.07 (0.29, 15)
	NS	$F_{2,11} = 19.3$ $P<0.01$ N:P P:G $P<0.05$ F = 0.19

Key:- mean ± s.e. (s.d., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 6.8 Eye movement measures for subject IG (covered eye recorded, constant)

Down saccades	Direction of primary saccade	Direction of ocular response at fixation
No background	177.89 ± 0.53 (2.06, 15)	177.69 ± 0.40 (1.56, 15)
Grid	176.99 ± 0.32 (1.18, 14)	177.47 ± 0.47 (1.74, 14)
Perspective	178.70 ± 0.38 (1.46, 15)	179.65 ± 0.35 (1.34, 15)
	$F_{2,13} = 3.48$ $P<0.05$ G:P $P<0.05$ F = 1.25	$F_{2,13} = 8.08$ $P<0.01$ N:P G:P $P<0.05$ F = 1.30
Up saccades		
No background	-0.17 ± 0.57 (2.22, 15)	-1.72 ± 0.39 (1.52, 15)
Grid	-0.84 ± 0.66 (2.48, 14)	-2.75 ± 0.37 (1.39, 14)
Perspective	-1.87 ± 0.72 (2.61, 13)	-4.40 ± 0.43 (1.54, 13)
	NS	$F_{2,12} = 11.24$ $P<0.01$ N:P G:P $P<0.05$ F = 1.10
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation
No background	10.47 ± 0.21 (0.79, 14)	11.06 ± 0.10 (0.39, 14)
Grid	10.57 ± 0.17 (0.62, 13)	11.61 ± 0.16 (0.58, 13)
Perspective	10.69 ± 0.11 (0.43, 14)	11.58 ± 0.11 (0.41, 14)
	NS	$F_{2,12} = 4.81$ $P<0.05$ N:G N:P $P<0.05$ F = 0.37
Right saccades		
No background	9.75 ± 0.14 (0.56, 15)	9.97 ± 0.07 (0.28, 15)
Grid	9.67 ± 0.24 (0.91, 14)	9.77 ± 0.10 (0.38, 14)
Perspective	9.43 ± 0.19 (0.71, 14)	9.25 ± 0.05 (0.20, 14)
	NS	$F_{2,13} = 23.32$ $P<0.01$ N:P G:P $P<0.05$ F = 0.22

Key:- mean ± s.e. (s.d., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 6.9 Eye movement measures for subject JS (viewing eye recorded, sudden onset)

Down saccades	Direction of primary saccade	Direction of ocular response at fixation
No background	179.16 ± 0.36 (1.67, 22)	179.21 ± 0.15 (0.68, 22)
Grid	178.86 ± 0.36 (1.68, 22)	178.89 ± 0.22 (1.04, 22)
Perspective	178.83 ± 0.29 (1.28, 19)	179.32 ± 0.24 (1.06, 19)
	NS	NS
Up saccades		
No background	-2.87 ± 0.28 (1.30, 22)	-3.46 ± 0.22 (1.02, 22)
Grid	-3.17 ± 0.30 (1.39, 22)	-3.40 ± 0.17 (0.81, 22)
Perspective	-3.42 ± 0.37 (1.73, 22)	-3.38 ± 0.22 (1.02, 22)
	NS	NS
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation
No background	10.26 ± 0.10 (0.49, 22)	10.84 ± 0.05 (0.23, 22)
Grid	10.19 ± 0.14 (0.67, 22)	10.92 ± 0.06 (0.31, 22)
Perspective	9.30 ± 0.22 (1.02, 22)	10.55 ± 0.05 (0.22, 22)
	$F_{2,21} = 13.46$ *P*<0.01 N:P G:P *P*<0.05 F = 0.42	$F_{2,21} = 13.17$ *P*<0.01 N:P G:P *P*<0.05 F = 0.16
Right saccades		
No background	9.50 ± 0.16 (0.60, 15)	10.00 ± 0.09 (0.33, 15)
Grid	9.63 ± 0.15 (0.51, 11)	9.92 ± 0.08 (0.26, 11)
Perspective	9.33 ± 0.16 (0.54, 12)	9.85 ± 0.08 (0.29, 11)
	NS	NS

Key:- mean ± s.e. (s.d., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 6.10 Eye movement measures for subject IG (viewing eye recorded, sudden onset)

Down saccades	Direction of primary saccade	Direction of ocular response at fixation
No background	180.30 ± 1.00 (3.75, 14)	178.61 ± 0.39 (1.47, 14)
Grid	178.62 ± 0.67 (2.51, 14)	178.34 ± 0.44 (1.66, 14)
Perspective	180.92 ± 0.49 (1.89, 15)	178.86 ± 0.31 (1.19, 15)
	NS	NS
Up saccades		
No background	-2.53 ± 0.99 (3.57, 13)	-1.84 ± 0.39 (1.42, 13)
Grid	-3.33 ± 0.60 (2.09, 12)	-1.01 ± 0.55 (1.91, 12)
Perspective	-2.64 ± 1.31 (4.73, 13)	-1.30 ± 0.88 (3.18, 13)
	NS	NS
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation
No background	10.17 ± 0.14 (0.56, 15)	10.83 ± 0.08 (0.31, 15)
Grid	10.09 ± 0.11 (0.41, 15)	10.90 ± 0.08 (0.31, 15)
Perspective	10.04 ± 0.10 (0.37, 15)	10.53 ± 0.05 (0.20, 15)
	NS	$F_{2,14} = 6.98$ $P<0.01$ N:P G:P $P<0.05$ F = 0.21
Right saccades		
No background	9.73 ± 0.21 (0.75, 13)	9.72 ± 0.09 (0.34, 13)
Grid	9.99 ± 0.15 (0.55, 13)	9.73 ± 0.09 (0.32, 13)
Perspective	9.76 ± 0.14 (0.52, 13)	9.72 ± 0.08 (0.29, 13)
	NS	NS

Key:- mean ± s.e. (s.d., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 6.11 Eye movement measures for subject JS (covered eye recorded, sudden onset)

Down saccades	Direction of primary saccade	Direction of ocular response at fixation
No background	180.87 ± 0.45 (1.75, 15)	180.74 ± 0.43 (1.68, 15)
Grid	180.76 ± 0.50 (1.94, 15)	180.48 ± 0.35 (1.37, 15)
Perspective	180.65 ± 0.40 (1.57, 15)	181.95 ± 0.32 (1.23, 15)
	NS	$F_{2,14}$ = 3.88 $P<0.05$ N:P G:P $P<0.05$ F = 1.15
Up saccades		
No background	0.82 ± 0.43 (1.65, 15)	-0.89 ± 0.33 (1.28, 15)
Grid	-0.60 ± 0.45 (1.75, 15)	-1.13 ± 0.34 (1.33, 15)
Perspective	-1.34 ± 0.39 (1.46, 14)	-2.55 ± 0.35 (1.33, 14)
	$F_{2,13}$ = 5.64 $P<0.01$ N:G N:P $P<0.05$ F = 1.4	$F_{2,13}$ = 6.41 $P<0.01$ N:P G:P $P<0.05$ F = 1.02
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation
No background	9.96 ± 0.17 (0.64, 15)	10.72 ± 0.08 (0.31, 15)
Grid	10.40 ± 0.13 (0.51, 15)	10.81 ± 0.05 (0.21, 15)
Perspective	10.09 ± 0.15 (0.57, 15)	11.07 ± 0.10 (0.40, 15)
	NS	$F_{2,14}$ = 4.45 $P<0.05$ N:P G:P $P<0.05$ F = 0.25
Right saccades		
No background	9.74 ± 0.34 (1.18, 12)	9.94 ± 0.11 (0.39, 12)
Grid	9.22 ± 0.49 (1.47, 9)	9.85 ± 0.09 (0.27, 9)
Perspective	9.11 ± 0.26 (0.79, 9)	9.28 ± 0.10 (0.29, 9)
	NS	$F_{2,8}$ = 8.32 $P<0.01$??

Key:- mean ± s.e. (s.d., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Table 6.12 Eye movement measures for subject IG (covered eye recorded, sudden onset)

Down saccades	Direction of primary saccade	Direction of ocular response at fixation
No background	177.68 ± 0.49 (1.83, 14)	177.97 ± 0.27 (1.03, 14)
Grid	176.85 ± 0.47 (1.81, 15)	177.02 ± 0.41 (1.59, 15)
Perspective	177.56 ± 0.42 (1.58, 14)	177.57 ± 0.60 (2.26, 14)
	NS	NS
Up saccades		
No background	-0.57 ± 0.41 (1.54, 14)	-4.89 ± 0.51 (1.90, 14)
Grid	-1.04 ± 0.50 (1.94, 15)	-3.39 ± 0.40 (1.55, 15)
Perspective	-1.45 ± 0.60 (2.33, 15)	-3.93 ± 0.72 (2.77, 15)
	NS	NS
Left saccades	Amplitude of primary saccade	Amplitude of ocular response at fixation
No background	10.06 ± 0.16 (0.64, 15)	11.33 ± 0.15 (0.58, 15)
Grid	10.12 ± 0.17 (0.63, 13)	10.98 ± 0.09 (0.34, 13)
Perspective	10.43 ± 0.16 (0.63, 15)	11.33 ± 0.12 (0.47, 15)
	NS	NS
Right saccades		
No background	9.67 ± 0.16 (0.61, 14)	9.75 ± 0.08 (0.32, 14)
Grid	9.87 ± 0.10 (0.38, 14)	9.59 ± 0.07 (0.27, 14)
Perspective	9.19 ± 0.14 (0.51, 14)	9.20 ± 0.11 (0.42, 14)
	$F_{2,13} = 6.92$ $P<0.01$ N:P G:P $P<0.05$ F = 0.39	$F_{2,13} = 10.53$ $P<0.01$ N:P G:P $P<0.05$ F = 0.26

Key:- mean ± s.e. (s.d., n). *P* values & F values (NS = not significant) shown for separate one-way ANOVA (repeated measures), for each subject, for each target direction, comparing means between conditions. Where a significant difference was found the significant results of Fisher's LSD post-hoc test comparing pairs of means are shown. For example, N:P indicates that a significant difference was found between the no background and perspective conditions.

Discussion

This experiment investigated whether a constant or sudden-onset perspective display would result in target directed disconjugate saccades (and/or vergence eye movements), under monocular viewing conditions, in the viewing or covered eye, with the accommodative vergence loop open, for 4 different target directions.

Saccade disconjugacy

No consistent evidence of disconjugate saccades, as elicited by linear perspective depth cues, was found in either display paradigm. Exceptions to this statement and anomalous results (italics) are shown in table 6.13.

Table 6.13 Summary of disconjugate saccades toward perspective targets.

	Constant display		Sudden-onset display	
	Viewing eye recorded	Covered eye recorded	Viewing eye recorded	Covered eye recorded
Subject JS	Right targets N:P, 0.44°	Up targets N:P G:P *N:G,* 2.14°, *1.53°*	*Left targets* *P:G N:G, 0.92°* *(divergence)*	Up targets N:P *N:G,* 1.45°, *1.42°*
Subject IG	Up targets N:P, 0.90°	Down targets P:G, 1.71°	--------	Right targets N:P G:P, 0.58°

Key:- N:P indicates that a significant difference in primary saccade amplitude was found between the no background and perspective conditions etc. *Italics* represent an anomalous response. Mean difference in primary saccade amplitude/direction (degrees), between the perspective conditions and the grid + no background condition or no background condition only (as appropriate), shown.

Under constant display and 'viewing eye recorded' conditions, subject JS showed, on average, a 0.44° and subject IG a 0.90° more convergent disconjugate saccade response to right targets and up targets respectively on a perspective background compared with the no background condition (but not the grid control condition).

Under constant display and 'covered eye recorded' conditions, subject JS showed, on average, a 2.14° more convergent disconjugate saccade response to up targets on a perspective background compared with the grid and no background conditions.

Under sudden-onset display and 'covered eye recorded' conditions, subject JS showed, on average, a 1.45° and subject IG a 0.58° more convergent disconjugate saccade response to up and right targets respectively on a perspective background compared with no background and, in the case of subject IG, also to a grid background.

However, under sudden-onset display and 'viewing eye recorded' conditions, neither subject showed any evidence of target directed disconjugate saccades in the perspective condition.

The limited evidence for disconjugate saccades, in the presence of perspective cues, is identical to the results obtained under the experimental conditions in chapter five, even though this experiment was conducted under open-loop accommodative conditions. Hence, the hypothesis that changes in accommodation levels via the accommodation-vergence cross link were responsible for the paucity of disconjugate saccades in chapter five has not been upheld. Misperception of the stimuli is again an unlikely explanation since both subjects showed target-directed vergence under 'covered-eye recording' conditions. The findings provide no support for the idea that insufficient time to develop a 3D percept capable of effecting ocular motor behaviour is an explanation for the paucity of disconjugate saccades found under sudden-onset conditions in this experiment or in chapter five, since increased evidence of disconjugate saccades was not found under constant display conditions. Indeed, the few cases of target-directed disconjugate saccades, shown by each subject, occur in the same (albeit limited) number of target directions for both the sudden-onset and constant display paradigms, suggesting that insufficient time for a 3D percept capable of affecting oculomotor behaviour to develop is not a valid alternative explanation.

However, it is difficult to envisage a plausible explanation to account for their being made in only certain target directions and to account for the anomalous disconjugate saccades and as such the above should be treated with some degree of caution.

Within the scope of this experiment it was not possible to investigate binocular measures with the levels of accuracy provided by the Purkinje Tracker (right eye).

Were this possible a greater insight into the occurrence of disconjugate saccades may have been provided.

Measurement errors are also unlikely to explain the lack of a disconjugate saccade response to perspective depth cues. As stated in chapter five, the Purkinje Tracker is quoted as having an accuracy and resolution of approximately one arc minute and is therefore adequate to measure even small effects. Eyetracker calibrations were conducted before and after each block of trials (appendix II, chapter five). Comparison of the degree per unit values for before and after calibrations showed close correspondence (horizontally 0.006° ± 0.006°, vertically 0.01°± 0.01°) indicating that negligible equipment drift had occurred. Further, the use of relative rather than absolute measures of eye position controlled for shifts in the centre calibration position (horizontally 0.12° ± 0.15°, vertically 0.14° ± 0.07°).

Lastly, Enright (1991) suggests that there would be an advantage to having separate time courses for saccades and vergence (i.e. not having saccade disconjugacy) in allowing for sequential stereopsis. Sequential stereopsis refers to an eye movement strategy of looking back and forth between two objects to enable an improved discrimination of their relative distances. It relies on the two eyes moving conjugately. Saccade disconjugacy, i.e. getting the eyes on target fast, would occur at a cost to this process and may therefore explain why saccade disconjugacy is not a clear cut effect.

Anomalous results

Two types of anomalous results were obtained for certain target directions and display conditions. These are (a) a differential effect of the two control conditions i.e. the grid (texture cues) and no background displays and (b) divergent disconjugate saccades. The specific details are as follows. An effect of the presence of a grid background was obtained. Under 'covered eye recorded' conditions subject JS made, on average, a 1.53° and a 1.42° more convergent disconjugate saccade response, to up targets, on a constant and sudden-onset grid display respectively, compared with the no background display. Also contrary to expectations, subject JS made a 0.92° more divergent disconjugate saccadic response, to left targets, on a perspective display compared with a grid and no background display.

Vergence

Both subjects showed consistent evidence of a convergence response toward the perspective target, in all four directions, under 'covered eye recorded' and constant display conditions. Subject JS showed the same response under sudden-onset display conditions. Both subjects also showed idiosyncratic, convergent responses toward certain perspective target directions under the other display and viewing conditions. A summary of these and various anomalous results obtained (shown in italics) are shown in table 6.14.

Table 6.14 Summary of vergence responses to perspective targets.

	Constant display		Sudden-onset display	
	Viewing eye recorded	Covered eye recorded	Viewing eye recorded	Covered eye recorded
Subject JS	Right targets P:G, 0.16° *Up targets P:N G:N (div):0.68°* *Left targets P:G P:N (div):0.32°*	All target directions P:G P:N Left: 0.45° Right: 0.50° Up: 1.3° Down: 2.17°	*Left targets N:P P:G (div):0.33°*	All target directions P:G P:N Left: 0.30° Right: 0.61° Up: 1.54° Down: 1.34°
Subject IG	*Left targets P:G P:N (div):0.35°*	All target directions P:G P:N Left: 0.24° Right: 0.62° Up: 2.16° Down: 2.07°	*Left targets P:N G:P (div):0.33°*	Right targets P:G P:N: 0.47°

Key:- N:P indicates that a significant difference in fixation amplitude was found between the no background and perspective conditions etc. *Italics* represent an anomalous response. Mean difference in fixation amplitude/direction (degrees), between the perspective conditions and the grid + no background condition or no background condition only (as appropriate), shown.

From table 6.14 it can be seen that the most consistent evidence of target directed vergence, during the perspective condition, was obtained under 'covered eye recording' and constant display conditions, with both subjects showing the effect. That the effect was not consistently shown under 'viewing eye recorded' conditions for either subject suggests that the majority of vergence was occurring in the covered eye i.e. asymmetrical vergence.

Subject JS also showed the effect under sudden-onset conditions ('covered eye recorded') whereas subject IG did not. Subject JS was right eye dominant whereas subject IG was left eye dominant. This may be relevant to explaining why subject JS showed the effect under the less optimal sudden-onset conditions.

Contrary to expectations, both subjects showed a divergent ocular motor response toward left target directions under 'viewing eye recorded' conditions for both display paradigms.

In summary, target directed vergence was elicited by perspective depth cues under optimal conditions (accommodative loop open and constant display paradigm) whereas target-directed disconjugate saccades were not. Ringach *et al.* (1996) suggested that a vergence response may be produced in accordance with a 3D percept built up from the depth cues available and the results from this experiment confirm that perspective cues may contribute to developing that percept. It might be expected that such a percept would also result in the production of at least some disconjugate saccades. That this was not the case suggests that the depth cues relevant to the production of disconjugate saccades are a subset of those responsible for producing a vergence response. In particular, that binocular viewing is necessary for the production of disconjugate saccades i.e. that disparity information is available.

As discussed in the introductory chapter one, it is generally suggested that disconjugate saccades between targets differing in direction and distance, such as have been shown by Enright (1992) and Erkelens *et al.* (1989a), are produced by one of two mechanisms. Either, by virtue of an interaction between a vergence and saccade subsystem (each subsystem producing symmetric ocular motor responses) or directly by the saccadic system, each eye responding to its own view of the target. Given that perspective depth cues elicited a target directed vergence response under optimal conditions, it would seem reasonable to anticipate that this response would interact with the saccadic subsystem to produce some evidence of disconjugate saccades. Indeed, if the production of disconjugate saccades occurs at the motor neuronal level then the lack of evidence for disconjugate saccades gives credence to the second explanation whereby disconjugate saccades are held to be the result of differences in the visual input to each eye. However, it is currently not determined whether the proposed interaction occurs peripherally (i.e. ocular muscles) or centrally. For example, Mays & Gamlin (1995) hypothesize that during the saccadic facilitation of vergence, the vergence burst neurons are disinhibited by the pontine omnipause neurons, which are involved in initiating saccades. If this is the case, it could be argued at least as a logical possibility, that an interaction between the vergence and saccadic system still occurs but that the vergence response to perspective depth cues is produced by a different collection of neurons, which are not subject to disinhibition by the saccadic system.

7

Comparison of oculomotor responses between natural and stereoscopic targets

Introduction

As discussed in chapter one, one potentially important benefit of presenting information on a HUD/HMD in three dimensions is the consequent decluttering of the information enabling particularly salient parts of the display to be easily and quickly attended to. Retinal disparity is one of the principle depth cues whose use is envisaged to present the information in three dimensions i.e. stereoscopic display. Eye pointing in such an environment requires the measurement of the location of the binocular point of foveation. The binocular point of foveation is the intersection of the two eye's line-of-sight, which occurs provided there is no vertical offset. Lemij & Collewijn (1992) and Collewijn *et al.* (1988b) have demonstrated very good (although not perfect) vertical alignment of the eyes. Hence, the assumption is made that there is an actual point of intersection.

It will also be necessary to compute the location of this point of intersection in real time, i.e. on-line, either continuously or at set points. Within the task of, for example switch designation, a protocol will then need to be decided to determine the sequence of events which signify that the operator actually requires the switch to activate and that they are not just cursorily examining it. Various suggestions have been put forward. For example, the operator may be required to fixate the switch for several seconds or to press a confirm button when they believe they are fixating the switch.

In order to determine the feasibility of either of these tasks, from a practical point of view, it is necessary to characterise the accuracy of placement of the binocular point of foveation, when a subject is asked to fixate a target in a particular direction and at a particular distance. Such a task requires that the subject makes both saccadic and vergence eye movements. Whilst saccadic eye movements take several hundred milliseconds to complete, vergence eye movements, which relocate the distance of the binocular point of foveation, are thought to take up to one second, although recent data concerning the speed of binocular re-fixation between targets, which are at different directions as well as distances from initial fixation (i.e. asymmetric gaze-shifts), suggests that the time to completion may be faster (Enright 1984, Erkelens *et al.* 1989a). However, it is not evident at which point in time, after re-fixation, the location of the binocular point of foveation should be determined as representative of on-target fixation. Whereas the point of fixation after a saccade, i.e. the time of saccade off-set, can be relatively unambiguously defined in velocity criteria, due to the high accelerations achieved by the eye, the point of fixation after a vergence movement, i.e. vergence off-set, is more ambiguous due to its slower velocity. Work, which has examined the vergence response from a theoretical framework, often circumvents this problem by considering the peak velocity of the vergence response (for example, Hung *et al.* 1994). As a result of focusing on velocity measures there is a paucity of information concerning the accuracy of the vergence response in terms of amplitude off-set from the target location at fixation. Collewijn *et al.* (1997) have defined the vergence response as completed, in the context of an asymmetric gaze-shift, when its velocity falls below 5°/sec (after the occurrence of a saccade). However, they concentrated on intra-saccadic events rather than fixation and hence did not provide explicit accuracy information.

Further, there are limited data concerning the efficiency and accuracy of binocular re-fixation between targets under 'natural' conditions i.e. targets with multiple depth cues available, against which to compare vergence performance to stereoscopic targets. Previous work has concentrated on eliciting vergence to single, isolated depth cues and has shown that retinal disparity (Westheimer & Mitchell 1956), image blur (Alpern & Ellen 1956; Enright 1986), change in size (looming) (Erkelens & Regan 1986; McLin *et al.* 1988), the kinetic depth effect (Ringach *et al.* 1996) and linear perspective (Enright 1987a, 1987b) were capable of independently evoking a vergence response. Erkelens *et al.* (1989a, 1989b) were the first to study vergence under natural binocular conditions. They showed that a more efficient vergence response (in terms of velocity) occurs under natural viewing with real targets in real depth, both in the mid-line (symmetric) and when involving a direction change (asymmetric), compared with disparity only conditions. They obtained vergence velocities of up to 100°/s compared with 20°/s found previously under disparity only conditions (Rashbass & Westheimer 1961; Erkelens 1989a). However, this study utilised a limited number of target positions, within the range of binocular viewing. In particular, their asymmetric condition assessed only one configuration, a target vergence change of 11° combined with a 45° change in direction.

More recently, Collewijn *et al.* (1995, 1997) have published data, measured by the accurate and precise scleral sensor-coil technique, concerning symmetric and asymmetric gaze-shifts, for a large range of target distances and directions. They focused on the intra-saccadic component of the gaze-shift, examining both the dynamics of version and vergence and the trajectories of the binocular fixation point. Their predominant findings were that symmetric gaze-shifts contain an intra-saccadic, transient divergence commencing coincident with the saccade start, and amounting to half a degree for ten degree saccades, the amount increasing with increasing vergence and version demand up to several degrees. The divergence was corrected for by a subsequent intra-saccadic convergence response, giving rise, overall, to an outward curving intra-saccadic trajectory. For far targets (vergence demand 5°) there was negligible saccade disconjugacy by the saccade end. However, for near targets (vergence demand 25°) the intra-saccadic divergence was not compensated for until after the saccade end, resulting in saccade disconjugacy and therefore retinal disparity for up to 40 msec subsequent to the saccade. The transient divergence is thought to result from the typical asymmetry between subjects' adducting and abducting eye movements. Transient divergence (but not the subsequent convergence) was also found during divergent asymmetric gaze-shifts but was absent in convergent asymmetric gaze-shifts. In contrast to symmetric gaze-shifts, the saccadic component of an asymmetric gaze-shift was always preceded by a pre-saccadic, symmetrical vergence component (defined as the vergence change between saccade onset and 200 msec earlier) in the direction of the imminent gaze-shift; its magnitude increasing with increasing vergence demand. However, the direction change toward the new target did not occur until saccade onset. Rather, the pre-saccadic vergence response was in a direction corresponding to the initial fixation target. The pre-saccadic response was larger for divergence than convergence.

In contrast to the above work, the present experiment was driven by practical considerations relevant to eye pointing. Its overall aim was to examine the pattern of eye movements between continuously visible real targets located at a wide range of distances and directions, in order to determine the pattern of natural viewing, paying particular attention to the post-saccadic response and accuracy of fixation. This is in contrast to the work by the authors outlined above, whose primary aim was to characterise the intra-saccadic component of conjugate and non-conjugate gaze-shifts. The present findings would then provide a baseline against which to compare and contrast the pattern of eye movements to the same selection of targets presented on a stereoscopic display.

Voluntary re-fixations, where the target position is predictable, were studied in order to provide the best conditions for accurate and efficient binocular re-fixations. For example, Lemij & Collewijn (1989) found an improvement in the accuracy of primary saccades to predictable targets compared with unpredictable targets. Findlay and Harris (1993) reported less saccade disconjugacy to their sudden-onset, disparity targets than had previously been reported by both Enright (1986) and Erkelens *et al.* (1989a) for voluntary re-fixations of predictable, real targets at differing distances and directions.

Lastly, the relative influence of two target sizes on binocular fixation and saccade accuracy was assessed. The rationale for this decision was related to the observation that Panum's fusional area increases with increasing target size (Tyler 1973). Therefore, under large target conditions, a less precise vergence response would presumably be required to provide a non-diplopic target view. Two target sizes were utilised in order to determine if this was the case.

In summary, the aims of this experiment were:-

- to examine the pattern of saccadic and vergence eye movements executed by subjects moving their gaze around a sequence of four real targets differing in distance and direction. In particular, to determine subjects' accuracy of binocular fixation of the targets as a function of vergence demand and to determine the proportion of any depth change in the location of the binocular point of foveation that occurred during the primary saccade.

- to compare this pattern of eye movements with those made to an identical target layout displayed on a stereoscopic monitor.
- to examine the effect of two target sizes, 0.5° and 1°, on subjects' binocular fixation accuracy, under both stereoscopic and natural viewing conditions.

Method

Subjects

Four subjects with an age range of 25-37, were recruited to participate in the experiment. Subject CF and CM were from the Durham University Psychology Department and subject AT and HH were from British Aerospace Sowerby Research Centre. All subjects had Snellen visual acuity (near and far) of, or better than, 6/6 (20/20) in each eye (normally or after correction). Subject CF and CM participated in the 'real' target condition and subject AT and HH participated in the 'virtual' target condition of the experiment. The muscle balance (Maddox Wing test) of each subject was normal. All subjects had stereo acuity of better than 40 seconds of arc (Titmus). The dominant eye of each subject was ascertained in the following manner. Subjects looked through an aperture (diameter ~3cm) held a few centimeters infront of them so that they were able to see a distant object (such as a light switch) with both eyes open. They then shut their left eye. If they could still see the object they were classed as left eye dominant, otherwise they were classed as right eye dominant.

Visual Conditions

Two target configurations were constructed. One consisted of sets of targets positioned in 3D space at different distances and in different directions ('real' targets). The other was a replica target configuration, created on a 2D computer display and presented via shuttering glasses, in 3D virtual space i.e. only disparity cues to depth available ('virtual' targets). Stereographics Crystaleyes shutter glasses were used. These had liquid crystal shutters, which were synchronised to the computer display's refresh rate of 120 frames per second via an infra-red transmitter.

The retinal size of the visual targets was held constant. Target sets were repeated using two sizes of visual targets subtending either 0.5° or 1°.

'Real' Targets

The 'real' targets comprised square pieces of card coated with fluorescent paint. The targets were suspended within a black box, which provided a non-structured, uniform, black background on all sides of the targets and removed all ambient light.

Consequently, the only illumination to the targets was from a fluorescent light, situated behind the subject. Target luminance averaged 0.35cd/m^2 and the background luminance was below the photometer's threshold.

'Virtual' targets

The 'virtual' targets comprised white squares on a black background displayed on a 14" VGA colour monitor and were created using the software package Superscape. Target luminance was 1.25cd/m^2 and background luminance was 0.00cd/m^2.

Target arrangement

Targets could be positioned within one of nine depth planes, chosen so as to subtend vergence angles within the range of 2-10°, at either 2°, 1° or 0.5° intervals. Within each depth plane three targets could be positioned so as to require either no change in eye direction i.e. in the midline or a 10° change in direction to the left or right of the midline (figure 7.0). Note that the vergence angles are based on an interocular distance of 65mm. Individual differences in interocular distance will slightly alter the vergence angles but not the target directions. All targets were located in the horizontal plane with the exception of the midline targets, where a vertical offset was introduced so that the targets did not obscure one another. A 1° and 2° offset was found to enable a clear, non-diplopic view of each midline 0.5° and 1° target respectively.

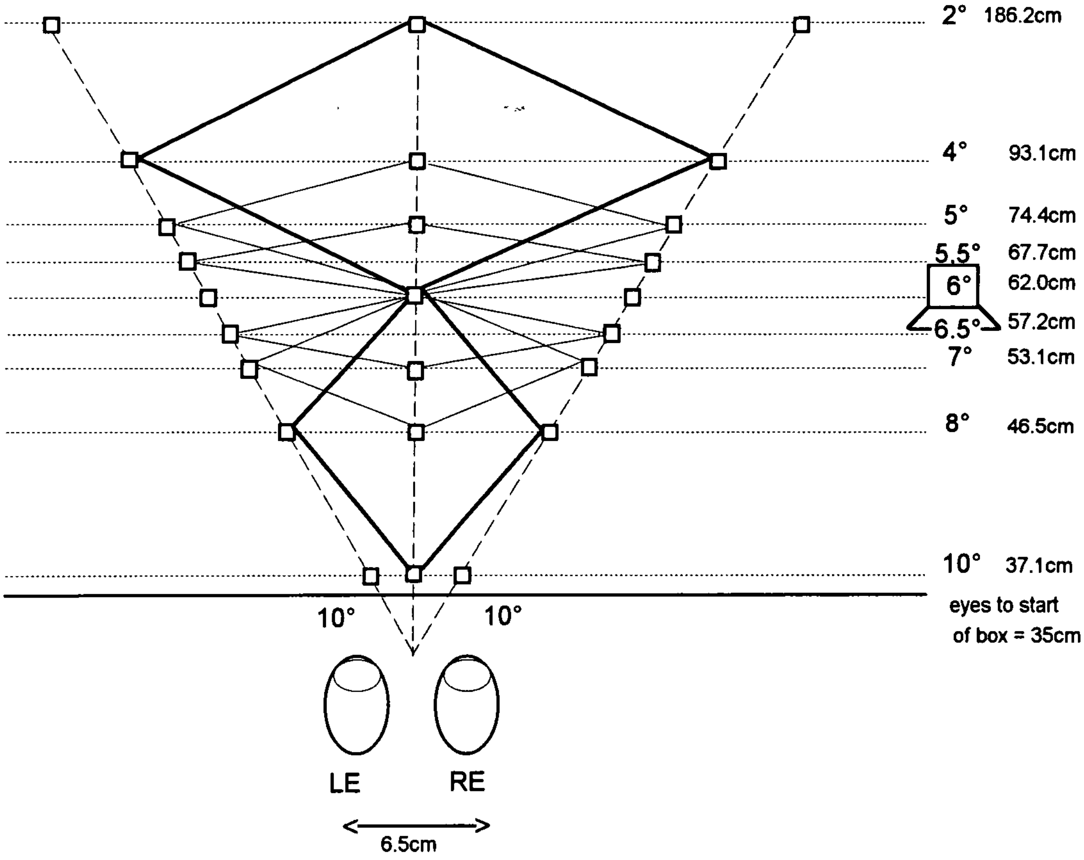

Figure 7.0 Diagram of all target positions, with diamond shaped target sets, requiring combined vergence and version, shown linked by lines.

Subjects were required to sequentially fixate two, three or four targets arranged in a set so as to require either combined vergence and version movements, 'pure' version or 'pure' vergence.

Combined vergence and version target sets

Six different target sets were used, as shown in Figure 7.0. Each set consisted of four targets arranged in a diamond configuration. The first target of each set, where subjects always commenced a trial, was positioned along the midline in the 6° depth plane. Each other target within the set required a direction change about the midline of 10° and convergence or divergence of either 0.5°, 1° or 2°. Differences in direction were arranged about the midline in order to avoid asymmetries in centripetal and centrifugal saccades. Subjects' instructions were to look as quickly and as accurately as possible from the centre of one target to the centre of the next target on the experimenter's command (precise instructions in appendix VI). In any one trial this involved looking around the sequence of four targets in either a clockwise or anti-clockwise direction. On-target time was approximately two seconds for both real and virtual targets.

'Pure' vergence target sets

Six target sets, each consisting of two targets, were positioned along the midline, and therefore, sequential fixation ostensibly only required vergence eye movements. One target was always positioned in the 6° depth plane with the remaining target positioned so as to require convergence and divergence of either 4°, 2° or 0.5°.

'Pure' version target sets

Five target sets, each comprising three targets, were positioned in either the 2°, 4°, 6°, 8° or 10° depth plane. Within each depth plane the targets were positioned in the midline and 10° to either side. Thus sequential fixation required only conjugate saccadic eye movements.

Experimental Procedure

Calibration measurements were carried out before and after each successive block of six trials. Measurements were recorded from nine points in a square configuration each 11cm apart and located at a distance of 57.5cm i.e. at 10.8° intervals. During a trial subjects were required to initially fixate the 6° midline target and then on subsequent voice commands (near, far, left or right) to look, as quickly and as accurately as possible, to the next target indicated, subsequently maintaining fixation at the centre of each target. During the 'real' target sessions, due to the impracticality of changing target sets quickly, each target set was displayed until the subject had repeated this procedure 12 times. Target sets were presented in random order. During the 'virtual' target sessions, trials were presented in random order and limited to 120 per session to reduce bias due to, for example, fatigue. Consequently, each subject attended between six and nine sessions, spread over a one week period, morning and afternoon.

Eye movement recording began at the start of each trial and continued for 12 seconds. For each subject 528 such measurement records were collected and stored for off-line analysis.

Eye movement recording and analysis

Binocular horizontal eye movements were measured, during the 'real' target trials, using the IRIS system manufactured by Skalar Medical. The 'virtual' target trials were conducted at Bae Sowerby Research Centre where a similar system was used to measure subjects' eye movements. Subjects were stabilised on a biteboard to increase the accuracy of eye movement recording.

The subject's eye movements were sampled at 100Hz during the calibration procedure and at 200Hz during the trials. Subjects were asked to refrain from blinking during the trials since blinking causes eye movements. Data were stored off-line for subsequent analysis. The raw data were calibrated i.e. the eye movement units were converted to degrees of eye movement (see appendix VII for the calibration procedure and calculation), the centre fixation cross being defined as 0°. The left calibration target was at -10° and the right calibration target was at +10°.

The following measures were computed using a semi-automated software package. This graphically plotted out the raw data for each eye, on a computer screen, with time along the x-axis and eye movement units along the y-axis:-

- For each eye, the amplitude of the primary saccade from the initial fixation point to the target was measured in degrees. This measure was a conversion of the horizontal and vertical eye movement raw data. For example, the amplitude was calculated as $[(\text{horizontal amplitude})^2 + (\text{vertical amplitude})^2]^{1/2}$. The start of the saccade was defined as the point where the velocity of the eye movement exceeded 15°/sec. The saccade's end was calculated as the point where the velocity of the eye movement decreased below 15°/sec. The software automatically picked out and placed a line cursor at each of these points so that its selection could be checked[1].

- Amplitude (relative to eye position at the start of the primary saccade) of each eye's movement one second after the end of the primary saccade. This will be termed 'fixation'.
- Vergence was calculated as left minus right eye position.
- Disconjugacy was calculated as the change in vergence occurring between the start and end of each saccade.
- Post-saccadic vergence was recorded as the change in vergence occurring between the end of each saccade and fixation (i.e. one second later).

Results

The first consideration in answering the question "do people make accurate vergence responses" is "are the vergence responses in the correct direction i.e. do the subjects converge and diverge appropriately?"

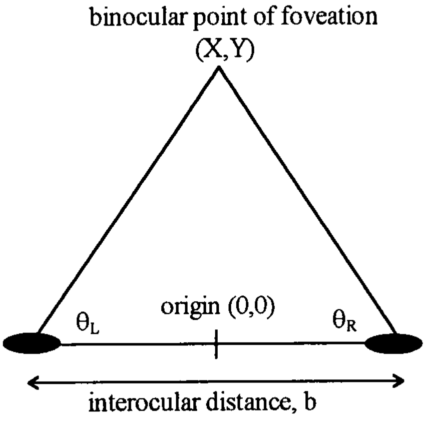

Figure 7.1 Definition of formulae terms

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[1] A primary saccade was deemed to be one whose amplitude was greater than or equal to 30% of the target amplitude. The velocity of this saccade must be greater than 15 degrees/second and its latency greater than 60 msec, i.e. the target was not anticipated.

The binocular point of foveation (X,Y) was calculated, for each fixation during a target set, according to the following formulae:-

$$Y = \frac{b(\tan\theta_R \ \tan\theta_L)}{\tan\theta_R + \tan\theta_L}$$

For leftward looking: $$X = \frac{0.5Y(\tan\theta_R - \tan\theta_L)}{\tan\theta_R \ \tan\theta_L}$$

For rightward looking: $$X = \frac{0.5Y(\tan\theta_L - \tan\theta_R)}{\tan\theta_R \ \tan\theta_L}$$

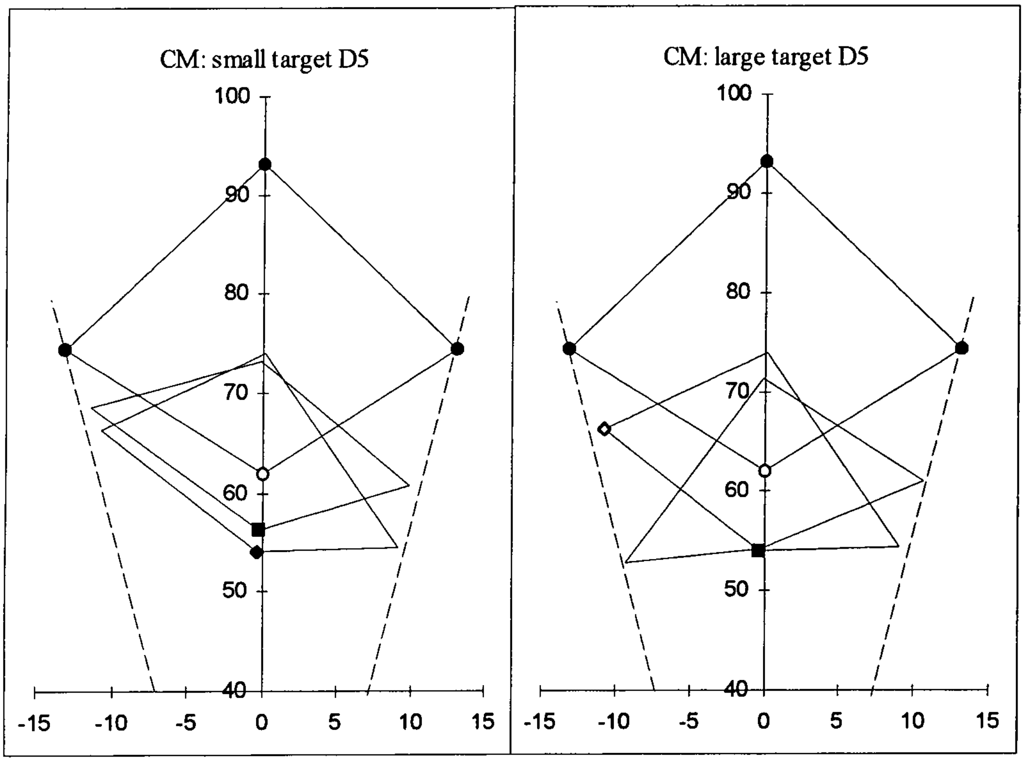
(Fixation = one second after primary saccade end)

Combined vergence and version target sets at fixation

Fixation 'one' corresponded to fixation of the initial target position i.e. the midline target located in the 6° depth plane. The assumption was made that the subject was accurately fixating this initial target position i.e. that the binocular point of foveation was centred over the initial target. θ_L and θ_R represent the recorded average amplitude of the left and right eye movement, respectively, made by each subject to attain fixation of the second target (relative to eye position at the start of the primary saccade to the second target). This position then served as the assumed 'start' position for the next gaze-shift to the third target in the set etc.

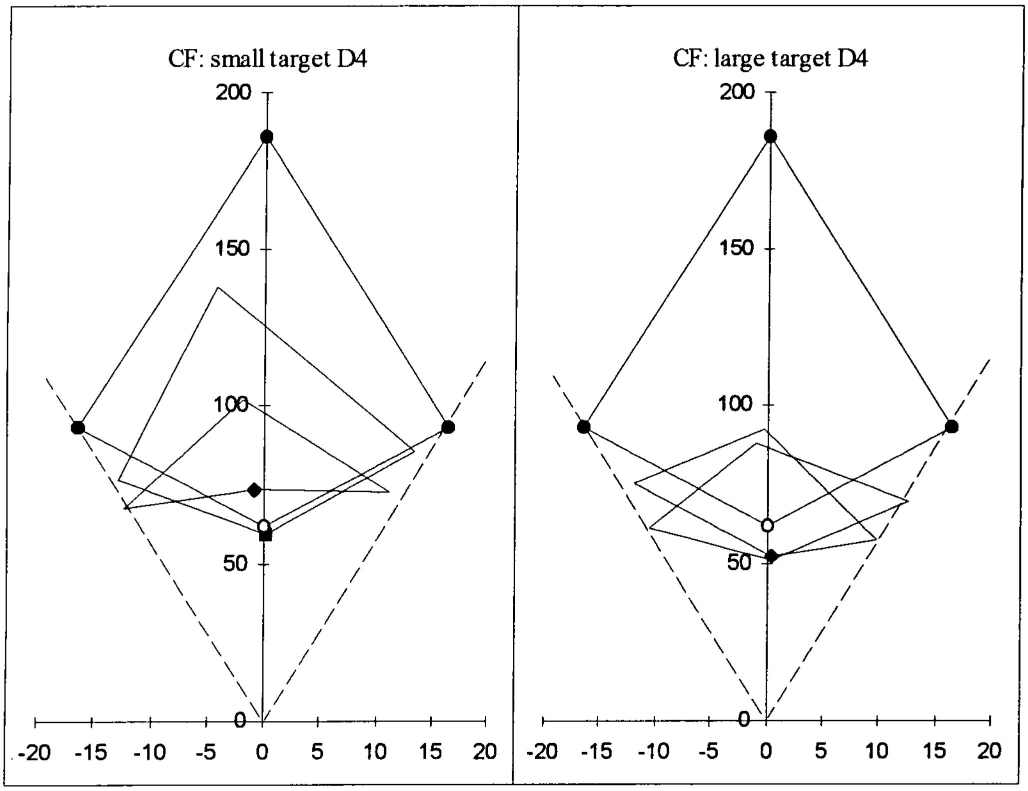
The results of these calculations are plotted separately, for each subject, as an aerial view of the fixation positions against actual target positions (for both clockwise and anti-clockwise directions of looking). Selected examples are shown in Figure 7.2, the full set being in appendix VIII. The ten degree iso-direction trajectory is shown as a dotted line. These graphs show that subjects, when looking around the target sets, converge and diverge appropriately in the majority of cases, only verging inappropriately to 10 out of the 40 target positions. They were no more likely to do so whether the targets were small, large, 'virtual' or 'real'.

‘Real’ targets



Key:-	square:	1st fixation, anticlockwise
	diamond:	1st fixation, clockwise
	white circle:	1st target position
	dark circles:	2nd, 3rd & 4th target positions
	dotted line:	10° iso-direction trajectory

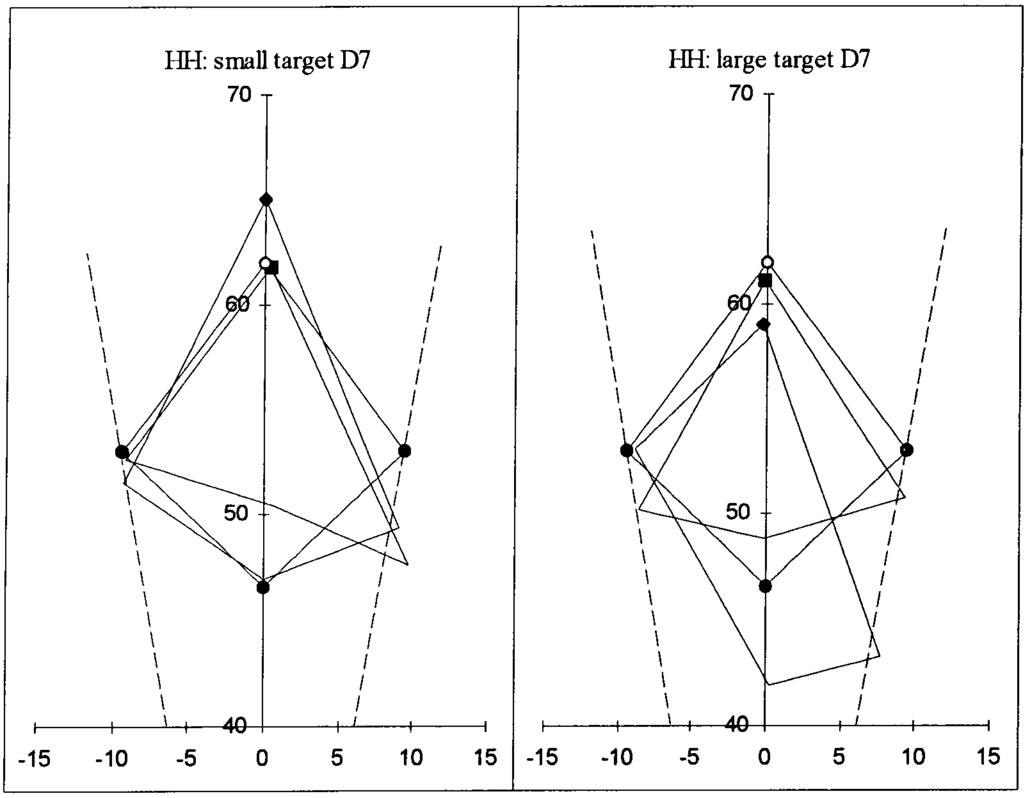
Figure 7.2 Aerial view of fixation locations during combined version/vergence (non-conjugate gaze-shifts) target sets. Scale of both axes is in centimetres.



CF: small target D4

CF: large target D4

‘Virtual’ targets



HH: small target D7

HH: large target D7

Figure 7.2 cont.

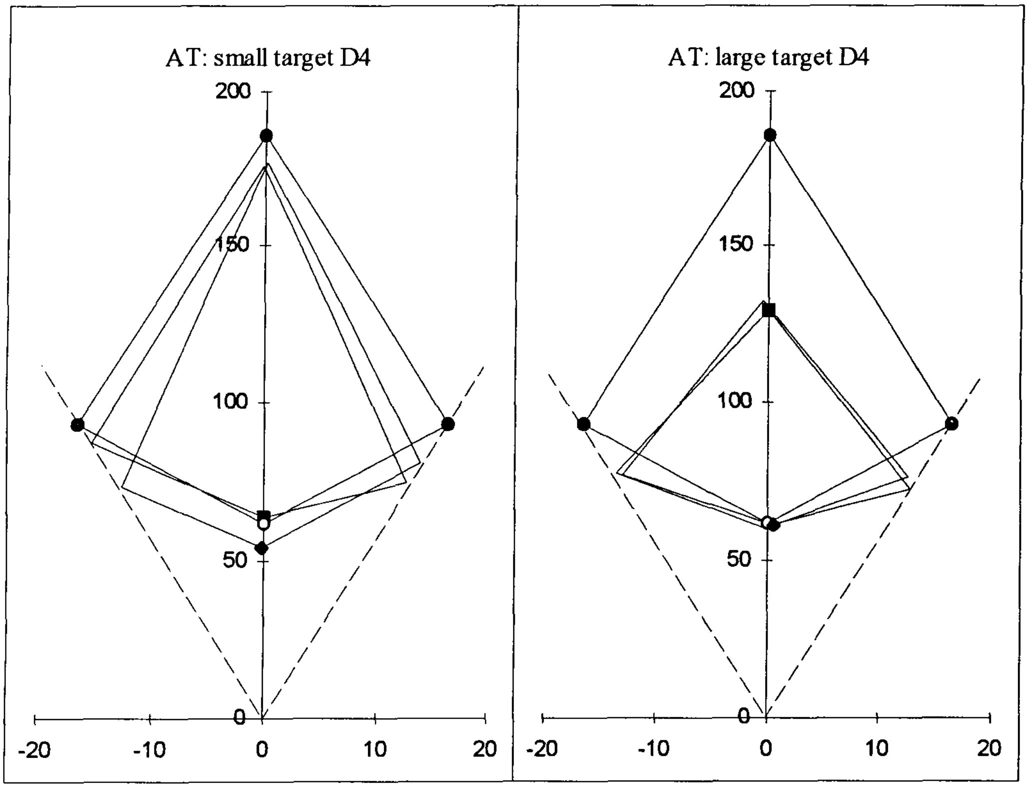


Figure 7.2 cont.

Inspection of the previous graphs suggests that, at fixation, the location of the binocular point of foveation in depth is less accurate than its location in direction. However, calculation of the difference between vergence offset and direction offset values, at fixation, for each subject and condition shows that this is primarily an illusion of scaling. In virtually every case the difference between vergence offset and direction offset was small. Interestingly, there were no differences in fixational accuracy between large and small targets (Table 7.0). Vergence offset was defined as target vergence minus subject vergence and similarly for direction offset.

Table 7.0 Mean difference in accuracy between the vergence and direction component of subjects' oculomotor response at fixation for each target size.

	Mean difference between direction and vergence offsets (deg)	
	small target	large target
CM 'real'	0.58±0.68	0.28±0.70
CF 'real'	-0.10±0.43	0.03±0.77
HH 'virtual'	0.18±0.72	0.32±0.66
AT 'virtual'	0.23±0.45	0.44±0.99

However, subject CM's responses seemed to be anomalous in showing larger vergence offsets. For example, consider subject CM's oculomotor responses to small targets in the diamond configuration, D5.5, in more detail. Figure 7.3 shows two aerial graphs, the first showing all the fixations individually. The second graph displays mean fixations with error bars representing one standard deviation for both direction and distance. The direction (X) and depth (Y) error bars equate to a mean value of 0.45° and 0.71° respectively. The mean offset of subject CM's vergence and direction, at fixation, from each target position are as follows:-

Table 7.1 Accuracy of subject CM's vergence and direction at fixation for D5.5.

Vergence condition	Target vergence[2] (deg)	Subject vergence (deg)	**Vergence offset (deg)**	Target direction (deg)	Subject direction (deg)	**Direction offset (deg)**
5.5	4.51	6.13	**1.62**	10.00	9.67	**0.33**
5	4.23	4.98	**0.75**	0.00	0.08	**-0.08**
5.5	4.51	5.20	**0.69**	-10.00	-8.80	**-1.20**
6	5.08	6.05	**0.97**	0.00	-0.24	**0.24**

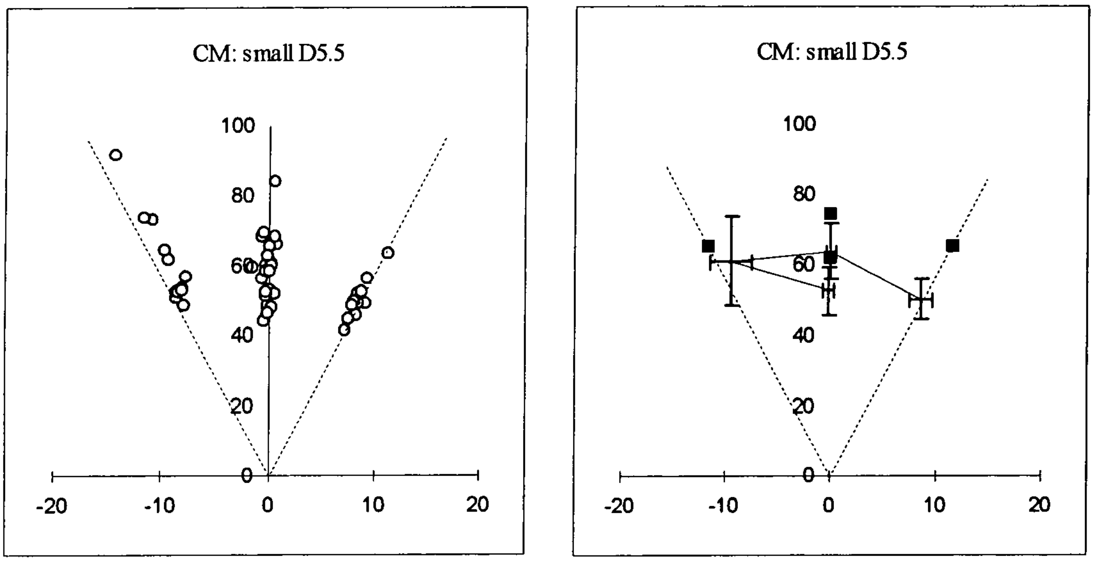


Figure 7.3 Aerial plot of fixation locations for subject CM for D5.5

Overall, in this example, the mean difference between vergence offset and direction offset was 0.8°. The following Table 7.2 details the results of comparisons between before and after calibrations for each subject. It can be seen that relative measures of eye position were accurate (standard deviation of degrees per volt) to within 0.1°. Centre values (V_{centre}), needed to measure absolute eye position, were more variable, with a mean offset of 0.25°. Consequently, assuming linearity across the equipment's measuring range, the measured relative differences in the accuracy with which the binocular point of foveation can be located in direction and distance are sufficiently large in the case of subject CM that they cannot be accounted for by measuring inaccuracies. Further, it is reasonable to assume that if such differences in the

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[2] Note that target vergence is less than 'vergence condition', since it has been scaled to take account of the subject's small intra-ocular distance.

accuracy of oculomotor responses existed for the other subjects, these would have been identified.

Table 7.2 Comparison of before and after calibrations for each subject.

CM		Mean	1 std dev	Max	Min
	V_{centre} (left eye)	0.225006	1.095275	1.908418	-2.75598
	V_{centre} (right eye)	0.088268	1.250089	3.838245	-3.15642
	$V_{horiz.\ scale\ 1}$	0.010935	0.090532	0.341538	-0.20568
	$V_{horiz.\ scale\ 2}$	0.021069	0.127032	0.326087	-0.28367
	$V_{horiz.\ scale\ 3}$	0.034855	0.153347	0.350061	-0.3518
	$V_{horiz.\ scale\ 4}$	0.030692	0.132034	0.243183	-0.52803
CF					
	V_{centre} (left eye)	0.042237	1.536954	3.544776	-2.86207
	V_{centre} (right eye)	0.714193	1.618998	3.47424	-2.5629
	$V_{horiz.\ scale\ 1}$	0.072133	0.136125	0.37153	-0.23256
	$V_{horiz.\ scale\ 2}$	0.039733	0.134759	0.400534	-0.26098
	$V_{horiz.\ scale\ 3}$	0.077018	0.149212	0.44728	-0.19078
	$V_{horiz.\ scale\ 4}$	0.067404	0.157676	0.446369	-0.14949
HH					
	V_{centre} (left eye)	-0.40391	1.263396	2.376	-4.42
	V_{centre} (right eye)	-0.05986	1.075051	3.01	-2.7025
	$V_{horiz.\ scale\ 1}$	0.000132	0.001094	0.009015	-5.6E-05
	$V_{horiz.\ scale\ 2}$	6.12E-07	1.43E-05	0.000056	-0.00003
AT					
	V_{centre} (left eye)	-0.46894	1.061126	1.389657	-4.26476
	V_{centre} (right eye)	-0.02652	1.231179	3.107275	-3.40444
	$V_{horiz.\ scale\ 1}$	-0.0076	0.05499	0.134545	-0.12461
	$V_{horiz.\ scale\ 2}$	0.000663	0.058907	0.119171	-0.10076
	$V_{horiz.\ scale\ 3}$	0.00635	0.060733	0.170141	-0.13034
	$V_{horiz.\ scale\ 4}$	0.019106	0.070249	0.171891	-0.1129

Key:- Refer to appendix VII for an explanation of V_{centre} and $V_{horiz.scale}$

Figure 7.4 shows that there were no time trends, with regards to vergence, across successive trials (between first and second target) i.e. the subject was not progressively converging or diverging. This suggests, accurate fixation of the initial target at the start of each trial.

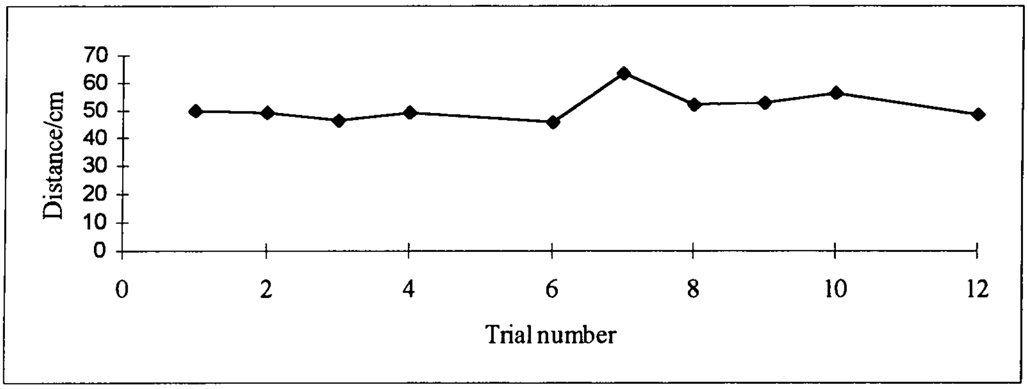

Figure 7.4 Distance (Y) values for successive trials within D5.5 target set, subject CM.

Considering, in more detail, the data from the two subjects who viewed the 'real' targets, the following table shows the mean difference between vergence and direction offsets for midline near and far targets and eccentric targets (note that the data for both large and small targets were pooled, since no effect of target size was found). Subject CM's vergence responses were of decreased accuracy compared with her direction responses, significantly so in the cases of the midline near and far targets ($t_{11} = 2.75$ $P<0.05$ and $t_{11} = 4.28$ $P<0.01$).

Table 7.3 Mean difference in accuracy between subjects' vergence and direction responses at fixation for midline near (Mn), midline far (Mf) and eccentric (E) 'real' targets.

Subject CM	'Real'	Mean difference between vergence and direction offsets (deg)	Subject CF	'Real'	Mean difference between vergence and direction offsets (deg)
	Mn target	0.46±0.58 $t_{11} = 2.75$ $P<0.05$		Mn target	0.00±0.43 NS
	Mf target	0.63±0.51 $t_{11} = 4.28$ $P<0.01$		Mf target	0.05±0.60 NS
	E target	0.31±0.80 NS ($t_{23} = 1.82$ $P<0.08$)		E target	-0.09±0.71 NS

Key:- mean ± s.d. *P* values & t values (NS = not significant) shown for separate t-test (two way, unequal variance) comparing mean difference between vergence and direction offsets with zero.

The following table displays the same variables, for the two subjects who viewed the 'virtual' targets. Both subjects showed similar levels of accuracy with respect to the placement of their binocular point of foveation in the depth and direction for eccentric targets. However, both subjects tended to show a difference in this accuracy toward midline far targets.

Table 7.4 Mean difference in accuracy between subjects' vergence and direction responses at fixation for midline near (Mn), midline far (Mf) and eccentric (E) stereoscopic targets.

Subject HH	'Virtual'	Mean difference between vergence and direction offsets (deg)	Subject AT	'Virtual'	Mean difference between vergence and direction offsets (deg)
	Mn target	0.43±0.86 NS		Mn target	0.55±1.27 NS
	Mf target	0.48±0.88 NS (t_{11} = 1.88 $P<0.08$)		Mf target	0.51±0.79 t_{11} = 2.21 $P<0.05$
	E target	0.04±0.60 NS		E target	0.14±0.68 NS

Key:- mean ± s.d. *P* values & t values (NS = not significant) shown for separate t-test (two way, unequal variance) comparing mean difference between vergence and direction offsets with zero.

Comparison of midline far and near vergence offsets, for each level of vergence demand, showed that each subject consistently converged closer when fixating the far compared with the near midline target.

Table 7.5 Comparison of accuracy of each subject's vergence responses to near and far targets at fixation for vergence intervals of 0.5°, 1° and 2°.

	Vergence offset$_{\text{far target}}$ - Vergence offset$_{\text{near target}}$ (deg)			
	'Virtual' targets		'Real' targets	
Target depth separation	subject HH	subject AT	subject CM	subject CF
1°	0.50±0.23	0.82±0.58	0.53±0.60	0.19±0.24
2°	0.50±0.88	1.44±0.81	0.76±1.27	0.06±0.06
4°	2.95±0.92	2.07±2.20	0.77±0.47	1.32±0.46

Key:- mean ± s.d.

The data in the following table pertain to the accuracy of binocular fixation as a function of vergence demand (0.5°, 1° and 2°). With the exception of subject HH, a difference between the direction and depth component of fixation accuracy was obtained at the 0.5° level of vergence demand. Subject CM and HH also showed such a difference at the 2° level of vergence demand. There were no differences in the precision of binocular fixation between the 'real' targets and the 'virtual' targets.

Table 7.6 Mean difference in accuracy between each subject's vergence and direction responses at fixation for vergence intervals of 0.5°, 1° and 2°.

	Mean difference between vergence and direction offsets (deg) (mean direction offset)		
	0.5° vergence interval	1° vergence interval	2° vergence interval
CM ('real')	0.42±0.67 (-0.06±0.39) $t_{15} = 2.51$ $P<0.05$	0.26±0.71(-0.15±0.56) NS	0.61±0.73 (-0.03±0.64) $t_{15} = 3.33$ $P<0.01$
CF ('real')	-0.27±0.39(-0.31±0.65) $t_{15} = -2.81$ $P<0.01$	-0.05±0.53(-0.27±0.83) NS	0.22±0.80 (0.21±0.80) NS
HH ('virtual')	0.06±0.38 (0.24±0.37) NS	0.09±0.52 (0.31±0.33) NS	0.60±1.10 (0.38±0.40) $t_{15} = 2.17$ $P<0.05$
AT ('virtual')	0.31±0.41 (0.05±0.32) $t_{15} = 2.97$ $P<0.01$	0.15±0.75 (-0.02±0.50) NS	0.54±1.29 (-0.08±0.61) NS

Key:- mean ± s.d. *P* values & t values (NS = not significant) shown for separate t-test (two way, unequal variance) comparing mean difference between vergence and direction offsets with zero.

Combined vergence and version target sets at primary saccade end

Finally, the location of the subjects' binocular points of foveation at the end of each primary saccade within a target set was considered (Table 7.7). Subject CF tended to align her left eye more closely with the target direction for leftward saccades and her right eye more closely for rightward saccades. Subject AT aligned her left eye more closely for leftward saccades but showed no differences in eye alignment for rightward saccades. Neither subject CM or HH tended to align one or other eye more closely with the target direction. There was no correspondence between the pattern of eye alignment and ocular dominance. Subject CF was left eye dominant and subject AT was right eye dominant.

Table 7.7 Mean difference between paired left and right eye target offsets, at primary saccade end, for each subject, separately for leftward and rightward saccades.

Subject	Mean difference between paired left and right eye target offsets (deg)	
	Leftward saccades	Rightward saccades
CM 'real'	0.12±2.04 NS	-0.58±2.19 NS
CF 'real'	0.77±2.28 $P<0.05$ $t_{47} = 2.34$ L_{eye} 0.01±1.49, R_{eye} -0.76±1.30	-0.99±1.91 $P<0.01$ $t_{47} = -3.59$ L_{eye} -0.85±1.16, R_{eye} 0.14±1.26
HH 'virtual'	-0.26±1.75 NS	-0.23±1.66 NS
AT 'virtual'	1.25±1.84 $t_{37} = 4.20$ $P<0.01$ L_{eye} 0.06±1.30, R_{eye} -1.19±1.54	-0.28±1.66 NS

Key:- mean ± s.d. *P* values & t values (NS = not significant) shown for separate t-test (two way, unequal variance) comparing mean difference between left and right eye target offsets with zero.

Table 7.8 shows the mean difference between subjects' "cyclopean" vergence and direction target offsets. They located their binocular points of foveation more accurately with respect to target direction than target depth, the difference being of the order of 0.8°.

Table 7.8 Mean difference between subject's "cyclopean" vergence and direction target offsets, at primary saccade end.

Subjects	Mean difference between "cyclopean eye" vergence and direction offset	Mean "cyclopean eye" direction offset
CM 'real'	0.79±1.34° $t_{43} = 3.91$ $P<0.01$	0.11±0.87°
CF 'real'	0.33±1.11° $t_{47} = 2.05$ $P<0.05$	-0.19±1.01
HH 'virtual'	0.89±1.31 $t_{47} = 4.71$ $P<0.01$	0.32±0.70
AT 'virtual'	1.21±1.43 $t_{47} = 5.90$ $P<0.01$	-0.12±0.89

Key:- mean ± s.d. *P* values & t values (NS = not significant) shown for separate t-test (two way, unequal variance) comparing mean difference between left and right eye target offsets with zero.

Figure 7.5 shows individual mean primary saccade disconjugacies separately for leftward and rightward saccades. Table 7.9 shows the results of the linear regressions for vergence level against saccade disconjugacy for these data. The slopes of the regression lines were in the expected direction i.e. saccade disconjugacy increased linearly with vergence demand. The slopes were significantly different from zero in five cases and approached significance in the three other cases i.e. subjects' disconjugate saccade amplitudes varied according to the level of vergence demand. On average 12% and 18% of the variation in saccade disconjugacy, for leftward and rightward saccades respectively, was explained by a change in vergence level. However, with the exception of subject AT, there was a leftward and rightward saccade asymmetry overlaid on these oculomotor responses. Saccade disconjugacies for leftward saccades were systematically more divergent than those for rightward saccades. This pattern was not associated with eye dominance. For example, subject CM was right eye dominant whereas subject CF was left eye dominant.

Table 7.9 Linear regression results, for leftward and rightward saccades, for each subject.

Subject	Leftward saccades	Rightward saccades
CM ('real')	Disconj. = (0.44 * verg. demand) - 0.76 $r^2 = 0.13$ $P<0.01$	Disconj. = (0.46 * verg. demand) + 0.40 $r^2 = 0.35$ $P<0.01$
CF ('real')	Disconj. = (0.19 * verg. demand) - 0.66 NS ($r^2 = 0.07$ $P=0.06$)	Disconj. = (0.29 * verg. demand) - 0.21 $r^2 = 0.14$ $P<0.01$
HH ('virtual')	Disconj. = (0.14 * verg. demand) - 0.52 NS ($r^2 = 0.08$ $P=0.06$)	Disconj. = (0.22 * verg. demand) - 0.10 $r^2 = 0.14$ $P<0.01$
AT ('virtual')	Disconj. = (0.19 * verg. demand) - 0.55 $r^2 = 0.20$ $P<0.01$	Disconj. = (0.15 * verg. demand) - 0.51 NS ($r^2 = 0.09$ $P=0.06$)

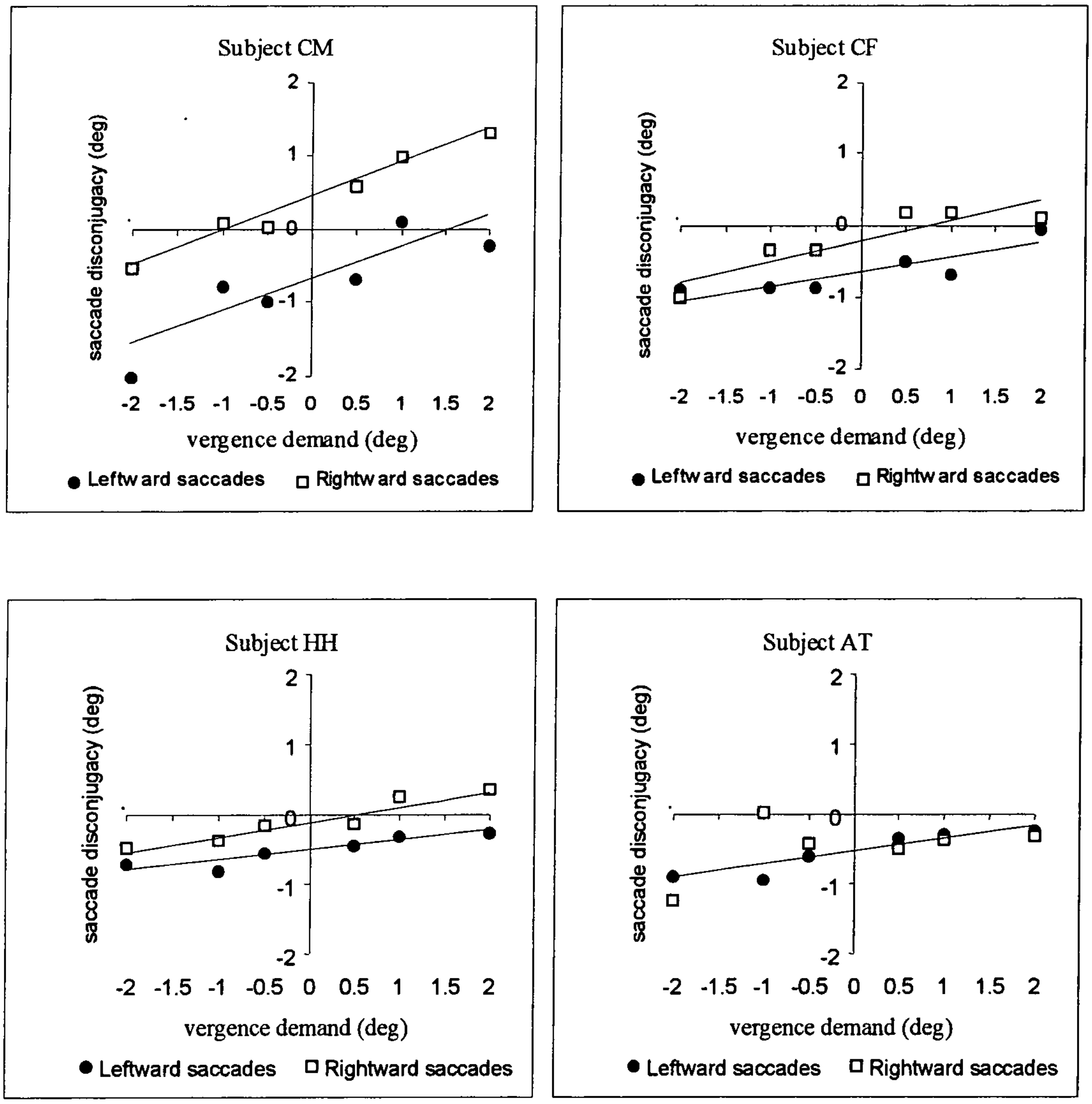

Figure 7.5 Mean saccade disconjugacy, for each level of vergence demand, for leftward and rightward saccades. Linear regression line through leftward and rightward data shown.

‘Pure’ vergence target sets

A representative record of the oculomotor responses shown during a ‘pure’ vergence trial (4° convergence demand) are shown in Figure 7.6. A slow vergence response was confirmed.

Figure 7.6 Oculomotor response to midline targets requiring only ‘pure’ vergence

‘Pure’ version target sets

Figure 7.7 shows an aerial view of binocular fixation positions (eye position one second after the end of the primary saccade) against target positions. The ten degree iso-direction trajectory is shown as a dotted line. Table 7.10 shows the vergence and direction offsets, in degrees, for each vergence level. The subjects, when looking between the ‘pure’ version targets, located their binocular point of foveation, overall, to within 0.5° of the target direction. Their responses were more variable with respect to the depth of the targets, but they were overall within 0.8° of the targets location in depth.

Table 7.10 Vergence and direction offset from target, for each subject, during iso-vergence trials.

	Vergence offset (deg)				Direction offset (deg)			
Vergence level	CM	CF	HH	AT	CM	CF	HH	AT
2°	-0.75± 1.07	-1.77± 1.99	0.03± 0.42	-0.30± 0.50	-0.27± 1.08	-0.62± 0.66	0.01± 0.28	-0.11± 0.24
4°	-0.20± 0.61	-1.04± 0.23	-0.95± 0.04	-0.28± 0.43	-0.15± 1.92	-0.57± 0.59	0.17± 0.69	0.12± 0.54
6°	-0.62± 0.20	-0.79± 0.16	0.83± 1.55	-0.60± 0.80	-0.40± 0.54	-0.25± 0.21	0.46± 0.69	-0.01± 0.53
8°	-0.09± 0.29	-1.78± 0.30	-0.35± 1.49	-0.13± 1.03	0.21± 0.30	-0.44± 0.52	0.05± 0.18	-0.13± 1.08
10°	0.34± 0.93	-1.66± 1.05	-1.07± 0.97	0.35± 1.38	-0.43± 1.43	0.18± 0.36	0.41± 0.61	0.29± 0.90

Key:- mean of leftwards and rightwards saccades ± s.d.

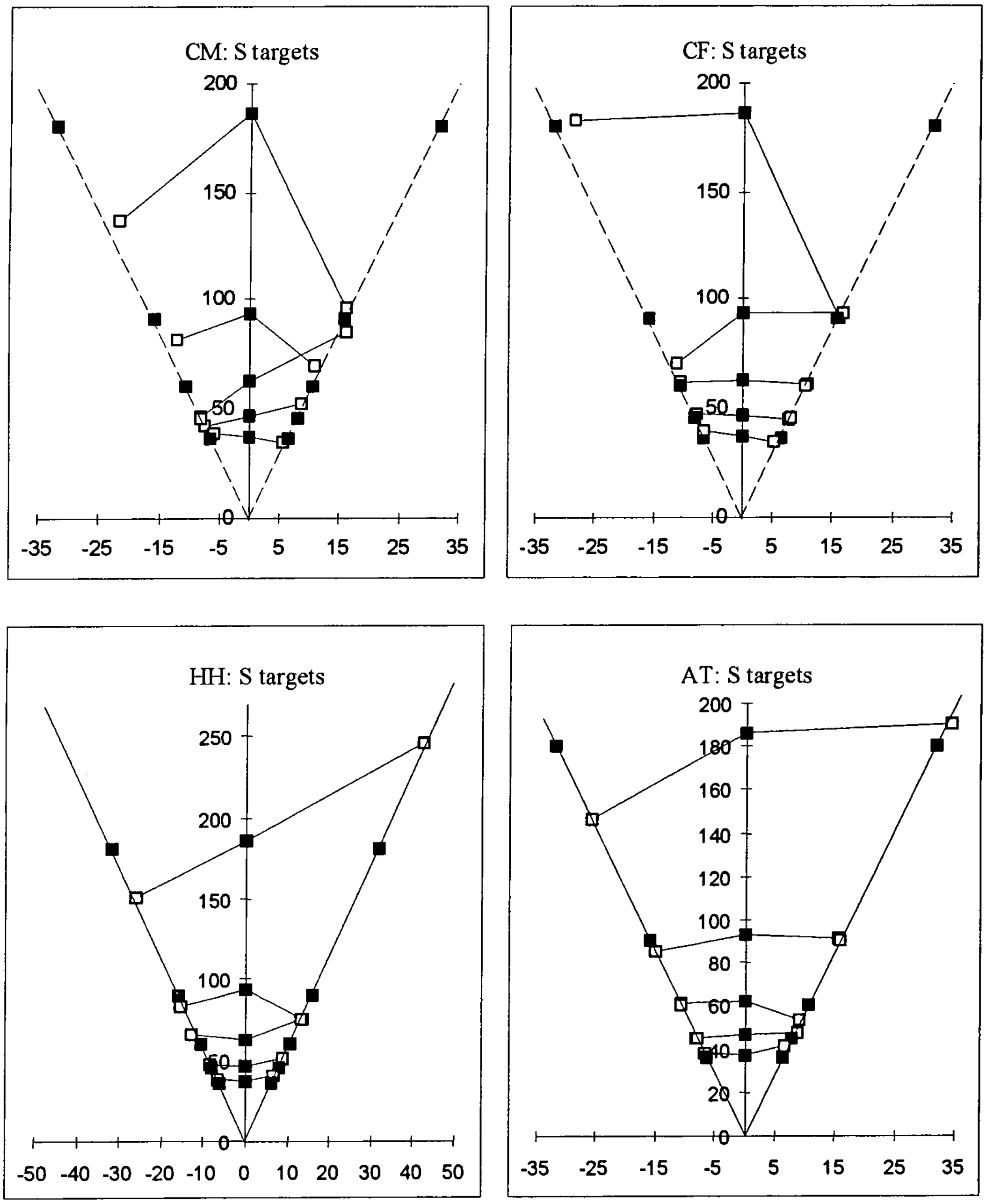

Figure 7.7 Aerial view of oculomotor response at fixation to targets requiring only 'pure' version

Discussion

This experiment sought to explore the pattern of eye movements executed as subjects looked around a sequence of targets differing in distance and direction, which were presented both stereoscopically and in 'real' space. Two sizes of target were used. The original rationale for expecting an effect of target size was based on the observation that Panum's area increases with target size. Hence, a less precise vergence will still provide a non-diplopic view. Therefore, at binocular fixation of the larger target, it was expected that a less accurate vergence response would indeed be observed. However, no effects of target size on vergence accuracy were found. It has been previously shown that saccade accuracy and precision are unimpaired by increases in target size and that observation was confirmed by this study (Kowler & Blaser 1995).

All subjects, except CM, showed similar levels of accuracy at fixation, with respect to the placement of their binocular point of foveation in terms of direction and distance. However, subject CM showed on average a 0.8° difference between paired values of direction and distance offset. As exemplified by the more detailed consideration of her oculomotor responses to small targets in the diamond D5.5 configuration, this difference was predominantly the result of a more inaccurate vergence response. Hence, although the standard visual tests showed that subject CM had normal muscle balance and good stereo acuity she nevertheless showed larger errors in vergence angles than direction. Westen *et al.* (1997) in their experiment on asymptomatic subjects and patients with convergence insufficiency also found that half of their asymptomatic subjects showed large errors in vergence angles. This has implications for the practical use of 3D eye pointing in that it suggests that the standard visual tests may not be a sufficient screening procedure for good 3D eye pointing performance.

Fixational accuracy during the combined version and vergence trials was also characterised as a function of vergence demand. None of the subjects showed a significant difference between vergence and target offsets at fixation for the 1° vergence interval. However, an effect was found for three of the subjects at the 0.5° vergence interval and for two subjects at the 2° vergence interval. Only in the case of subject CM and AT did this represent a more accurate vergence than direction response. No differences were found in the accuracy of fixation during the 'pure' version trials, either with respect to distance or direction, as a function of vergence level. Collewijn *et al.* (1997) also found no effect of the magnitude of iso-vergence on the main sequence parameters of primary saccadic version, including the actual amplitudes of the primary saccades.

Only one difference was found between the pattern of eye movements made to the 'real' and 'virtual' target layouts. Namely, both subjects who viewed the 'virtual' targets, showed a difference in accuracy between the distance and direction of placement of their binocular point of foveation, when fixating the midline far target. This may represent an accentuation of the general and interesting finding, that each subject made a consistently greater convergence error (in the direction of the near target) when fixating the far compared with the near midline targets. At the 0.5° and 1° level of vergence demand this amounted to, on average, 0.6° of convergence and at the 2° level of vergence demand, to 1.8° of convergence. This suggests that the near midline target may have been exerting a considerable influence on the oculomotor response to the far target, "pulling" the subjects' vergence response inwards. This has both practical and theoretical implications. From a theoretical viewpoint it fits in with the Mallot *et al.* (1996) finding that disparity-evoked vergence is directed towards the average depth of two depth planes. They suggested a population coding hypothesis, where the vergence system would combine all disparities present in the visual scene, thereby determining a global disparity value, which would then drive the vergence response. This idea is analogous to the centre of gravity mechanism suggested by Findlay (1982) to explain the observation of direction averaging in saccades to multiple targets. Due to the symmetrical target layout used it is not clear whether or not the eccentric targets played a role in this depth averaging. However, data obtained by Popple *et al.* (1998) suggest that disparities contributing to the initiation of vergence are pooled over an area of approximately 6°. This would preclude the influence of the eccentric targets.

The finding also has implications from a practical point of view regarding 3D eye pointing. It suggests severe limitations in the extent to which nearby targets, separated only by depth, can be differentiated by the placement of the binocular point of foveation.

As expected, on average, at primary saccade end, the subjects landed closer to the target direction than the target depth, the difference being of the order of 0.8°. Subsequent vergence eye movements removed this difference.

Finally, this experiment aimed to obtain further data relating to saccade disconjugacy with both 'real' and 'virtual' targets. Saccade disconjugacy increased linearly with increased vergence demand, the level of vergence demand accounting for approximately 15% of the variation in saccade disconjugacy. With the exception of subject AT, saccade disconjugacy was systematically more divergent for leftward compared with rightward saccades i.e. movements were larger in the abducting compared with the adducting eye for leftward saccades. This difference was smaller or reversed for rightward saccades. Such directional asymmetry has not been reported in the literature for normal subjects where saccade disconjugacy has been found divergent at saccade offset (for 10° saccades) regardless of the saccade direction (Collewijn *et al.* 1988, 1995). The subjects had good stereo vision and no ocular muscle imbalances. The asymmetry did not seem to be associated with ocular dominance or an attempt by the subject to align one or other eye more closely with the target and its cause remains unclear. As discussed in chapter four, which reported similar findings, directional asymmetry has been reported for horizontal saccades (iso-vergence) performed by strabismic and microstrabismic subjects, although similarly the authors could find no explanation for its occurrence (De Faber *et al.* 1993, Kapoula *et al.* 1996). It remains a possibility either that the subjects, although asymptomatic by standard visual tests, did have some binocular anomaly or that such directional asymmetry is a more common quality of binocular oculomotor responses.

Lastly, directional disconjugacy may develop as a by-product (a function is hard to envisage) of the process of reading. Ygge & Jacobson (1994) studied saccade conjugacy in children (dyslexic and good readers) during a reading task. They found disconjugacies of between 0.1-3° in the saccade data of both groups of children (although not all children) in the convergent and divergent direction. In the sample eye movement record they provide, a large divergent disconjugate saccade is associated with leftward saccades (return sweep to fixate new text line) whereas smaller convergent disconjugate saccades were associated with rightward saccades (reading text line). Unfortunately, it is unclear whether this correspondence is shown in the remainder of their data since they did not comment on it. They proposed that the 'spatial disconjugacy' was due to an immaturity in the control of the saccadic system with respect to eye movement reading skill. To my knowledge there are no studies of saccade disconjugacy during adult reading. However, from the results of this experiment it would appear that such directional disconjugacy is found in adult saccade data to visually presented targets and it therefore seems likely that it will be present during adult reading.

8

Summary & Recommendations

This thesis comprises an investigation of the eye movement factors related to the development and use of binocular eye pointing devices with three dimensional (3D) displays. Two types of 3D display were considered, stereoscopic and non-stereo linear perspective displays. In order for eye pointing to be used as a successful device for input-control of a 3D display it is necessary to characterise the accuracy with which the binocular point of foveation can locate a particular point in 3D space. Chapters five and six investigated this factor in the context of a linear perspective display. Chapter seven sought to answer this question for two sizes of targets, by comparing the fixational accuracy between targets, presented at different depths on a stereoscopic display and in 'real' space. The target configuration also enabled the influence of a nearby target on the fixational accuracy of another to be assessed.

One of the benefits of eye pointing in two dimensions is the fast speed with which the eye's line-of-sight can be directed to a new target. Moving the binocular point of foveation to a new target in a different depth plane has been characterised as a slower process, since it involves vergence eye movements. However, recent evidence has suggested that this process may be faster than was originally supposed due to the occurrence of disconjugate (unequal) saccades. Chapters four to seven sought to ascertain the visual conditions under which these disconjugate saccades occur.

Accuracy of binocular eye pointing to 3D displays

Accuracy is defined as the extent to which repeated measures of the same value are correct. The accuracy of an entire eye pointing system (i.e. composite of equipment and subject) in 3D space can be characterised by the vergence and direction offsets of fixation from the target's true position together with their standard deviation values. It seems reasonable to expect the eye pointing operator to be on-target 95% of the time. Hence, in terms of specifying an eye pointing system with a 95% confidence limit, target size will need to be [target direction offset + [2 x standard deviation]]. Further, targets will need to be separated in depth by at least [target vergence offset + [2 x standard deviation]].

Stereoscopic displays

Differential accuracy of fixation with respect to target direction and depth?

For the purposes of this thesis, the operator was deemed to have achieved fixation of a target one second after the start of the primary saccade to that target. Using this definition, the data in chapter seven revealed that, in general, the subjects attained a similar level of accuracy with respect to both direction and depth. The average difference between direction and vergence target offsets, across all subjects, was 0.24±0.76°. However, one of the four subjects, showed larger target vergence offsets than target direction offsets i.e. there was a difference between the accuracy of target fixation with respect to direction and depth. This difference was maintained during viewing of both the 'real' and stereoscopic targets. All the subjects performed well on the standard tests of binocular vision. This suggests that more refined tests will be necessary to identify those subjects who may perform less well with respect to the placement of their binocular point of foveation at a particular distance compared to in a particular direction.

Fixational accuracy and target size

The data in chapter seven also revealed that there were no differences in accuracy between fixation of small (0.5°) and large (1.0°) targets, either when they were presented on a stereoscopic display or in 'real' space.

Similarly, there were no overall differences in accuracy between fixation of stereoscopic and 'real' targets.

However, close proximity (in terms of direction) between two targets at different depths did affect the accuracy of fixation of those targets with respect to depth (but not direction). This effect was most pronounced when the depth separation between the two targets was 4°. It places a limit on target proximity. A 10° horizontal direction separation is sufficient to remove this influence, whereas 0° horizontal and 1° vertical separation is not. Further research would be necessary to specify the size of this limit more finely.

The mean direction offset for the isolated eccentric targets, for all four subjects, was 0.5°±0.5°. Hence, the specification for minimum target size is (0.5 + (2 x 0.5))° i.e. 1.5°. The corresponding mean vergence offset was 0.5°±0.6° giving a specification for the minimum target depth separation of (0.5 + (2 x 0.6))° i.e. 1.7°.

The mean direction offset for the proximal midline targets was slightly less and gave a minimum target size of (0.4 +(2 x 0.3))° i.e. 1.0°. However, the corresponding mean vergence offset gave a larger minimum target depth separation of (0.2 + (2 x 1.1))° i.e. 2.4°. This larger value might in part be due to the influence of the far midline target on the fixation response to the near midline target (depth averaging).

Linear perspective display

Binocular viewing of targets perceived at different depths on a linear perspective display did not elicit any target-directed change in the distance of the binocular point of foveation. Consequently, linear perspective cues to depth, alone, are not sufficient to enable binocular eye pointing to resolve different perceived positions in depth of two targets.

Visual conditions eliciting disconjugate saccades

Chapter four examined the speed of the eye's response in changing fixation between stationary and sudden-onset targets, located at different depths and in different directions, on a stereoscopic display. Ocular measures focused on quantifying the amount of target-directed depth change in the location of the binocular point of foveation, which occurred during the primary saccade to the targets i.e. saccade disconjugacy. Target-directed saccade disconjugacy was confirmed in some cases. However, in general the direction of saccade disconjugacy was best predicted by the horizontal direction of the target. No difference in the occurrence or magnitude of target-directed saccade disconjugacy were found between the stationary and sudden-onset targets. However, the different visual conditions did influence the extent of the directional disconjugacy.

Chapter seven compared oculomotor responses made to identical target layouts presented on a 'virtual' display and in 'real' space. No differences in the occurrence or form of disconjugate saccades was found between either type of display condition. Similarly to chapter four, with the exception of one subject, the disconjugacy displayed a directional asymmetry. Leftward saccade disconjugacy was more divergent than rightward. This asymmetry was overlaid on a disconjugacy response, which when considered in relative terms, was appropriate for the level of vergence demand i.e. saccade disconjugacy increased linearly with increased vergence demand. The cause of the asymmetry remains unclear. It was not associated with ocular dominance and all subjects performed well on the standard visual tests.

Directional asymmetry has been previously reported for strabsimic and microstrabismic subjects (De Faber *et al.* 1993, Kapoula *et al.* 1996), although the authors could not find a cause. The most likely explanation seemed to be that it was related in some way to the abnormal visual status of their subjects i.e. some type of mechanical asymmetry in the ocular muscles or ligaments. However, all the current subjects had good muscle balance. Further, they exhibited the directional asymmetry throughout the trials, including the initial ones. Hence, they were not exhibiting a latent muscle imbalance initiated by fatigue. Further, the finding in chapter four that the extent of the directional disconjugacy was influenced by visual conditions, argues for a centrally mediated rather than peripheral mechanism.

Chapter five sought to ascertain whether target-directed disconjugate saccades and/or vergence eye movements could be triggered by perspective depth cues, under monocular or binocular viewing conditions. Targets were presented in unpredictable locations for 2.5 seconds. No consistent evidence of target-directed disconjugate saccades or target-directed post-saccadic vergence was found. Chapter six concentrated on monocular viewing and examined two theoretical explanations for the previous result. Firstly, it was hypothesised that the target and perspective background may not have been displayed for a sufficient length of time to allow a depth percept, capable of affecting oculomotor behaviour, to have developed.

Consequently, the length of time for which the target and background were presented was extended. Again, no consistent evidence of saccade disconjugacy and only partial evidence of target-directed vergence was found. Secondly, it was hypothesised that any vergence response would cause target blur through the accommodation-vergence cross link and that this blur would then act as a stimulus to maintain the subjects' near responses in the depth plane of the display. Once more, no consistent evidence of disconjugate saccades was found. However, both subjects showed consistent evidence of target-directed (asymmetric) vergence, the movement being in the covered eye only, toward the constantly displayed target. One subject also made such eye movements under the sudden-onset target conditions.

In summary, disconjugate saccades occurred, when changing fixation between targets presented at different depths on a 'virtual' display and in 'real' space. When considered relative to one another, they were target directed (convergent or divergent), but were also associated with a directional (leftward or rightward gaze shift) asymmetry. Linear perspective cues did not elicit disconjugate saccades but did prompt target-directed asymmetric vergence (in the covered eye) under optimal conditions (monocular viewing, accommodative loop open and constant display paradigm).

From a practical point of view, linear perspective depth cues are not sufficient to elicit a fast change in the binocular point of foveation. Further, even though saccade disconjugacy is elicited by stereoscopic depth cues, it is not precise enough to locate the binocular point of foveation immediately close to the target's depth plane. The subsequent vergence response must be awaited. Hence, at least one second must be allowed for the subject to be on-target.

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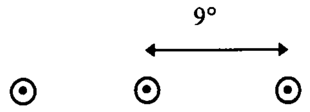
Appendices

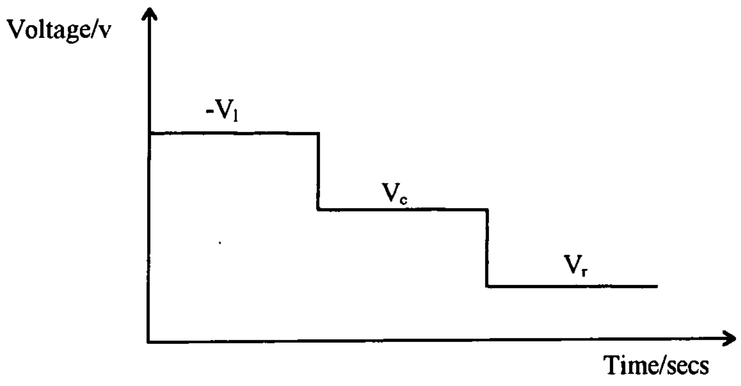
APPENDIX I

Calibration procedure (chapter 4)

At the start and end of each experimental block (40 target presentations) three calibration circles, a left hand one, a centre one and a right hand one, were presented to the subject. The calibration circles were 9° apart. The subject was asked to look at each circle in the following order:- centre, left, centre, right, centre.



Right and left eye channel data were calibrated separately. Considering the left eye channel, the eye's movement was sampled at 100Hz. The output voltage, which was proportional to the amplitude of movement of the eye's line-of-sight, was plotted against time. A sample was identified corresponding to the time when the subject was fixating the central calibration position and was defined as the centre. Eye positions to the right and left side of this centre position were calibrated separately i.e. a non-linear calibration.



Key:- **V** = voltage, subscripts **l** = left fixation position, **c** = central fixation position and **r** = right fixation position

Each fixation position was separated by 9°. The eye's line-of-sight position was defined as 0° when it was fixating the central position.

Hence, for the **left side** of the left eye $V_l - V_c \equiv 9°$ and therefore $1 \text{ volt} \equiv 9 \div (V_c - V_l)$.

For a particular output voltage (v),

If $v = V_c$ then v represents an eye line-of-sight position (A) of 0°.

If $v < V_c$ then $A = v - V_c \times (9 \div (V_c - V_l))°$.

For the **right side** of the left eye $V_c - V_r \equiv 9°$ and therefore $1 \text{ volt} \equiv 9 \div (V_r - V_c)$.

For a particular output voltage (v),

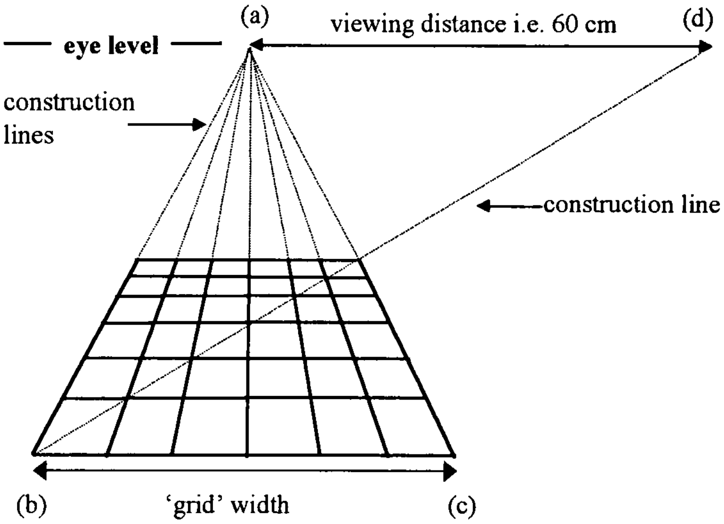
If $v = V_c$ then v represents an eye line-of-sight position (A) of 0°.

If $v > V_c$ then $A = v - V_c \times (9 \div (V_r - V_c))°$.

APPENDIX II

Construction of linear perspective display (chapters 5 & 6)

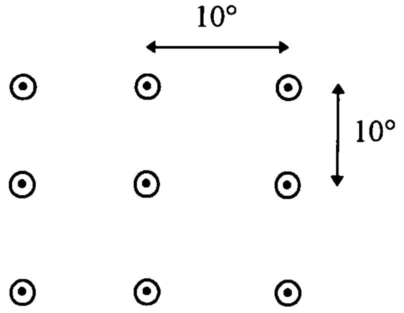
The geometry of the perspective display was constructed in the following way. The fixation cross was positioned at (a), the screen centre. The 'grid' base (bc) was drawn centrally at the bottom of the screen. The point (d) was located 60cm, equal to the viewing distance, from (a) in the horizontal plane. A construction line was drawn from (b) to (d). The 'grid' base (bc) was then divided into equidistant sections (grid tile width). Each section was joined by a straight line to (a). The horizontal grid lines were then drawn so as to cross each straight line at their intersection with the construction line (bd).



APPENDIX III

Calibration procedure (chapters 5 & 6)

At the start and end of each experimental block (90 target presentations) a square array of nine calibration circles was presented to the subject for 20 seconds. The calibration circles were 10° apart from each other. The subject was asked to look at the centre of each circle in the following order:- top row left, top row centre, top row right, middle row left, middle row centre, middle row right, bottom row left, bottom row centre, bottom row right.



The eye's movement was sampled at 100Hz. The output voltage, which is proportional to the amplitude of movement of the eye's line-of-sight, was plotted against time. Nine samples were identified each corresponding to the time when the subject was fixating each of the calibration positions. Horizontal and vertical eye channel data were calibrated separately. Each fixation position was separated by 10°. The eye's line-of-sight position was defined as 0° when it was fixating the central position.

$$V_{centre} = (V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8 + V_9) \div 9$$

$$V_{horiz.scale} = 20° \div (((V_3 - V_1) + (V_6 - V_4) + (V_9 - V_7)) \div 3)$$

$$V_{vert.scale} = 20° \div ((V_7 - V_1) + (V_8 - V_2) + (V_9 - V_3)) \div 3)$$

For a particular output voltage (v),

Horizontal eye line-of -sight position in degrees = $(v - V_{centre}) \times V_{horiz.scale}$

Vertical eye line-of -sight position in degrees = $(v - V_{centre}) \times V_{vert.scale}$

APPENDIX IV

Instructions for subjects (chapters 5 & 6)

This session is going to include some practise trials, 2 calibration trials before and after each experimental block and 2 experimental blocks. Each experimental block will consist of 90 trials and should take 20 minutes to complete. In between blocks you will be able to relax.

Once you have been set-up on the eye tracker it is important not to talk and to keep your head as stationary as possible until the eye tracker has been switched off. During the trials please try to refrain from blinking.

During each trial a white central cross and a white target square will be presented for 2.5 seconds. Please move your eyes as quickly and as accurately as possible from the central cross to the black dot in the centre of the target square. **It is important to continue to fixate precisely on this black dot until the display disappears.** In between each trial a central white square will be presented on a black background for 2 seconds. Please fixate in the centre of this square.

If there is anything you don't understand, please ask now.

Thank you very much for your time.

APPENDIX V

Instructions for subjects (chapter 6)

This session is going to include some practise trials, 2 calibration trials before and after each experimental block and 2 experimental blocks. Each experimental block will consist of 18 trials and should take 20 minutes to complete. In between blocks you will be able to relax.

Once you have been set-up on the eye tracker it is important not to talk and to keep your head as stationary as possible until the eye tracker has been switched off. During the trials please try to refrain from blinking.

During each trial a white central cross and a white target square will be presented for 20 seconds. You will be asked to look to and from the central cross and the black dot in the centre of the target square on my voice command, spending approximately 2.5 seconds at each location. Please move your eyes as quickly and as accurately as possible. **It is important to continuously fixate precisely on the black dot or the centre cross as appropriate.** In between each trial a central white square will be presented on a black background for 2 seconds. Please fixate in the centre of this square.

If there is anything you don't understand, please ask now.

Thank you very much for your time.

APPENDIX VI

Instructions for subjects ('real' targets) (chapter 7)

This experimental session is going to include approximately 50 trials and should take 60 minutes to complete.

Once you have been set-up in the eyetracker it is important not to talk and to keep your head as stationary as possible until the eye tracker has been switched off. During the trials please try to refrain from blinking.

During each trial you will be asked to look around a sequence of 2, 3 or 4 targets. On my voice command ('top' or 'centre') please look at the middle of the top, central square (approximately 2 seconds). On subsequent voice commands (left, right or bottom) please look, **as quickly and as accurately as possible,** at the square indicated. It is important to **continue to look precisely at the centre of that target** until the next command is given. If you see double, please look at either target or in between, which ever feels most appropriate.

If there is anything you don't understand, please ask now.

Thank you very much for your time.

Instructions for subjects ('virtual' targets)

This experimental session is going to include 120 trials and should take 30 minutes to complete.

Once you have been set-up in the eyetracker it is important not to talk and to keep your head as stationary as possible until the eye tracker has been switched off. During the trials please try to refrain from blinking.

During each trial 2, 3 or 4 off-white targets will be presented on a black background for approximately 12 seconds. Some of these target squares will be presented in stereo and may be hard to fuse.

On my voice command (top) please look at the middle of the top, central square (approximately 2 seconds). On subsequent voice commands (left, right or bottom) please look, as quickly and as accurately as possible, at the square indicated. It is important to continue to look precisely at the centre of that target until the next command is given. If you cannot fuse the target squares, please look at either target or in between, which ever feels most appropriate. The squares may fuse after some seconds.

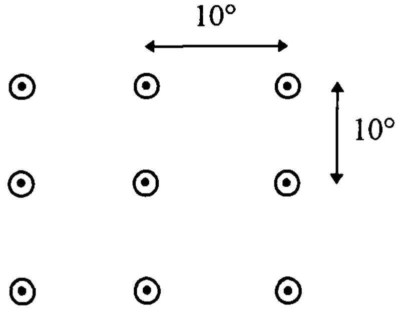
If there is anything you don't understand, please ask now.

Thank you very much for your time.

APPENDIX VII

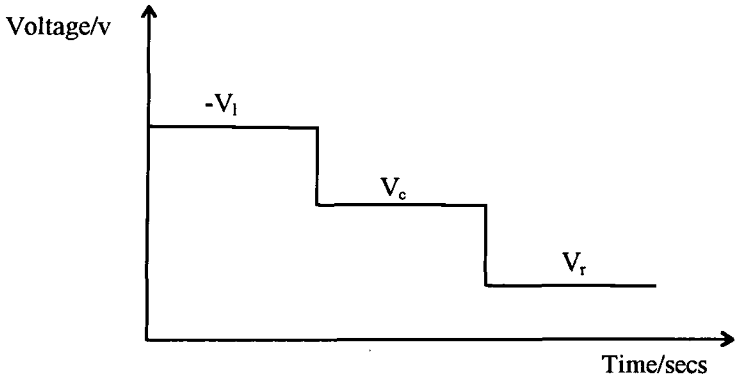
Calibration procedure (chapter 7)

At the start and end of each experimental block a square array of nine calibration circles was presented to the subject for approximately 20 seconds. The calibration circles were 10° apart from each other. The subject was asked to look at the centre of each circle in the following order:- top row left, top row centre, top row right, middle row left, middle row centre, middle row right, bottom row left, bottom row centre, bottom row right.



Right and left eye channel data were calibrated separately. Considering the left eye channel, the eye's movement was sampled at 100Hz. The output voltage, which was proportional to the amplitude of movement of the eye's line-of-sight, was plotted against time.

Nine samples were identified each corresponding to the time when the subject was fixating each of the calibration positions. Each fixation position was separated by 10°. The eye's line-of-sight position was defined as 0° when it was fixating the central position. Eye positions to the right and left side of this centre position were calibrated separately i.e. a non-linear calibration.



Key:- **V** = voltage, subscripts **l** = left fixation position, **c** = central fixation position and **r** = right fixation position

For a particular output voltage (v),

$$V_{\text{centre}} \quad = \quad (V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8 + V_9) \div 9$$

$$V_{\text{horiz.scale}} \quad = \quad 20^\circ \div (((V_3 - V_1) + (V_6 - V_4) + (V_9 - V_7)) \div 3)$$

Hence, for the **left side** of the left eye $V_l - V_c \equiv 10^\circ$ and therefore 1 volt $\equiv 10 \div (V_c - V_l)$.

For a particular output voltage (v),

If $v = V_c$ then v represents an eye line-of-sight position (A) of 0°.

If $v < V_c$ then $A = v - V_c \times (10 \div (V_c - V_l))^\circ$.

For the **right side** of the left eye $V_c - V_r \equiv 10^\circ$ and therefore 1 volt $\equiv 10 \div (V_r - V_c)$.

For a particular output voltage (v),

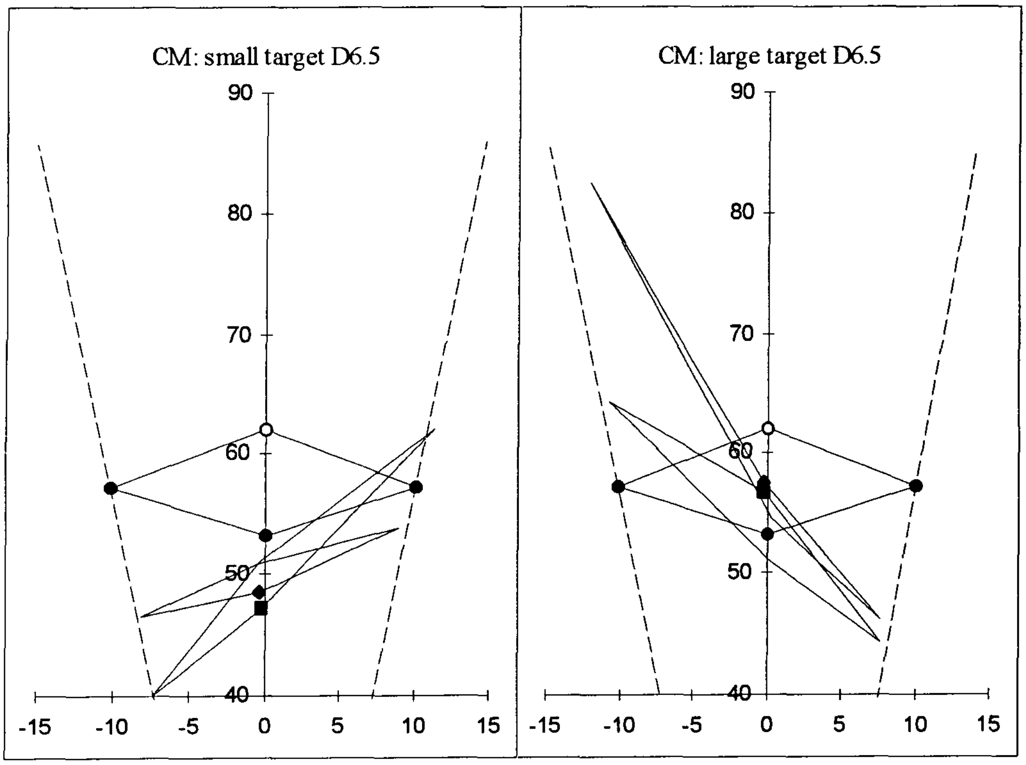
If $v = V_c$ then v represents an eye line-of-sight position (A) of 0°.

If $v > V_c$ then $A = v - V_c \times (10 \div (V_r - V_c))^\circ$.

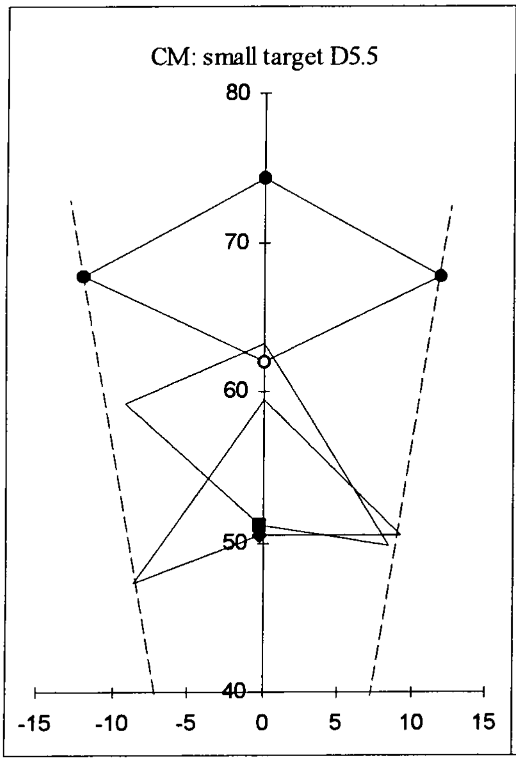
The right eye was calibrated similarly.

APPENDIX VIII

Aerial view of fixation locations during combined version/vergence (non-conjugate gaze-shifts) target sets. Scale of both axes is in centimetres.



Key:-	square:	1st fixation, anticlockwise
	diamond:	1st fixation, clockwise
	white circle:	1st target position
	dark circles:	2nd, 3rd & 4th target positions
	dotted line:	10° iso-direction trajectory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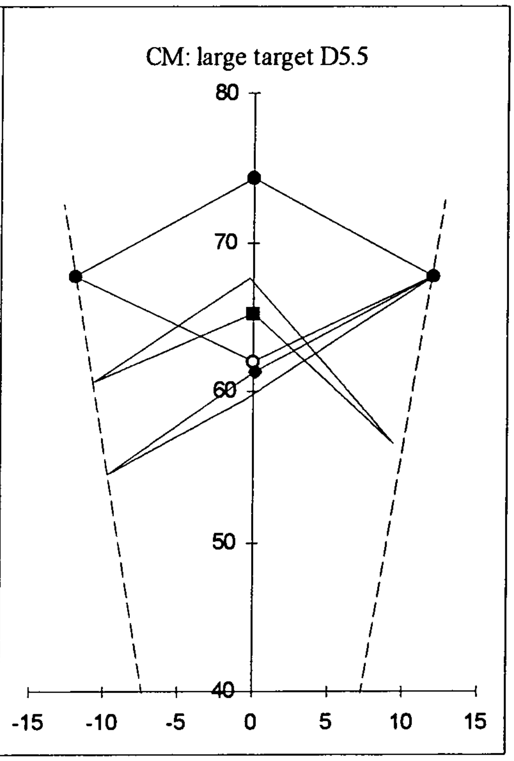
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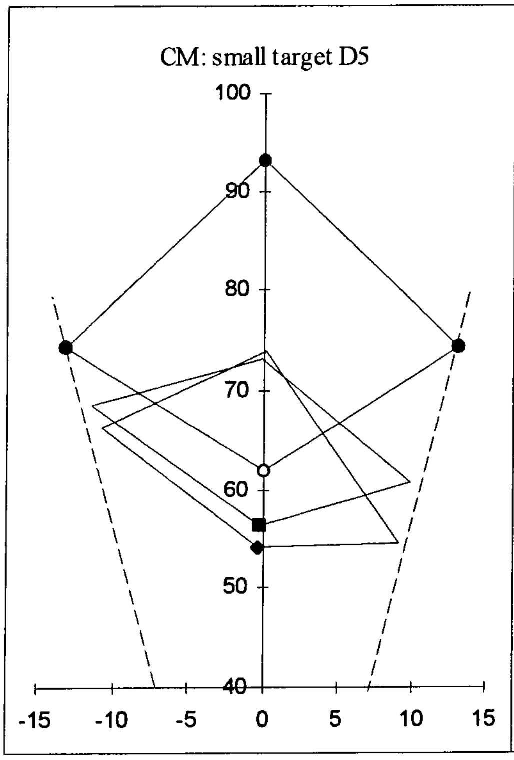
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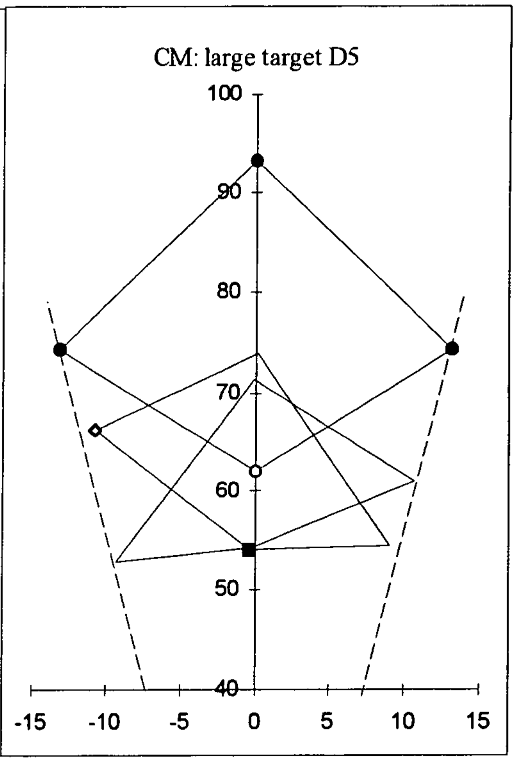
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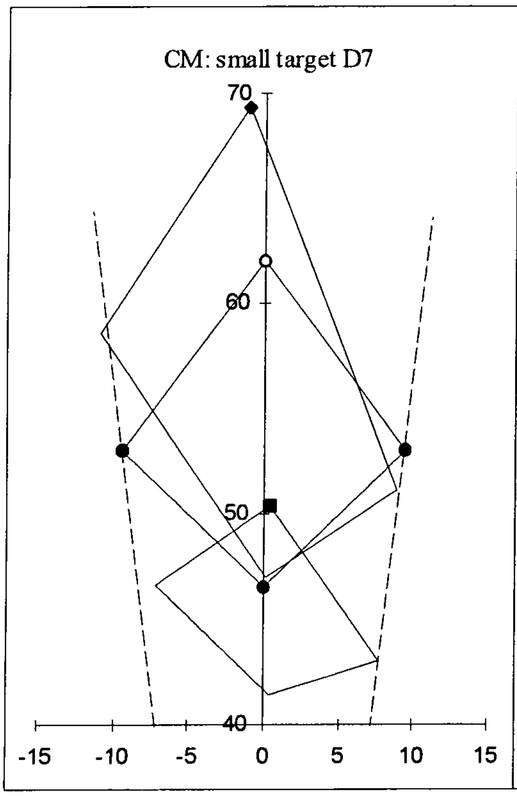
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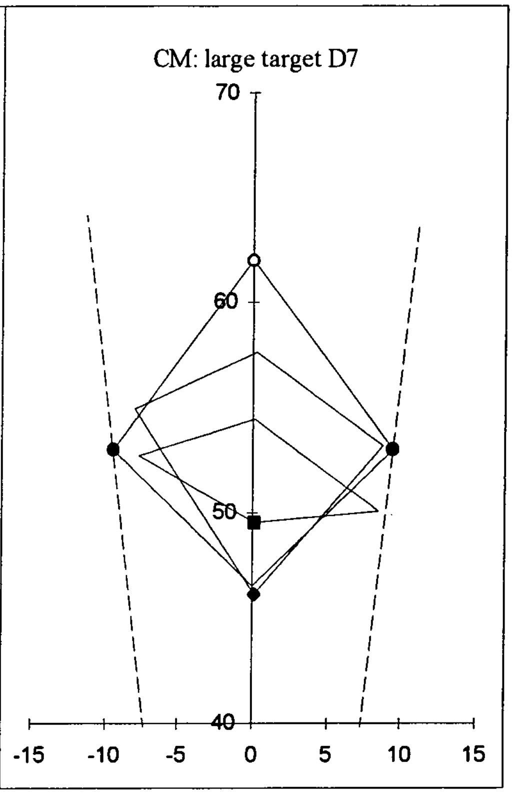
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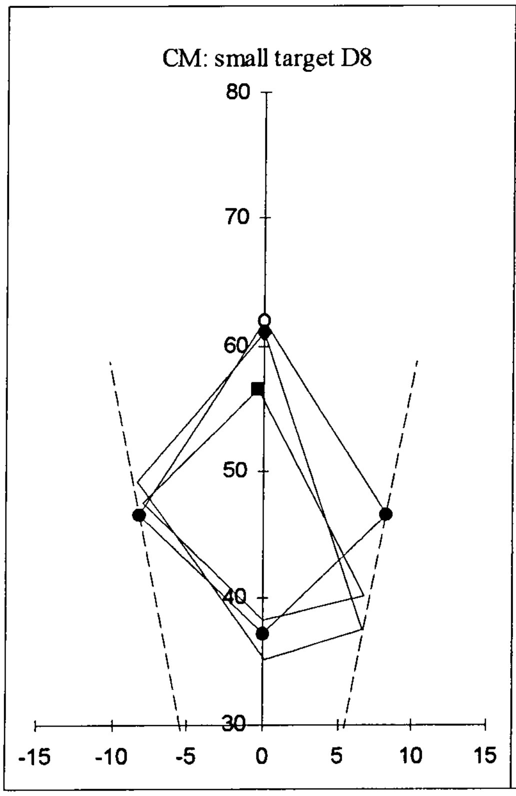
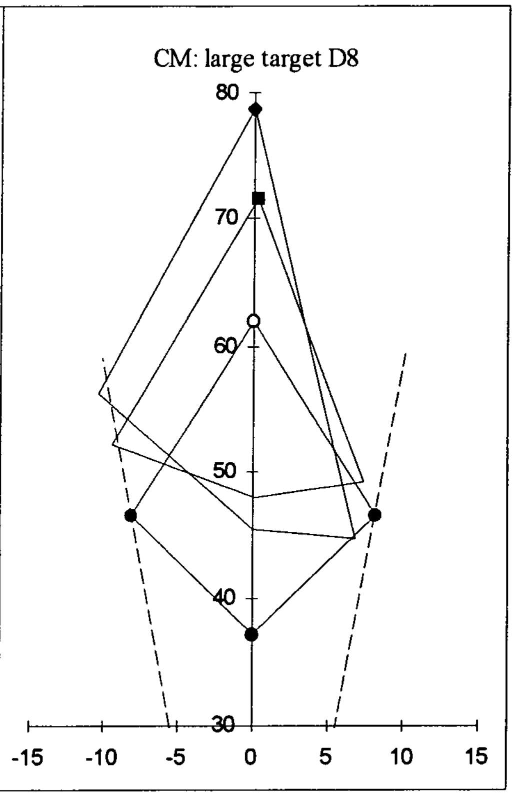
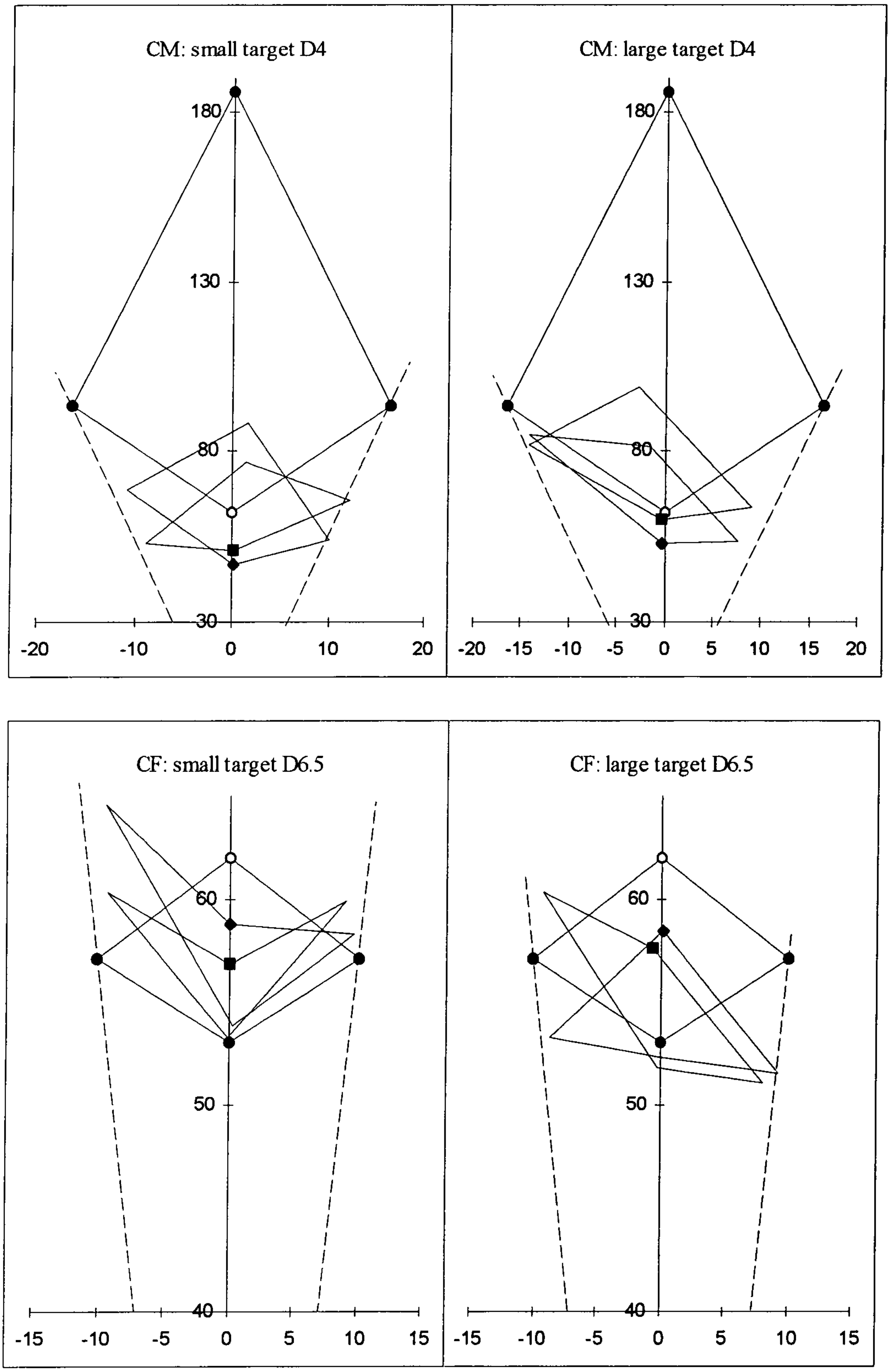

CM: small target D8


CM: large target D8


CM: small target D4
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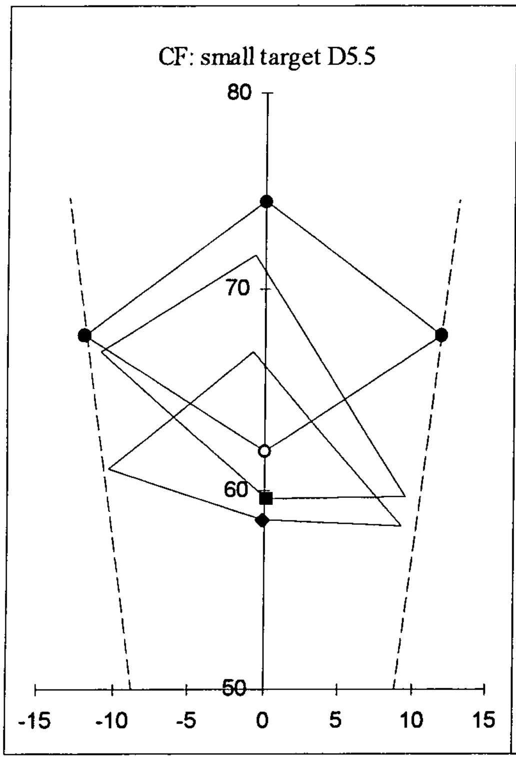
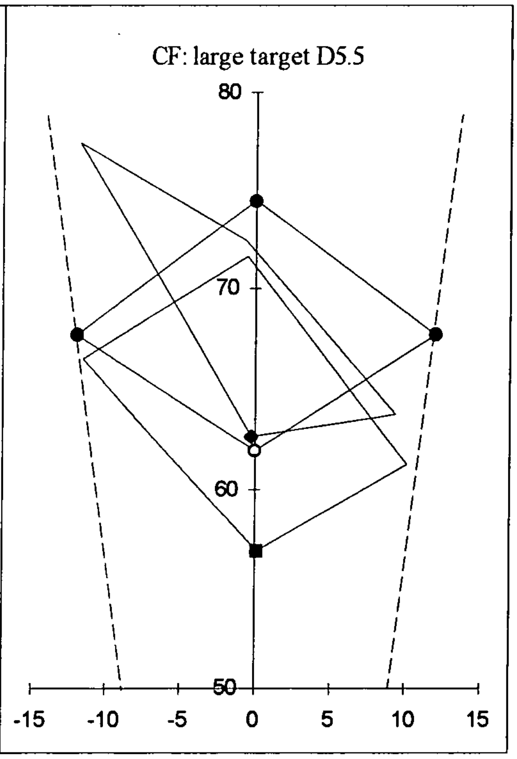
130
80
30
-20
-10
0
10
20
CM: large target D4
180
130
80
30
-20
-15
-10
-5
0
5
10
15
20
CF: small target D6.5
60
50
40
-15
-10
-5
0
5
10
15
CF: large target D6.5
60
50
40
-15
-10
-5
0
5
10
15


CF: small target D5.5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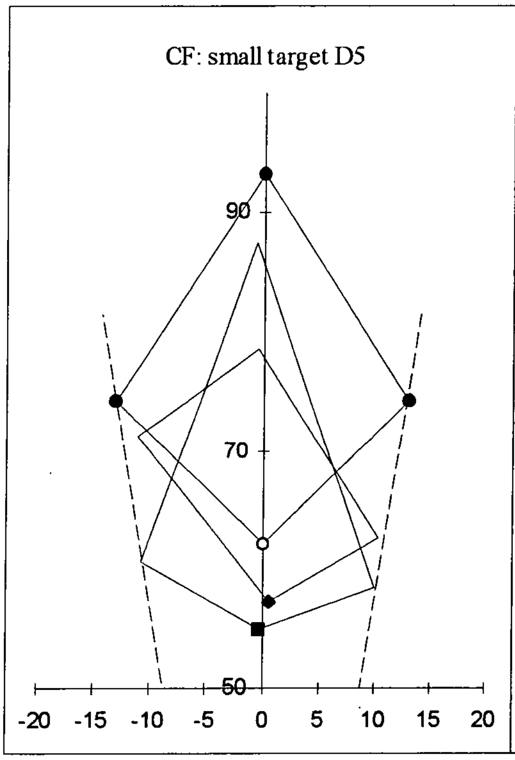
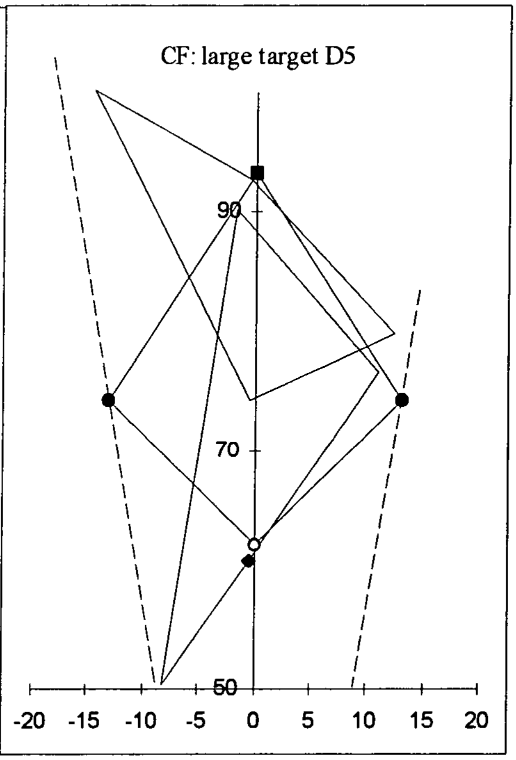

CF: small target D5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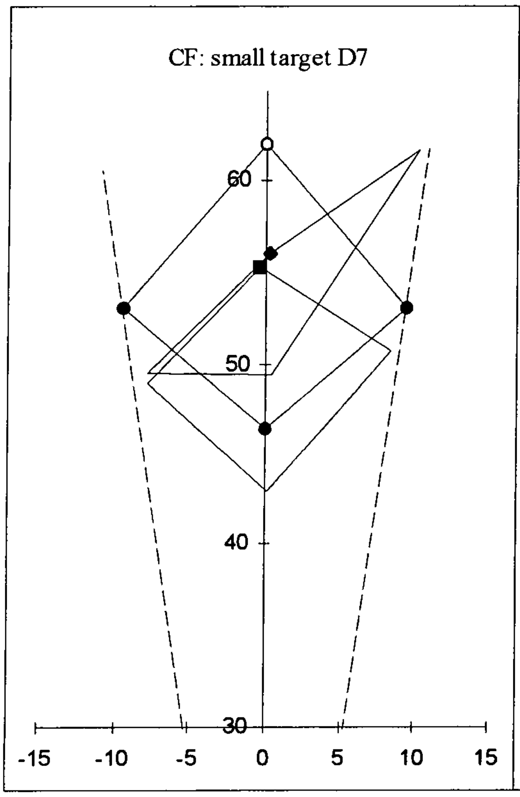
CF: small target D7
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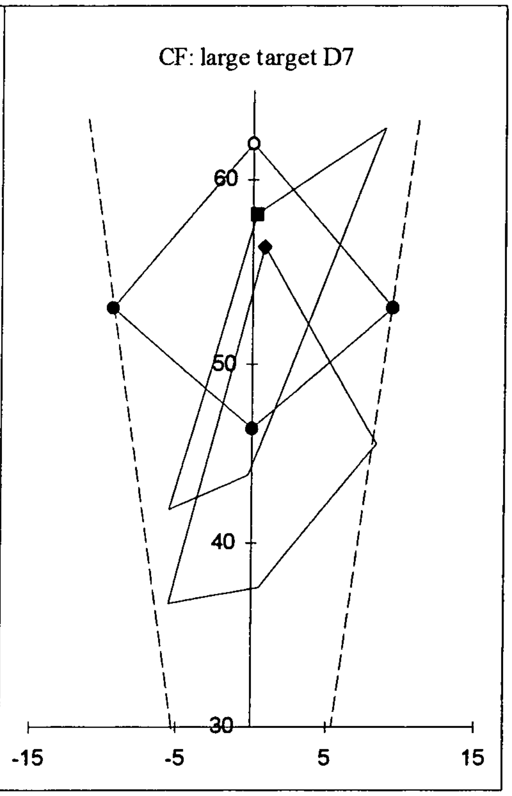
-15
-10
-5
0
5
10
15


CF: large target D7
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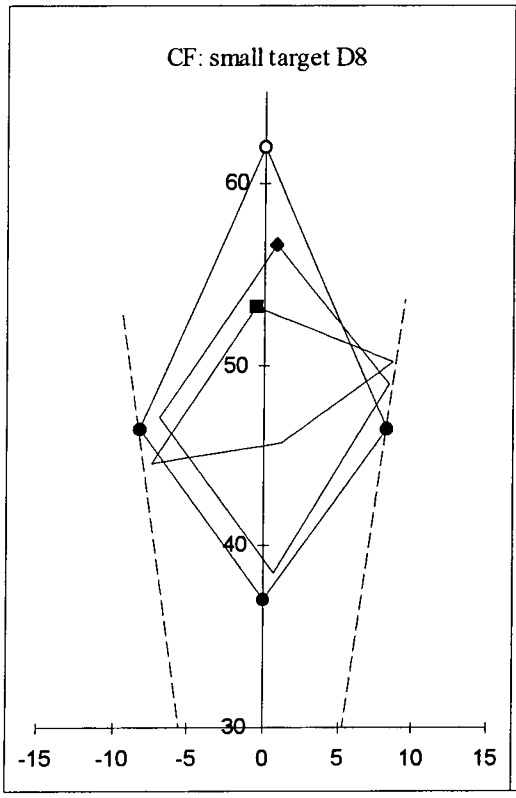
-15
-5
5
15


CF: small target D8
60
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40
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-15
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-5
0
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10
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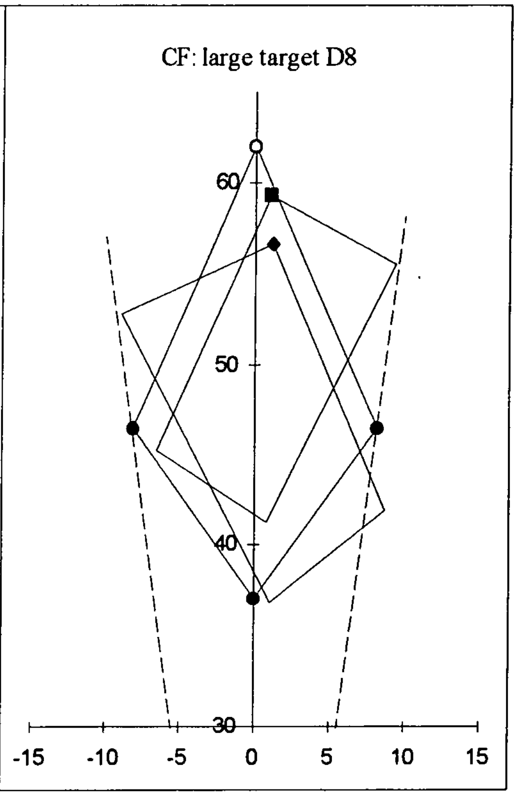
CF: large target D8
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40
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-15
-10
-5
0
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10
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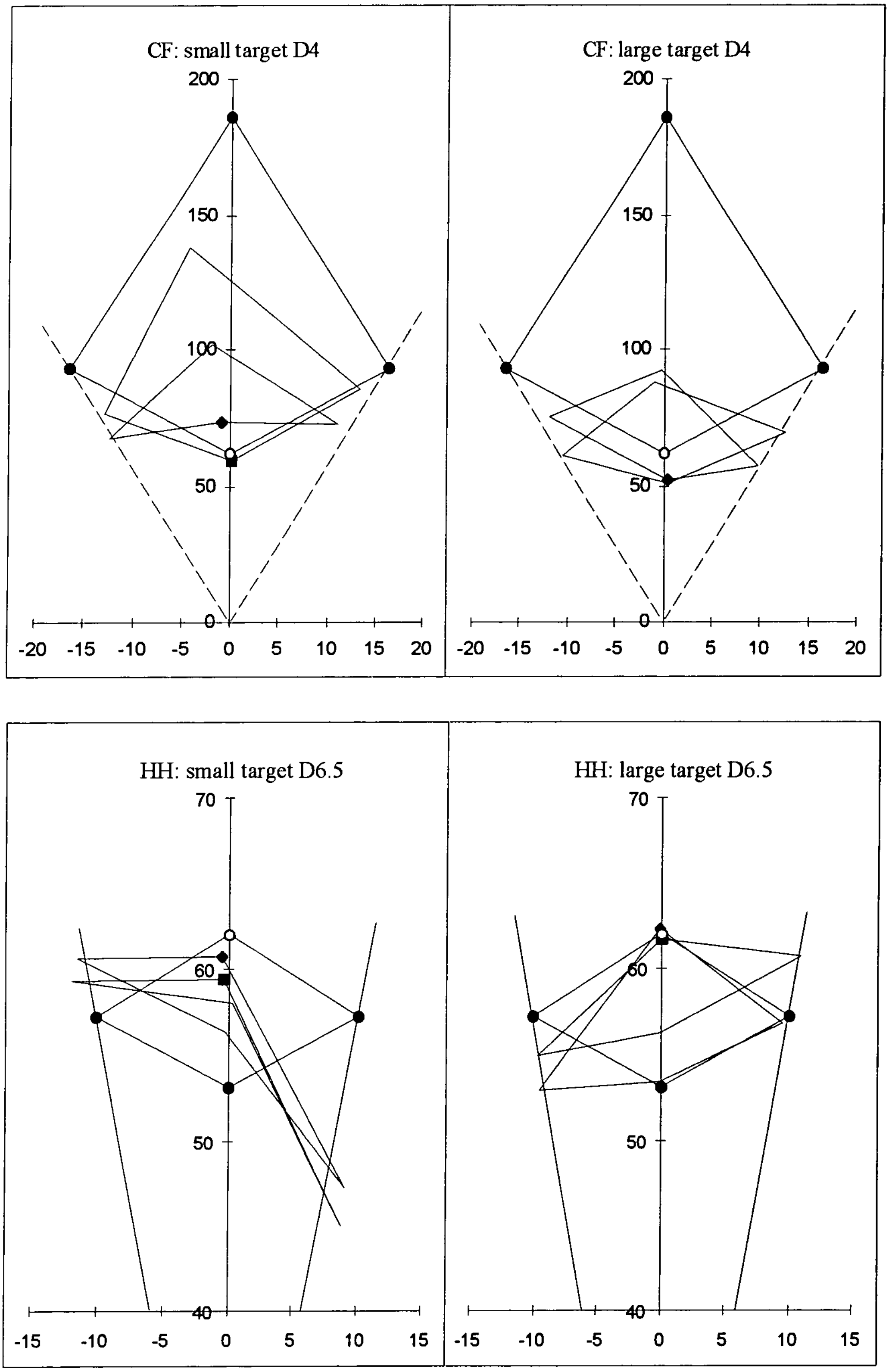
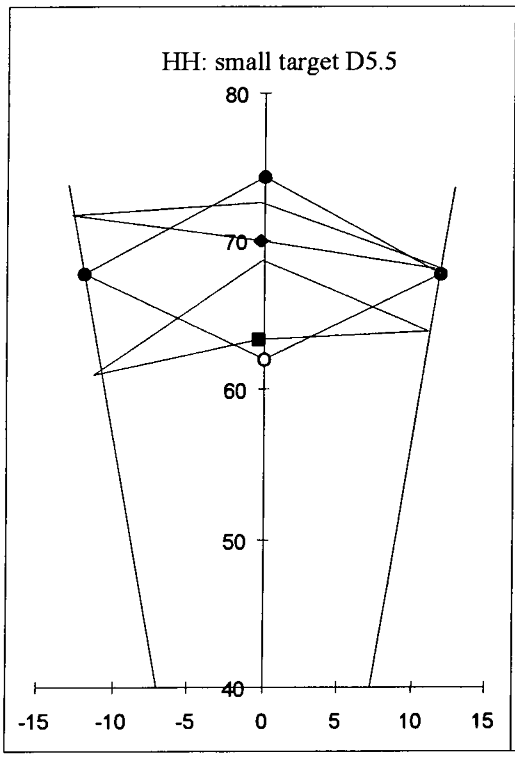

CF: small target D4
200
150
100
50
0
-20 -15 -10 -5 0 5 10 15 20
CF: large target D4
200
150
100
50
0
-20 -15 -10 -5 0 5 10 15 20
HH: small target D6.5
70
60
50
40
-15 -10 -5 0 5 10 15
HH: large target D6.5
70
60
50
40
-15 -10 -5 0 5 10 15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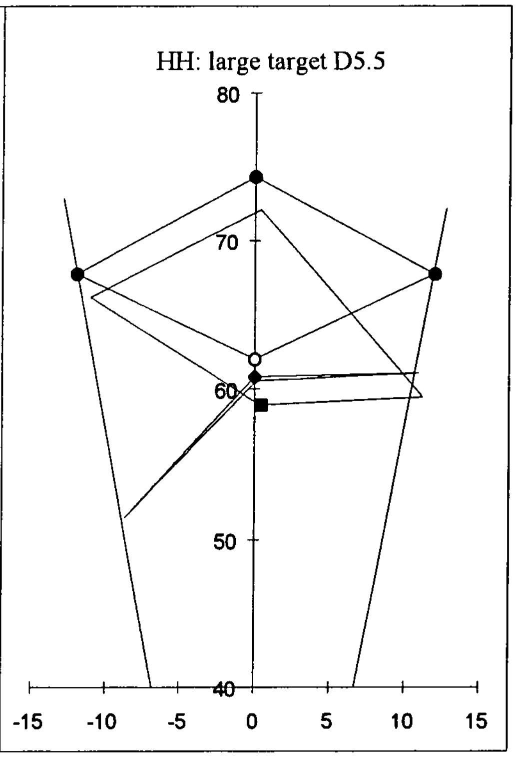
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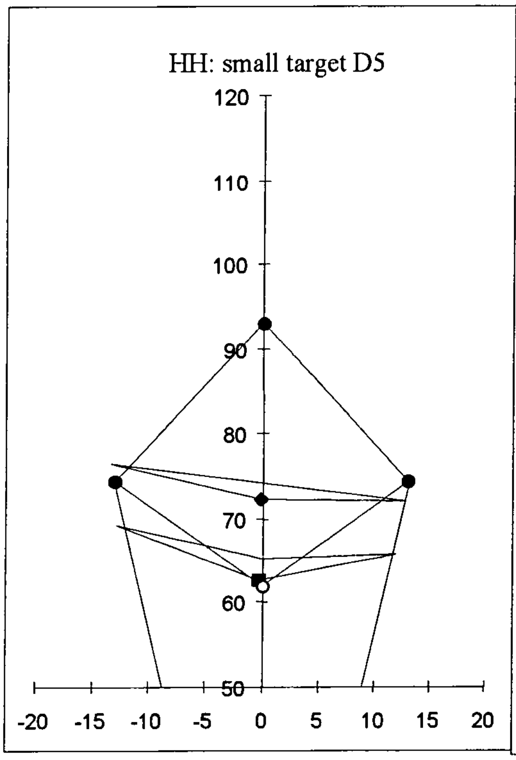
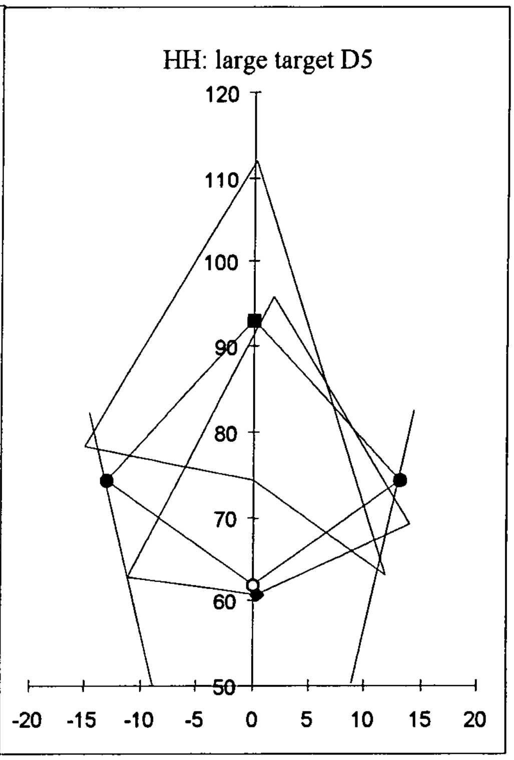
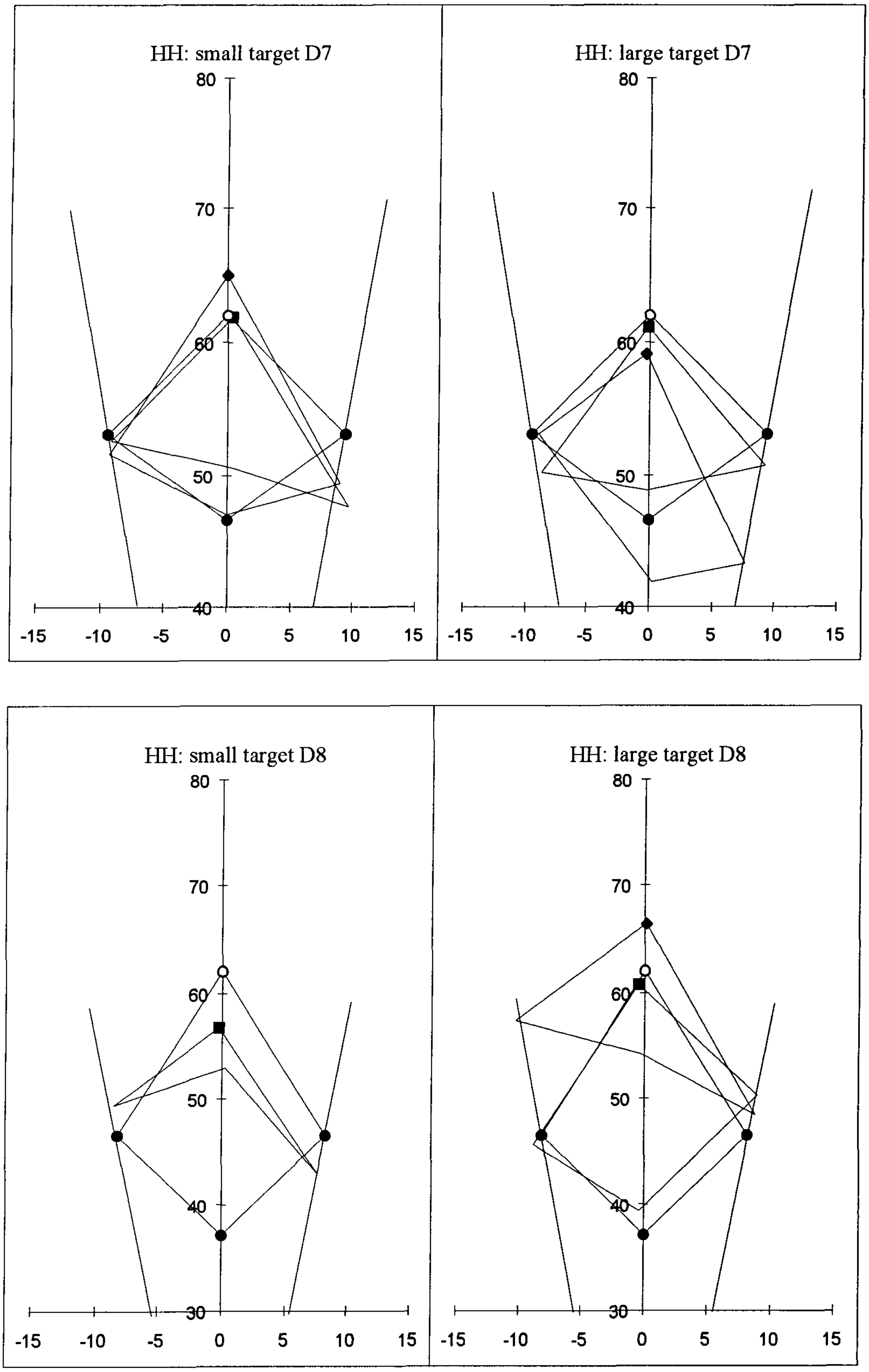

HH: small target D5


HH: large target D5


HH: small target D7
80
70
60
50
40
-15
-10
-5
0
5
10
15
HH: large target D7
80
70
60
50
40
-15
-10
-5
0
5
10
15
HH: small target D8
80
70
60
50
40
30
-15
-10
-5
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HH: large target D8
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70
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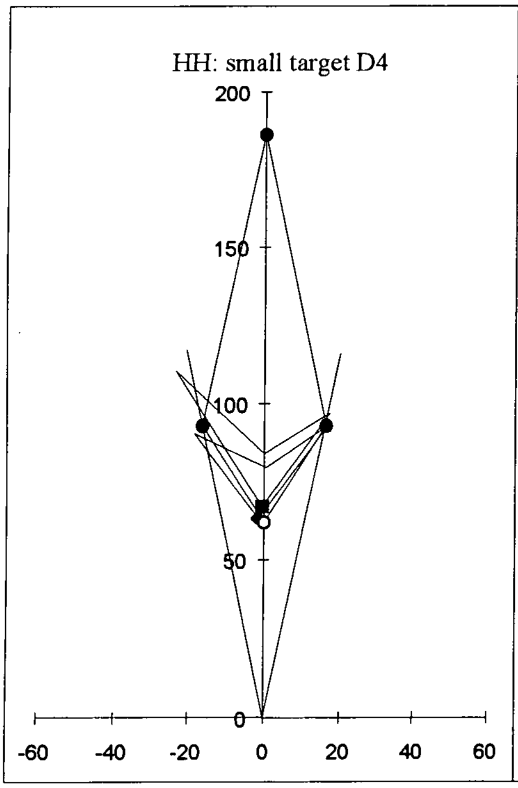
HH: small target D4
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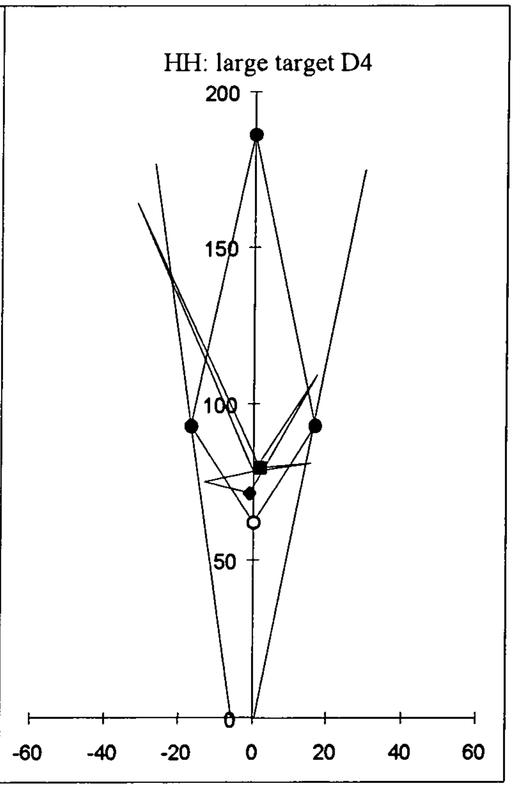
150
100
50
0
-60
-40
-20
0
20
40
60


HH: large target D4
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0
-60
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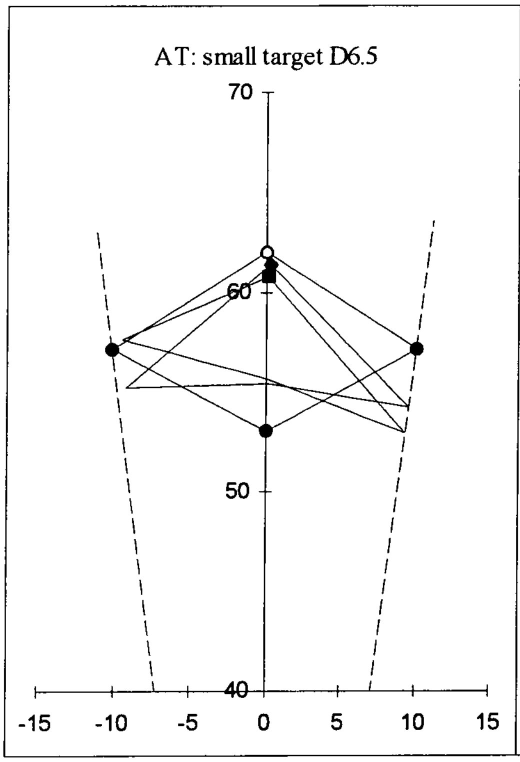
-20
0
20
40
60


AT: small target D6.5
70
60
50
40
-15
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-5
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5
10
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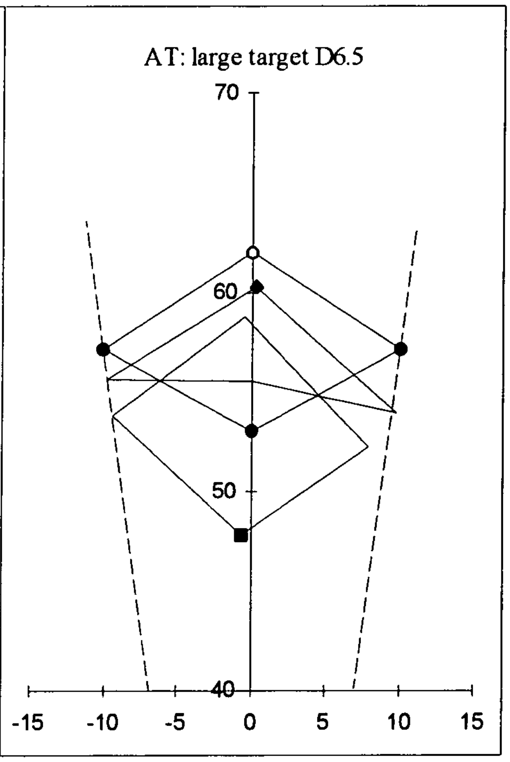
AT: large target D6.5
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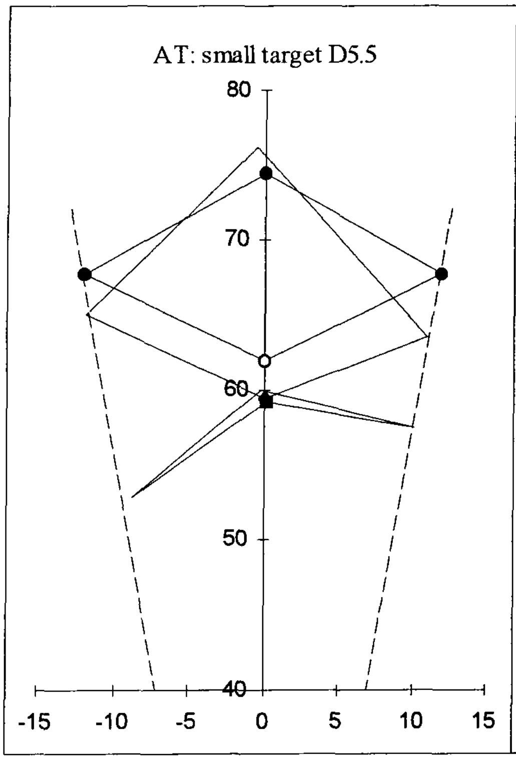
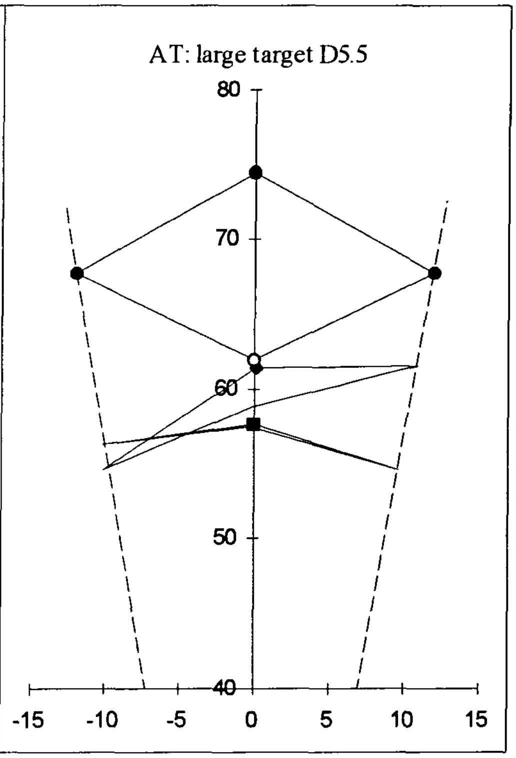


AT: small target D5.5



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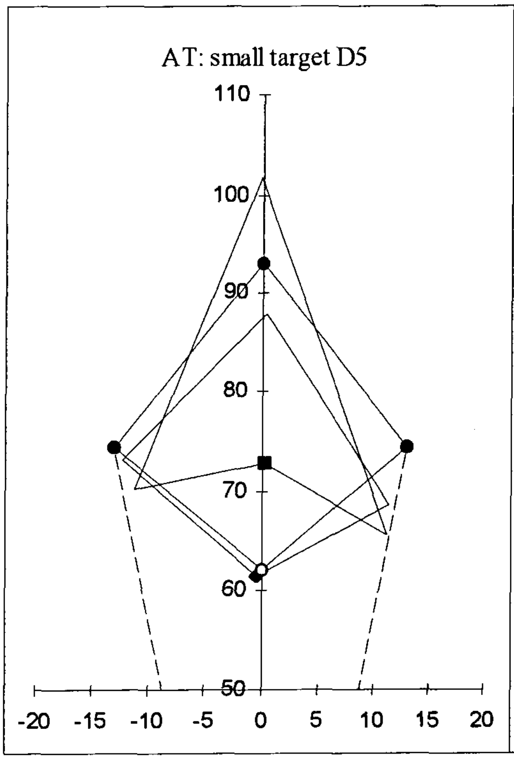

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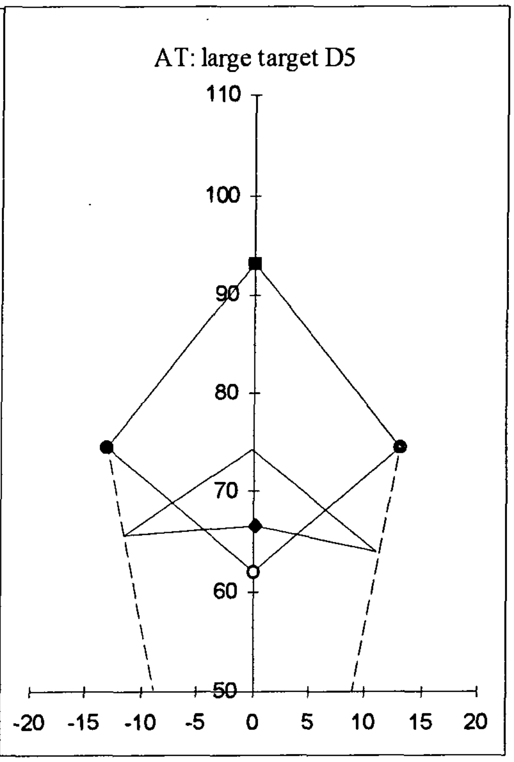

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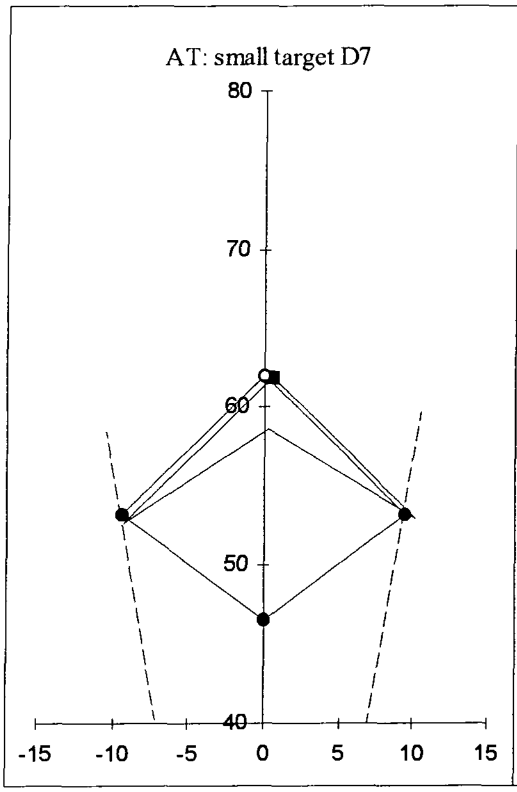
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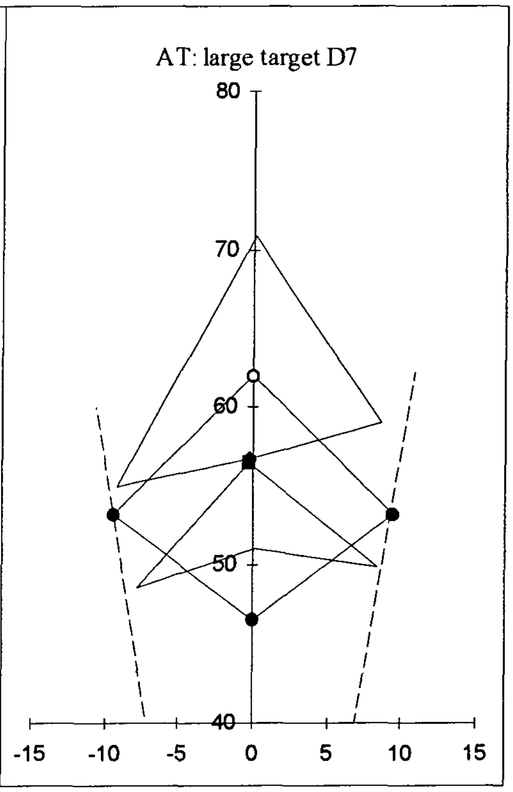
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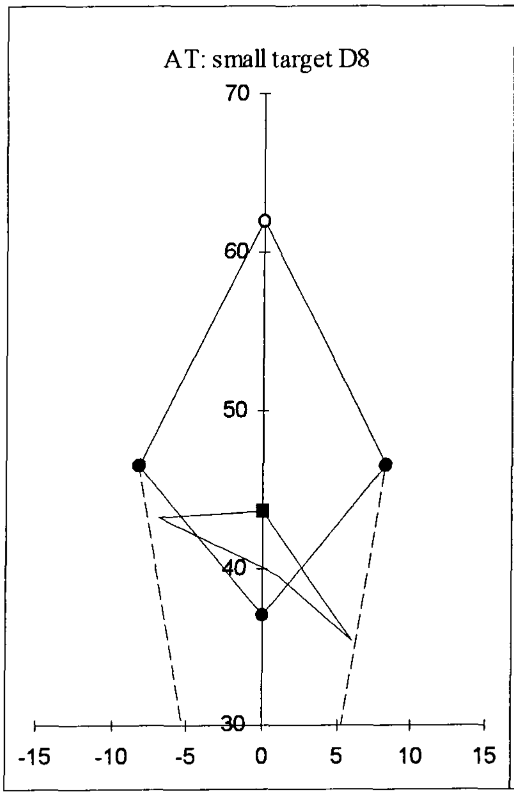
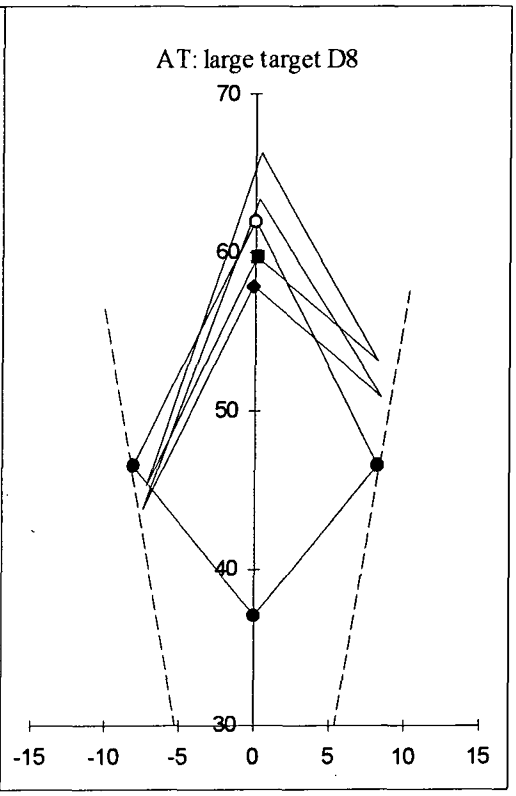

AT: small target D8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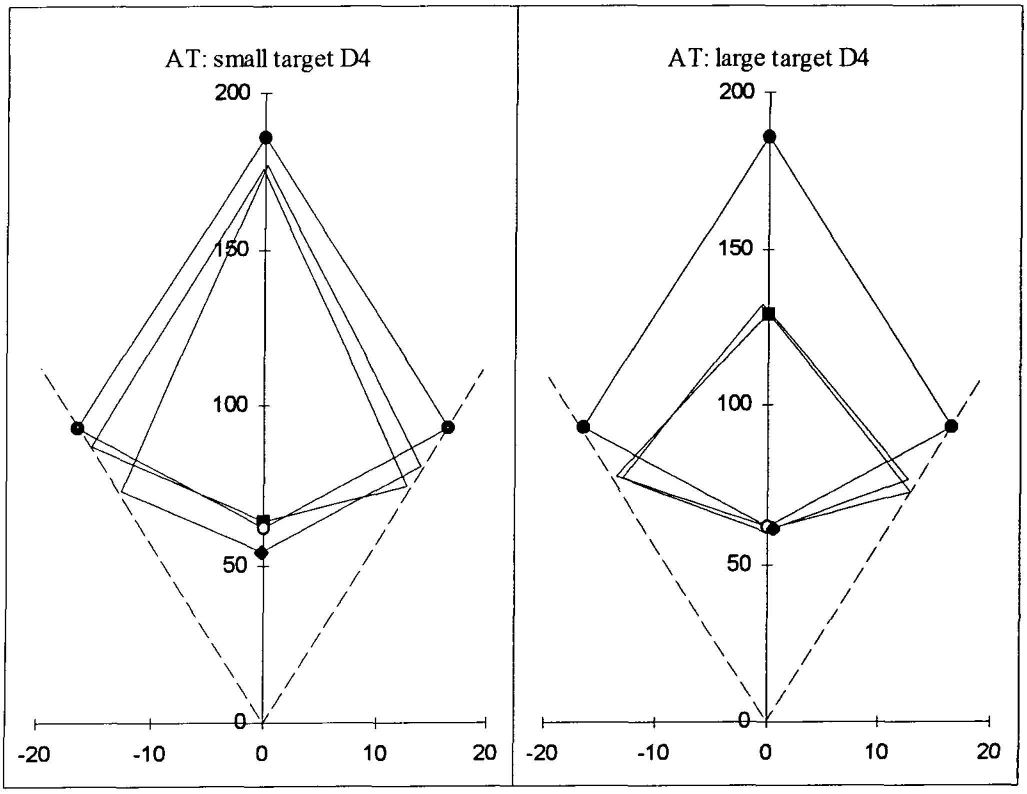
AT: small target D4
AT: large target D4
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