## The Effects of Binocular Vision Impairment on Adaptive Gait. The effects of binocular vision impairment due to monocular refractive blur on adaptive gait involving negotiation of a raised surface.

## Abstract

## The Effects of Binocular Vision Impairment on Adaptive Gait



*Keywords:* Falls, adaptive gait, stair negotiation, binocular vision, anisometropia, monovision, stereopsis, monocular cues.


Impairment of stereoacuity is common in the elderly population and is found to be a risk factor for falls. The purpose of these experiments was to extend knowledge regarding impairment of binocular vision and adaptive gait. Firstly using a 3D motion analysis system to measure how impairment of stereopsis affected adaptive gait during a negotiation of a step, secondly by determining which clinical stereotest was the most reliable for measuring stereoacuity in elderly subjects and finally investigating how manipulating the perceived height of a step in both binocular and monocular conditions affected negotiation of a step.

In conditions of impaired stereopsis induced by acutely presented monocular blur, both young and elderly subjects adopted a safety strategy of increasing toe clearance of the step edge, even at low levels of monocular blur (+0.50DS) and the effect was greater when the dominant eye was blurred. The same adaptation was not found for individuals with chronic monocular blur, where vertical toe clearance did not change but variability of toe clearance increased compared to full binocular correction. Findings indicate stereopsis is important for accurately judging the height of a step, and offers support to epidemiological findings that impaired stereoacuity is a risk for falls. Poor agreement was found between clinical stereotests. The Frisby test was found to have the best repeatability. Finally, a visual illusion that caused a step to be perceived as taller led to increased toe elevation. This demonstrates a potential way of increasing toe clearance when stepping up and hence increase safety on stairs.

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## Inserted Material

CD-ROM containing data from all six studies

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# List of Presentations and Papers

## Papers

Vale A., Scally A., Buckley J. G and Elliott D. B. (2008). The effects of monocular refractive blur on gait parameters when negotiating a raised surface. *Ophthalmic Physiol. Opt.,* **28***:*135-142

Vale A., Buckley J. G. and Elliott D. B. (2008) Gait alterations negotiating a raised surface induced by monocular blur. *Optom. Vis. Sci.,* **85** (12) 1128-1134

Elliott D. B., Vale A., Buckley J. G. and Whitaker D. Does my step look big in this? A visual illusion leads to safer stepping behaviour. In press. *PLoS ONE*

## Poster Presentations

- Abstract presented at European Conference for Visual Perception, Utrecht, 24-28th August 2008

  Vale, A., Buckley, J.G. Whitaker D., Elliott, D.B.

  Does my step look big in this?

## Oral Presentations

- Introductory talk: Presented to Bradford School of Optometry and Vision Science 01/12/2006

Effect of monocular blur on adaptive gait

- Paper Critique: Presented to Bradford School of Optometry and Vision Science 27/02/2007

  Ivers, R. Q., Norton, R., Cumming, R. G., Butler, M. and Campbell, A. J. Visual impairment and risk of hip fracture. *Am. J. Epidemiol.,* **152:**633-639

- Data Presentation: Presented to Bradford School of Optometry and Vision Science 04/04/2008

  Does my step look big in this?

# Aims and Structure of Thesis

## Introduction and Aims

Falls in the elderly are an increasing problem, due to the ageing population and the high morbidity and mortality rates associated with falling (Chapter 4, section 4.3). Visual impairment has been identified as a risk factor for falls (Chapter 4, section 4.4) including reductions in different aspects of visual function, such as visual acuity, contrast sensitivity, visual fields and stereopsis, although the epidemiological studies provide variable conclusions regarding which aspects of visual function are most important.

In order to further investigate why impairment of vision may lead to falls, laboratory studies have investigated mobility in subjects with impaired vision, caused by eye disease or artificially induced (Chapter 3, section 3.3). To date the effects of binocular visual impairment on the ability to negotiate a mobility course, obstacles or negotiate steps has been investigated but there is a lack of experimental studies investigating the role of monocular visual impairment, leading to the loss of binocular vision.

The aims of the experimental studies presented in this thesis were therefore to explore the effects of monocular vision impairment on the negotiation of a step within the travel path. Step negotiation was chosen as many falls occur on steps or stairs and it represents an everyday, familiar task. Monocular visual impairment was induced with occlusion or refractive blur of one eye which allowed us to explore the effects of different magnitudes of monocular impairment.

## Outline of Thesis

Chapter 1 outlines the basis of binocular vision including the perception of depth and stereopsis and explains the role of ocular dominance. Chapter 2 investigates the factors that can cause a reduction in stereoacuity, including amblyopia and various age-related factors. Chapter 3 explains human gait patterns and what is meant by adaptive gait. It goes on to describe how gait is controlled, highlighting the importance of vision in gait control and outlining current literature on how the impairment of vision can affect adaptive gait. Chapter 4 explores the literature regarding falls in the elderly including risk factors for falls. The role of vision as a risk factor for falls is outlined here and includes a discussion of which visual functions are most important and how this relates to the control of adaptive gait as outlined in chapter 3. The difficulties of identifying which visual functions are most important in falls risk is discussed. Chapter 5 is a general methodology chapter that outlines which tests were used for the experimental studies and why particular tests were chosen, including tests for assessment for vision, an overview of the laboratory set up, recruitment of research participants and how collected data were processed and analysed.

The experimental chapters in this thesis outline a series of experimental studies investigating the effect of impairment of binocular vision, through refractive monocular blur or occlusion of one eye. Chapters 6 (Study 1) and 7 (Study 2) investigated the effect of a single level of monocular blur (+2.00DS) on adaptive gait in young participants. Study 1 investigated how monocular blur or occlusion affected the negotiation of single step from a standing start and Study 2 investigated how monocular blur and monocular occlusion affected adaptive gait. Subjects were asked to negotiate a raised platform within the travel path to explore the effects, not just on negotiation of the step but also foot placement and step length prior to the step. Study 3 (Chapter 8) expands on the previous studies by investigating the importance of monocular blur on adaptive gait in elderly participants, and investigated a greater range of amplitude of refractive blur including very low levels of monocular blur (0.50DS). In all three chapters the blur was presented acutely. Therefore Study 4 (Chapter 9) investigated the effects of chronic monocular blur on adaptive gait, using participants who had worn monovision correction in their contact lenses for a minimum of three months, with the aim to investigate if patients are able to adapt to monocular blur and use different stepping strategies to subjects in conditions of acute monocular blur. In addition the effect of chronic monocular blur when subjects stepped down was investigated.

In order to determine if measurements of stereoacuity in the elderly are repeatable and reliable, a range of stereotests that have been used in fall epidemiological studies were assessed in Study 5 (Chapter 10). This included measuring the repeatability of clinically available stereotests and the relationship between stereoacuity levels determined by each test. The main focus of the study was to recommend the best test to use in future epidemiological studies to determine the importance of stereopsis as a risk factor for falls. The recommended test could also be used in all future laboratory studies involving stereoacuity and adaptive gait.

The final study (Study 6, Chapter 11) asked whether negotiation of a step could be influenced by a visual illusion that changed how the step height was perceived. Whether toe clearance of the step could be manipulated by the horizontal-vertical illusion was explored, in both binocular and monocular conditions, not only to assess if toe clearance could be changed, but also if the change was greater in the absence of binocular vision, when the subjects relied on only monocular cues.

The concluding chapter summarises the findings of all the studies undertaken, including how the work undertaken here can be expanded in future studies.

## Ethical Approval

Ethical approval was granted by the University of Bradford ethics committee for all studies. All studies were conducted according to the Declaration of Helsinki, and prior to any collection of data, all study participants were given written information regarding the purpose and conduct of each study, and were given the opportunity to have any questions answered. All subjects then gave written informed consent prior to any collection of data.

# Chapter 1

# Binocular Vision and Perception of Depth

## 1.1 Binocular Vision

There are several advantages of having two eyes compared to one. Firstly one eye acts as a spare if one eye is damaged or lost and secondly having two eyes means that a larger area of the environment can be seen at any one time. For example, animals with laterally placed eyes have extended visual fields, so that a rabbit has a visual field that extends to 360º. This is advantageous to hunted species, as predators can be seen approaching from any direction without the need for head or eye movements (Hughes, 1977). In contrast, frontal eyed species, such as a cat, have reduced visual field extent, with disappearance of the rear field. However the overlap in visual fields, giving rise to binocular vision, is advantageous as it allows stereoscopic depth perception (section 1.2.2) and in addition there is summation of binocular input, leading to an improvement in detection thresholds (section 1.1.5). Binocular vision is commonly found in predators, for example birds of prey and animals that use fine movements of the hands (primates, Hughes, 1977). The following sections detail different aspects of binocular vision.

### 1.1.1 Visual Field

The monocular visual field is the solid angle in which an object is visible to the stationary eye. In humans it extends 95º temporally and 56º nasally. The total visual field is the angle subtended from the midpoint between the eyes by all points which are visible to either eye (Figure 1, Henson, 2000). The binocular visual field is the portion of the total visual field in which a point can be seen by both eyes. It is flanked on either side by two monocular fields which extend 37º laterally from the boundary of the binocular visual field (Howard and Rogers, 1995).

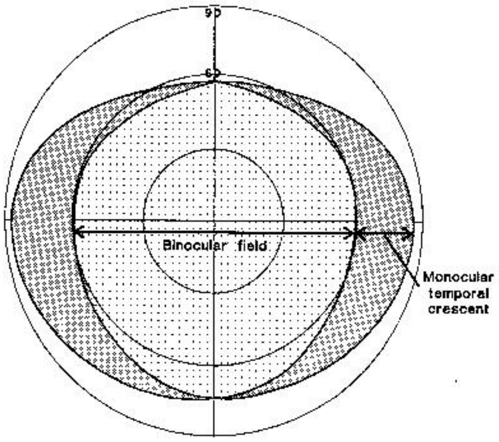



Figure 1. The total visual field of both eyes. Taken from Henson (2000).

### 1.1.2 Corresponding Retinal Points

Corresponding retinal points refer to any points of the two eyes which share a common visual direction and give rise to a single percept of an object. For the principle visual direction (the direction in which the eye is fixated) the corresponding retinal points are the foveae of both eyes (Ogle, 1950). Retinal elements that do not share a common visual direction are called non-corresponding or disparate elements with respect to a given point in the other eye and will give rise to diplopia (von Noorden and Campos, 2002).

### 1.1.3 The Horopter

The horopter is defined as the locus of all object points that are imaged on corresponding retinal elements at a given fixation distance (von Noorden and Campos, 2002). Images that fall on the horopter are perceived as single whilst images away from the horopter will be seen as diplopic. This diplopia is called physiological diplopia and is a fundamental property of binocular vision. It can be seen easily by fixating a distance target and noticing the diplopic images of closer objects, however it is usually disregarded (von Noorden and Campos, 2002).

If it is assumed that there is a geometrical distribution of corresponding points across the retina then the corresponding retinal points would be at equal horizontal and vertical positions relative to the fovea in either eye. Based on this assumption the longitudinal horopter can be imagined as a circle that passes through both eyes at the centre of rotation and the point of fixation. This circle is called the Vieth-Muller circle (Figure 2)

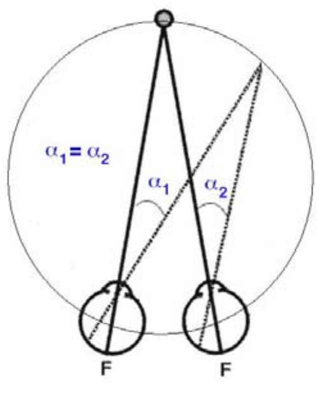



Figure 2. The Vieth Muller Circle

www.webvision.med.utah.edu (Sept 2008)

However Hering and Hillebrand (1864) demonstrated, using experimental determination of the horopter curve, that the Vieth-Muller circle does not accurately describe the horopter. Instead they described the empirical horopter which has a flatter curve, due to the differences in distribution of corresponding retinal points in the nasal and temporal retina (Ogle, 1950).

### 1.1.4 Fusion

Sensory fusion is defined as “the unification of visual excitations from corresponding retinal images into a single image percept” (von Noorden and Campos, 2002). Motor fusion is the vergence movement of the eyes necessary to cause the images to fall close or on to corresponding retinal areas in response to disparate retinal images (Millodot, 2002). For sensory fusion to occur images received by both eyes must share similar properties, for example size, brightness and colour (von Noorden and Campos, 2002). If the images are dissimilar, for example gratings with different orientations then rather than fusion, a phenomenon known as binocular rivalry will occur. This is where both images are not processed simultaneously (Howard and Rogers, 1995) but instead flick from one image to the other or are perceived as a mixture or mosaic of the contours (von Noorden and Campos, 2002).

Panum demonstrated in 1858 that images did not have to fall precisely onto corresponding retinal points for fusion and described instead an area in which sensory fusion would still occur. Panum’s fusional areas increase in size in the periphery (Ogle, 1950) measuring horizontally 6 to 10 minutes of arc close to the fovea, increasing to 30 to 40 minutes of arc at 12º in the periphery (von Noorden and Campos, 2002). The areas are elliptical in shape, being larger horizontally and smaller vertically (Howard and

Rogers, 1995). Because of Panum's fusional areas, it is possible for fusion to occur even if the eyes are under or over converged so the object of interest does not fall on corresponding retinal points. This phenomenon is called fixation disparity. The angular value of fixation disparity is the amount that the images in either eye are displaced in respect to each other (Ogle, 1950).

### 1.1.5 Binocular Summation and Inhibition

Binocular summation is the phenomenon of a visual task being performed more effectively when binocular than when compared to monocular performance (Legge, 1984). Binocular summation has been explained in terms of the probability summation model in which having two eyes acting as independent light detectors increases the likelihood of a flash of light being seen, compared to one eye alone (Pirenne, 1943). However the probability summation model does not fully account for the measured increase in binocular sensitivity, compared to monocular sensitivity (Blake and Fox, 1973, Blake et al., 1981). The neural connection between the eyes has therefore been implicated in summation and the increase in performance in binocular conditions over that predicted by probability summation is classed as neural summation (Blake and Fox, 1973). For a task such as contrast detection, the thresholds have been found to be 1.4 times lower (i.e. more sensitive) in binocular compared to monocular viewing (Campbell and Green, 1965). Campbell and Green proposed that each monocular output contains noise. The standard error of $n$ measurements of a process with noise will decrease in proportion to $\sqrt{n}$ so that the decrease in threshold using two eyes will be by a factor of $\sqrt{2}$ (1.41). This finding is consistent for contrast detection thresholds across all spatial frequencies (Campbell and Green, 1965). The decrease in binocular threshold compared to monocular threshold is also consistent for form recognition and flicker detection (Blake and Fox, 1973) or if measured objectively using electrophysiology (Visual Evoked Response, Pardhan et al., 1990).

The decrease in binocular threshold occurs when both eyes are equally illuminated. However Fechner noted a phenomenon, subsesequently called Fechner's paradox (Fechner, 1860), where if there is a difference in monocular luminance then the binocular threshold is worse than the better monocular performance. A neutral density filter placed over one eye causes a decline in binocular contrast sensitivity detection. As the strength of the filter increases, binocular summation decreases until binocular threshold equals monocular threshold. If the strength of the filter is increased further the binocular threshold becomes higher than the monocular threshold (binocular inhibition). A further increase in filter density results in suppression of the filtered eye and the binocular thresholds return to the monocular threshold level (Pardhan and Elliott, 1991)

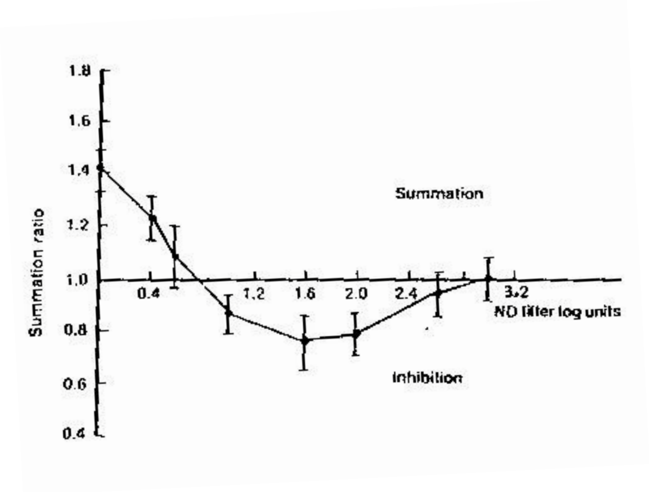



Figure 3. Average summation ratios of monocular and binocular contrast thresholds through neutral density filters of different strength placed over one eye. Taken from Pardhan et al., (1990)

Maximal inhibition occurs when the luminance difference between the two eyes is 1.5 to 2 log units (Pardhan et al., 1990). Similar findings have been found for monocular defocus, where 2.50DS of blur was found to cause maximum binocular inhibition for contrast sensitivity targets of 6 cycles per degree (Pardhan and Gilchrist, 1990). In addition binocular inhibition was found in patients with unilateral cataract (section 2.7.1 Pardhan and Elliott, 1991).

## 1.2 Basis of Depth Perception

Perception of depth is the judgement of the absolute distance of the object from the observer or the relative distance between two objects (Millodot, 2002).

### 1.2.1 Monocular Cues

Monocular cues are present in both monocular and binocular vision (von Noorden and Campos, 2002). They can be static, based on geometric principles or conditions of illumination or due to differential motion across the visual field either when the subject is moving through the environment or objects in the scene are moving relative to each other (Blake and Sekuler, 2006). The following cues are static cues:

- Overlying contours or occlusion where an object that interrupts the contours of a second object is perceived as being closer. In addition the second, further away objects is also higher in the visual field (von Noorden and Campos, 2002);
- linear perspective, where lines which are parallel, for example railway tracks, appear to converge to a point in the distance (von Noorden and Campos, 2002);
- the size of familiar objects, for example, if the size of an object is known from experience, the distance of the object can be judged from the retinal image size;

- aerial perspective which is the effect of the atmosphere, due to light scattering from dust and moisture in the air, on the appearance of far objects. For example far mountains having a blue haze (von Noorden and Campos, 2002);
- texture gradient, which consists of visible texture on a surface that recedes in depth, the density of texture will vary with distance, in addition a sudden change in texture gradient signals a corner or edge of a surface (Blake and Sekuler, 2006);
- highlights and shadows, the visual system assumes the light source comes from above and that the position of shadows can determine depressions and elevations (Blake and Sekuler, 2006).

In addition to the above static cues, motion parallax is the cue gained from motion of the head or body within the environment or movement of objects within the environment. Objects further away from the viewer will appear to make a larger movement than a closer object (von Noorden and Campos, 2002). When a viewer fixates a certain point, objects in front of the point of fixation move opposite to the viewer's motion whilst objects beyond the point of fixation will move in the same direction (Blake and Sekuler, 2006). Relative depth judgements based on motion parallax have been found to be close to the accuracy of judgements based on binocular disparity (Graham and Bartlett, 1965) which will be discussed in the next section (1.2.2).

### 1.2.2 Stereopsis

Stereopsis is defined as awareness of the relative distances of objects from the observer, by means of binocular vision only and based on retinal disparity (Millodot, 2002) and occurs when the eyes are aligned.When the eyes fixate on an object, fixation will fall on two corresponding retinal points (the foveae) of either eye. Parts of the object that are closer to the observer will stimulate retinal areas that are further apart and further away parts of the objects will stimulate retinal areas closer together. However due to the horizontal separation of the eyes these parts of the objects will stimulate disparate retinal rather than corresponding retinal points (Kandal et al., 1991) as shown in Figure 4.

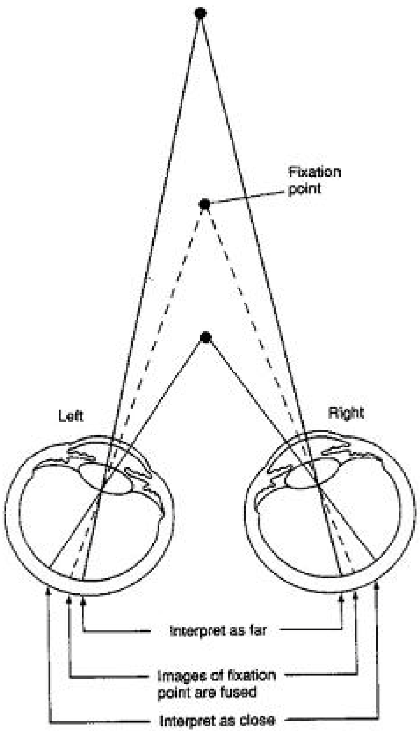



Figure 4. Horizontal Retinal Disparity. Taken from Kandal (1991)

Sensory fusion of the disparate points will result in the perception of depth, providing that the fused image occurs within Panum's area (von Noorden and Campos, 2002). If the point of the object is in front of the fixation plane then the disparity is classed as crossed, as the visual axis cross in front of the horopter. The disparity is described as uncrossed if the object is behind the plane of fixation as the visual axis is uncrossed at the horopter (Howard and Rogers, 1995).

Stereopsis was first recognised and described by Charles Wheatstone in 1838, who designed the stereoscope (Figure 5) where two photographs which were identical apart from a horizontal disparity of approximately 6cm were presented dichoptically using mirrors to give a single image with the illusion of depth (Hubel, 1988).

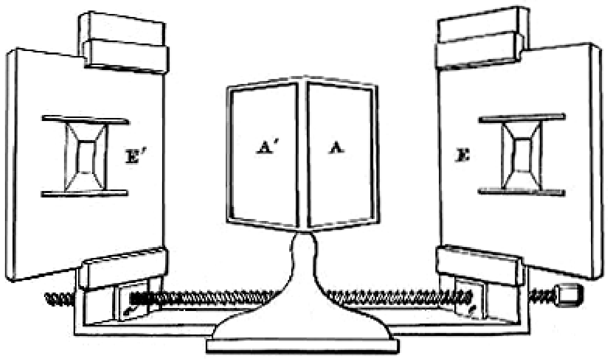



Figure 5. The Wheatstone Stereoscope, the angled mirrors (A) reflected stereoscopic images (E) towards the viewer's eyes. www.acmi.net.au (Sept 2008)

Stereoacuity ($\eta$) is the minimum disparity that still produces a stereoscopic effect and is expressed in seconds of arc. The angle of stereoacuity is calculated from the difference in depth between the target and background and the depth of the background, as set out in the formula below, where d is the distance of the objects, $\Delta d$ is the difference in depth between the target and the background and a is the separation between the two eyes (pd). The outcome is multiplied by 206,000 to convert the angle from radians to seconds of arc.

$$\eta = \frac{a\Delta d}{d^2} \times 206{,}000$$

In 106 young subjects with normal vision, stereoacuity was measured by Howard in 1919 using the Howard-Dolman apparatus, which consists of two vertical rods viewed at 6 metres though an aperture. One rod is in a fixed position and the other can be moved forward and back. Subjects had to identify if the moveable rod appeared to be positioned in front or behind the fixed rod. Stereoacuity was determined as the least depth distance discriminated correctly 75% of the time at 6 metres. The best stereoacuity scores achieved were between 1.8 and 2.7 seconds of arc (Graham and Bartlett, 1965). Stereopsis occurs across the binocular visual field but the lowest threshold is achieved close to fixation. Stereoacuity also varies with the duration of the stimulus, with best stereoacuity measured when the presentation of the target is 3 seconds or over (Ogle, 1950). Other factors which affect stereoacuity will be discussed fully in Chapter 2.

### 1.2.3 Random Dot Stereograms

Fusion of disparate targets occurs when matching contours occur on disparate retinal points. However in 1961 Julesz demonstrated that it was possible to perceive disparity without the presence of monocular contours by designing random dot stereograms (Figure 6). When the images are viewed monocularly both images appear to be a homogenous pattern with no recognisable features. When viewed stereoscopically there is strong impression of depth, in the case of Figure 6 a square appears in depth in front of the background.

Figure 6. A Random Dot Stereogram. When viewed stereoscopically a central square appears in depth, in front of the background. www.cognitivescience.org.uk (Sept 2008)

Random dot stereograms are computer generated, where the pattern of each pair is designed so there are corresponding areas of zero disparity and corresponding picture elements which are shifted horizontally within each pattern to generate horizontal disparity and give rise to the perception of depth (Julesz, 1964). Random dot stereograms demonstrate that correspondence of objects in the retinal image can be established without recognition of the object (Julesz, 1964). In contour based stereograms the disparity can be detected by the matching of similar contours, which Julesz referred to as local stereopsis. Disparity cannot be detected in random dot stereograms by matching of the points due to the ambiguity in which points could be matched up. Therefore matching occurs between global areas, larger than the individual elements in the stereogram, hence giving the term global stereopsis (Howard and Rogers, 1995).

### 1.2.4 Oculomotor Cues

The amount the eyes converge and adjust focus (accommodate) to view near objects can be used to provide limited depth judgements based on proprioceptive cues from the eye muscles. Both cues are restricted in range, for example convergence is limited to no further than six metres and accommodation to less than this (Blake and Sekuler, 2006). Accommodation has not been found to be an accurate cue and convergence has been found to be a useful depth cue only in the absence of other visual cues (Blake and Sekuler, 2006). However, it has been suggested that convergence angle is used with horizontal disparity. Horizontal disparity can only gauge relative depth, and therefore information from the oculomotor system regarding the fixation distance can be used to scale the judgement of horizontal disparity to provide a judgement of absolute depth. Although there is some support for this, the extent of interaction and at what level in visual processing the interaction between the ocular motor system and disparity sensitive cells (section 1.3.2) occurs is not yet known (Gonzalez and Perez, 1998).

### 1.2.5 Integration of Depth Cues

Normally monocular cues and stereoscopic cues work in conjunction. If monocular cues are introduced that conflict with stereoscopic cues then the greater weight given to each cue can vary from individual to individual, with some observers giving more weight to monocular cues whilst others being more sensitive to disparity cues (von Noorden and Campos, 2002).

The angular limit of stereoacuity is the same for both distance and near (Wong et al., 2002) although the absolute depth perceived increases with distance. For example at 40cm, stereoacuity of 20 secs of arc (with a pd of 65mm) is equivalent to a depth of

0.2mm, but at 5 metres this is equivalent to a depth of 373mm. Therefore the relative importance of stereopsis as a depth cue declines for distances over 10 metres (Schor and Flom, 1969) with only monocular cues used for distances over approximately 30 metres (Kandal et al., 1991).

## 1.3 Neural Basis of Stereopsis

### 1.3.1 Parvocellular and Magnocellular Pathways

The visual system can be divided into two segregated pathways, the magnocellular and the parvocellular. The visual pathway is shown in Figure 7 from the retina to the primary visual cortex.

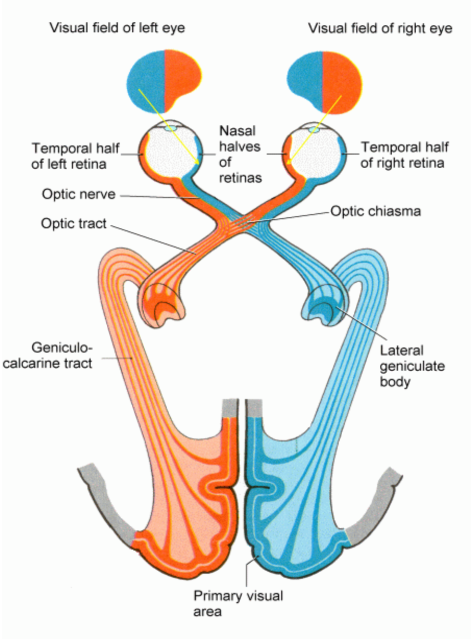



Figure 7. The Visual Pathway. www.instruct.uwo.ca (modified Sept 2008)

The division into parvo and magnocellular pathways starts at the level of retinal ganglion cells, which can be divided into type A cells, which have larger receptive fields and project to the magnocellular layers of the lateral geniculate nucleus (LGN) and smaller type B cells which project to parvocellular layers in the LGN. The layers of the LGN are shown in Figure 8. The separation of the pathways continues to the primary visual cortex. It is thought that the parvocellular pathway is selective for colour and form whilst the magnocellular pathway encodes movement and depth perception (Livingstone and Hubel, 1988).

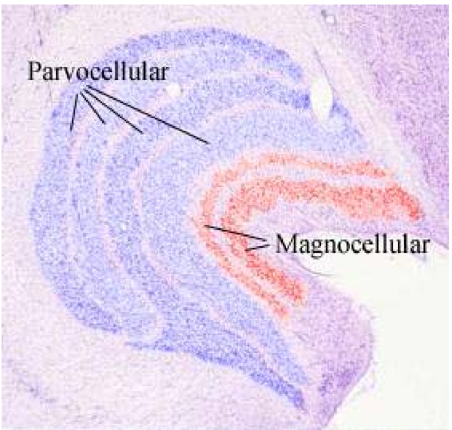



Figure 8. Layers of the LGN. www.psych.ucalgory.ca (Sept 2008)

### 1.3.2 Binocular Cells

Within the primary visual cortex (V1) half of cells have been found to be binocular, i.e. they receive input from both right and left eyes (Hubel, 1988). Four different types of binocular cell have been identified in primates which are tuned excitatory cells, tuned inhibitory cells and near and far cells (Poggio and Fischer, 1977, Poggio and Talbot, 1981). Excitatory cells are tuned to show maximum response to a narrow range of disparity, including zero disparity, and therefore get maximal input from images on the horopter and very fine stereopsis. Inhibitory cells are suppressed by disparities of zero and activated by disparities other than zero. Near neurons receive maximum stimulation from stimuli in front of fixation (crossed disparity) and far neurons receive maximum stimulation from stimuli behind fixation (Poggio and Fischer, 1977, Poggio and Talbot, 1981). Cells that are sensitive to disparity also show orientation specificity and respond well to moving stimuli (Hubel, 1988). The amount of disparity that gives rise to the maximum response varies from cell to cell (Blake and Sekuler, 2006). Cells that are sensitive to disparity are also found in higher processing areas within the visual pathway, including V2, V3 and the middle temporal (MT) visual area and medial superior temporal (MST) visual area (Kandal et al., 1991, DeAngelis, 2000). Other types of cells, for example cells which are orientation selective are arranged into columns, so that each column contains cells with maximum tuning to a certain orientation (Blake and Sekuler, 2006). However, there is no strong evidence that disparity sensitive cells are arranged in columns in V1, but there is some evidence of topographical organisation, in stripes of disparity tuned cells in V2 and MST (DeAngelis, 2000)

### 1.3.3 Processing of Local and Global Stereopsis

It has been proposed that processing of local and global stereopsis occur in different regions of the visual pathway, as patients who had temporal or occipital brain damage demonstrate differential impairment to global compared to local stereopsis (Cowey and Porter, 1979, Ptito et al., 1991). However if the targets used for testing local and global stereopsis are matched in terms of stimulus size then the results appear to show only one mechanism with one peak sensitivity, dependent on stimulus size (Richards and Kaye, 1974). Furthermore it has been shown that adaptation to a global stereopsis stimulus resulted in after effects that affect both local and global stereopsis (Rose and Price, 1995). Therefore the evidence now appears to show that there is no obvious differentiation of processing of global and local stereopsis.

## 1.4 Ocular Dominance

### 1.4.1 Definition of Ocular Dominance

Ocular dominance was first proposed by Porta in 1593, upon noticing that in some circumstances when both eyes were open, the input from only one is used (Porac and Coren, 1976). Ocular dominance was initially attributed to laterality, for example right handedness (Coren and Kaplan, 1973). However handedness reflects hemispheric dominance, but this cannot be the case for ocular dominance as due to semidecussation of the optic nerve fibres at the optic chiasm (Figure 7), both eyes project to both cerebral hemispheres and, in addition ocular dominance has been consistently found not to correlate with handedness (Mapp et al., 2003). A review paper (Porac and Coren, 1976) has identified several definitions of ocular dominance, which are dependent on the test used to identify the dominant eye. The different definitions are as follows;

- Sighting dominance, the eye used for monocular viewing, for example through a telescope;
- Unconscious sighting dominance, where one eye is not deliberately chosen as above but the subjects believe they are using binocular viewing, usually for alignment of a distant target with a near target, but only one eye is used for the task in order to avoid diplopia. A common example of this type of sighting test

is the Miles test where subject view a distant target through a cardboard cone, with the cone held by both hands (and hence avoiding the influence of the dominant hand). The dominant eye is the eye aligned with the cone aperture;

- Binocular rivalry, where disparate images are presented to the two eyes, the dominant eye is defined as the one that maintains its image for the longest period;
- Acuity tasks, where the dominant eye is defined as the eye with the best resolution acuity;
- Motor tasks, where the dominant eye is the eye that displays better motor control, for example the eye that maintains fixation during a near convergence task or even the eye that is more difficult to wink, or cannot be winked without some lowering of the contralateral eye lid;
- Clarity tests, where the dominant eye is the eye with the clearer and more intense image. This has been related to pupil aperture, so the dominant eye is defined as the eye with the largest pupil diameter;
- Innervation density, the dominant eye is defined as the eye with greater receptor density.

Ocular dominance is most commonly defined as sighting dominance. Most studies find that the vast majority (on average, 97%) of observers have a dominant eye, with approximately two thirds being right eye dominant and one third being left eye dominant (Porac and Coren, 1976). If ocular dominance was a single phenomenon then the different tests of ocular dominance would consistently determine the same eye. However this is not the case, for example there is no relationship between sighting dominance and the eye with the better acuity (Pointer, 2007). Based on the outcomes and correlations between 13 different tests of ocular dominance, Coren and Kaplan (1973) identified three distinct types of ocular dominance which account for variance in the test results: sighting dominance which included both types of sighting tests outlined above, sensory dominance which includes binocular rivalry tests, and finally acuity dominance, which accounts for little of the variance in a normal population with mainly equal acuity, but may be a stronger factor in a population with amblyopia (Coren and Kaplan, 1973).

In contrast to the above findings, it has been found that in tests of binocular rivalry the image presented to the sighting dominant eye has a longer duration than the image presented to the non-dominant eye (Porac and Coren, 1978, Handa et al., 2004b, Handa et al., 2005). The image presented to the sighting eye being viewed for 3 seconds longer, on average, that the image presented to the non-sighting eye (Porac and Coren, 1978). In addition, by adjusting the relative contrast of the targets the strength of ocular dominance could be assessed, classifying subjects as having weak or strong dominance (Handa et al., 2004b, Handa et al., 2005). However other measures classed as sensory dominance, for example blur suppression do not show any link with sighting dominance (Schor et al., 1989).

### 1.4.2 Ocular Prevalence

Ocular or stereo prevalence is the perceived deviation towards the left or right from the physical midline of aligned stereo images (Ehrenstein et al., 2005) and  refers to objects that fall within Panum's area. This differs from ocular dominance where ocular (sighting) dominance uses two targets than fall outside of Panum's area and result in diplopia and hence one eye is chosen over the other. Ocular prevalence is determined by asking subjects to vertically align two stereo targets. In the presence of ocular prevalence the images are misaligned, with one target shifted to the right or left, depending on which eye is prevalent. The amount the image is shifted can be used to define the extent of the ocular prevalence (Kommerell et al., 2003). Studies that have investigated prevalence have demonstrated that it occurs close to stereothreshold and at the edge of Panum's area and that subjects with ocular prevalence do not show any deterioration in stereoacuity (Kromeier et al., 2006). Ocular prevalence has been found to correspond to sighting dominance in the majority of subjects (Kommerell et al., 2003, Ehrenstein et al., 2005).

### 1.4.3 Neurophysiology of Ocular Dominance

Binocular cortical cells in the primary visual cortex (V1) display ocular dominance in that they show a stronger activation depending on whether the input is from the left or right eye. Cells that favour the left or right eye are organised in alternating ocular dominance columns within the primary visual cortex, where all the cells in the column are maximally stimulated by the same eye (Blake and Sekuler, 2006). Functional MRI studies have confirmed the presence of ocular dominance columns in humans, using binocular and monocular stimulation of the eyes by LEDs mounted on to the head (Menon et al., 1997). An fMRI study has also been used to show a functional basis for ocular dominance. Sighting dominance was determined in 22 young volunteers. Eight were found to be left eye dominant and 14 were right eye dominant. Volunteers were stimulated with LED goggles monocularly or binocularly. Stimulation of the dominant eye showed a bigger area of activation, compared to activation of the non-dominant eye and this reached statistical significance for right eye dominance (Rombouts et al., 1996)

To summarise, there is still no clear consensus on ocular dominance, whether there is just one dominant eye or whether different functions have different dominant eyes. However sighting dominance is the most commonly defined type of dominance, and it has been found to correlate to eyedness (the eye chosen for monocular tasks) as well as ocular prevalence and the most recent studies have found a link between sighting dominance and sensory dominance. In addition sighting dominance has been found to have a functional basis. Therefore within the experimental chapters, ocular dominance will be defined and assessed using a sighting test.

# Chapter 2

# Disruption to Stereopsis

## 2.1 Strabismus

Heterotropia, also called strabismus or squint is the misalignment of the visual axis relative to each other and results in a manifest deviation of the eyes (von Noorden and Campos, 2002). The prevalence of strabismus is about 2.3% (180 out of 7825 seven year olds) of children in the UK (Williams et al., 2008), with similar levels (2.5 and 2.4%) found in American black and Hispanic children (Varma et al., 2008). Strabismus has been found to be more common in children from a poor socioeconomic background (Williams et al., 2008). Strabismus can be classified by the direction of the deviation. For example, if the visual axes converge then the deviation is classed as an esotropia, though the deviation can be vertical (hypertropia) or torsional (cyclotropia). The deviation can also be classified according to whether the deviation is concomitant (equal in all directions for a given fixation distance) or incomitant where the deviation varies in size in different positions of gaze, depending on the direction of action of the paretic or paralytic muscle (von Noorden and Campos, 2002).

In strabismus the image of one eye is suppressed in order to prevent diplopia. In the majority of cases suppression is regional, occurring in the deviated eye at both the fovea and the peripheral region on which the object of attention is imaged, giving rise to two functional scotomas (von Noorden and Campos, 2002). Patients with a large manifest deviation do not have useful stereopsis. Small deviations (microtropias) of less than 8 prism dioptres can demonstrate stereopsis, although it is impaired (von Noorden and Campos, 2002).

## 2.2 Amblyopia

### 2.2.1 Prevalence and Cause

Amblyopia is defined as a unilateral or bilateral decrease in visual acuity, caused by deprivation of pattern vision or abnormal binocular interaction, for which no cause can be detected by physical examination of the eye and which in appropriate cases can be corrected by therapeutic means (von Noorden and Campos, 2002). Prevalence of amblyopia varies with population and definition with studies reporting prevalence in adults of between 1 and 5% (Webber and Wood, 2005). In an older population of 3654 adults aged over 49 years, prevalence was found to be 3.2% with amblyopia defined as acuity of 6/9 or less in the absence of any eye disease or injury (Attebo et al., 1998). Likely causes were found to be anisometropia for the majority of cases (50%), strabismus in 19% of cases and a mixture of strabismus and anisometropia in 27% of cases. Visual deprivation, assumed in patients with a history of congenital cataract, ptosis or corneal or other media opacities, accounted for only 4% of cases (Attebo et al., 1998). Treatment of amblyopia involves correction of the underlying cause, for example refractive error or cataract surgery and penalisation of the non-amblyopic eye, of which patching remains the most effective method (Campos, 1995).

### 2.2.2 Visual Function in Amblyopia

Amblyopia is usually defined in terms of impaired visual acuity, as stated above. A review of the literature shows that in amblyopic eyes visual acuity measured with single letter acuity is better than visual acuity measured with lines of letters, a phenomenon thought to be due to crowding, attributed to contour interaction, abnormal eye movements found in amblyopia or attentional factors (Campos, 1995). In addition visual acuity in an amblyopic eye is found to be less affected by a drop in luminance than a non-amblyopic eye (Campos, 1995).

Other measures of visual function have also been found to be impaired in amblyopia including contrast sensitivity (Campos, 1995) and stereoacuity (Lee and Isenberg, 2003, McKee et al., 2003). The presence of stereopsis was found to vary depending on the cause of amblyopia. Two thirds of subjects with anisometropic amblyopia passed a stereotest (defined as being able to correctly identify any disparity targets on the Randot "circles" stereotest test) compared to only 10% of those with strabismic amblyopia (McKee et al., 2003). A study investigating stereoacuity in 61 children (mean age 5.1 years, range 3.5 to 8 years) with amblyopia, secondary to anisometropia, microtropia or intermittent heterotropia, found a linear relationship between monocular acuity of the amblyopic eye and stereoacuity following occlusion therapy. Occlusion therapy (mean duration 36 weeks, range 12-102 weeks) was found to significantly improve visual acuity and stereoacuity, regardless of the cause of amblyopia, from a mean stereoacuity of 1167 seconds of arc to 101 seconds of arc (Titmus stereotest, Lee and Isenberg, 2003).

## 2.3 Impairment of Contrast and Stereopsis

Simons (1984) measured stereoacuity using three clinical tests, Frisby, Randot and TNO, with a 'fogging' lens placed over one or both eyes. Findings indicated that monocular fogging of the target impaired stereoacuity compared to binocular fogging, by a ratio greater than two to one. This finding was consistent for all three tests (Simons, 1984). The decline in contrast caused by the fogging lenses was not quantified, although it is reported that Snellen visual acuity was reduced to approximately 6/30. In addition, subjects reported suppression of the fogged eye when one eye was fogged (using the suppression target on the Randot stereotest) with no suppression reported with binocular fogging. The findings have since been repeated using psychophysical tests, with contrast of the targets adjusted rather than the eyes being fogged. When the contrast presented to the two eyes is equal then the stereoacuity is approximately inversely proportional to the square root of the target contrast, so reducing the target contrast will cause an increase in stereothreshold (Legge and Gu, 1989). If contrast is reduced for a target in front of one eye only, then there is a greater impairment of stereoacuity than a binocular reduction of contrast target (Halpern and Blake, 1988, Legge and Gu, 1989, Schor and Heckmann, 1989, Larson and Bolduc, 1991, Cormack et al., 1997). The decline caused by loss of contrast presented to one eye was almost five times greater than the same binocular loss of contrast (Legge and Gu, 1989). Although this differs from the values found by Simons (1984) it is likely that the difference in findings may be due to differences in spatial frequency of the tests. The different effect between binocular and monocular decline in target contrast on stereoacuity was found for targets with low spatial frequency but is less so at higher spatial frequencies (Schor and Heckmann, 1989, Cormack et al., 1997). The different effects on stereoacuity between monocular and binocular contrast reductions disappears at spatial frequencies over 5 cycles per degree (Cormack et al., 1997). In addition it was found that stereoacuity measured on random dot stereogram targets, which contain high spatial frequency information showed no difference between monocular and binocular reduction in contrast (Cormack et al., 1997). This differs from Simons (1984) where there was a greater effect of monocular fogging, compared to binocular fogging on clinical tests that utilise random dot stereograms. It is not clear why there is this difference in findings, but it may be related to differences in impairment of contrast, which can not directly be compared between the studies.

## 2.4 Refractive Error

Refractive blur acts as a low pass filter i.e. it selectively attenuates higher spatial frequencies. Binocular refractive blur causes a significant impairment to stereoacuity levels, whether measured on real depth cues (Larson and Lachance, 1983, Wood, 1983), line based stereotests (Westheimer and McKee, 1980) or random dot stereograms (Schmidt, 1994). As with declining contrast of stereotargets, the effect on stereoacuity is significantly greater when there are disparate levels of blur between the two eyes (Westheimer and McKee, 1980, Larson and Lachance, 1983, Wood, 1983, Schmidt, 1994) and monocular refractive blur was found to cause a suppression scotoma in the blurred eye, which increases in size with increasing levels of blur (Brooks et al., 1996). Most studies have found that 0.50DS to 1.00DS of monocular blur causes a measurable decline in stereoacuity (Ong and Burley, 1972, Westheimer and McKee, 1980, Lovasik and Szymkiw, 1985, Brooks et al., 1996) whilst one study reported a decline in stereoacuity with as little as 0.125DS of monocular blur (Larson and Lachance, 1983). Studies have also investigated whether refractive blur also causes a decline in stereoacuity due to an imbalance of accommodation and/or convergence (Westheimer and McKee, 1980, Lovasik and Szymkiw, 1985). In both studies no effect on stereoacuity was found, and it was concluded that changes to accommodation or convergence induced by refractive lenses do not contribute to the reduction in stereoacuity.

An additional effect of refractive blur that does reduce stereoacuity is a change of retinal image size due to spectacle magnification (aniseikonia, Lovasik and Szymkiw, 1985) with no measurable stereopsis for image size differences greater than 32% (Lovasik and Szymkiw, 1985). It is likely that monocular refractive blur causes a decline in stereoacuity through both attenuation of high spatial frequency contrast sensitivity and aniseikonia as 1.50DS over one eye causes aniseikonia of 4%, but diminishes stereoacuity to the same level as an afocal lens that causes aniseikonia of 8% (Lovasik and Szymkiw, 1985).

Most studies have investigated the effect of spherical refractive blur on stereoacuity. In studies that have investigated astigmatic blur the effect was found to be less that the same magnitude of spherical blur (Brooks et al., 1996), but the outcome appears to be dependent on the position of the cylindrical axis (Brooks et al., 1996, Savage et al., 2003, Chen et al., 2005). However the results from these different studies are conflicting. For example, with binocular cylindrical blur, oblique orientation of induced astigmatism was found to cause the greatest decline in stereoacuity, followed by against-the-rule, then with-the-rule astigmatism (Chen et al., 2005). However another study found that stereoacuity was better with against-the-rule compared to with-the-rule astigmatism (Savage et al., 2003), even though it used the same test of stereoacuity (Titmus) as Chen et al. In addition no effect of axis orientation of monocularly induced cylindrical blur on stereoacuity was found by Chen and colleagues (Chen et al., 2005), whilst Brooks et al., 1996 found that monocular oblique astigmatism caused a greater decline in stereoacuity

**Comment [j1]:** Already said

than against-the-rule astigmatism (Brooks et al., 1996). In contrast to spherical blur, no difference was found in the decline in stereoacuity caused by equivalent powers of monocular and binocular induced astigmatic blur (Chen et al., 2005).

## 2.5 Monovision

### 2.5.1 Definition of Monovision

Monovision is a method of correcting presbyopia where only one eye is focussed for near vision with the other focussed for distance viewing (Evans, 2007). Presbyopia is the refractive condition where the accommodative ability of the eye is insufficient for near vision work (Millodot, 2002). In spectacle wearers, presbyopia is typically corrected with near spectacles or multifocal lenses; although a monovision approach could be used. However monovision is not commonly used in spectacle correction due to the prismatic effects induced by differential spectacle powers and aniseikonia induced through monocular differences in refractive power (Section 2.4). However for contact lens wearers who do not wish to wear additional spectacles or who are unwilling to accept the visual compromises from multifocal contact lenses (section 2.5.6) then monovision can be a successful solution. Contact lenses do not have either of the drawbacks of prismatic or aniseikonic effects associated with spectacle monovision wear and therefore are a suitable modality for monovision correction. Furthermore, monovision has also been suggested as a desirable outcome for refractive surgery (Wright et al., 1999, Goldberg, 2001, Jain et al., 2001, Greenbaum, 2002, Miranda and Krueger, 2004, Levinger et al., 2006, Reilly et al., 2006, Braun et al., 2008).

#### 2.5.2 Success of Monovision

The success of monovision contact lens correction (defined as percentage of participants wishing to continue with regular monovision wear) has been reported as ranging from 64 to 94% (Koetting, 1970, Sheedy et al., 1988, Back et al., 1989, Gauthier et al., 1992, Harris et al., 1992, du Toit et al., 1998). The higher success rates occurred in patients who were pre-existing contact lens wearers (Koetting, 1970) or subjects who had been screened to ensure they had no high visual demands that may be unsuitable for monovision (Sheedy et al., 1988, Harris et al., 1992). The lower success rates occurred in groups of subjects who were not pre-existing contact lens wearers or had discontinued lens wear in the past (Back et al., 1989, Gauthier et al., 1992, du Toit et al., 1998) and therefore discontinuation of wear was not necessarily related to monovision but may have been due to contact lens related difficulties, such as difficulties with lens handling (Gauthier et al., 1992). Overall monovision contact lens correction achieves a high level of successful wear in contact lens patients. Furthermore presbyopic patients who have undergone surgical monovision correction have a higher reported success rate of 88% to 100% (Wright et al., 1999, Goldberg, 2001, Jain et al., 2001, Greenbaum, 2002, Miranda and Krueger, 2004, Levinger et al., 2006, Reilly et al., 2006, Braun et al., 2008). Here the success rate was defined as the number of patients who had not undergone further surgery to remove monovision correction. The higher success rate than in contact lens induced monovision, may be due to the absence of contact lens related difficulties, a reluctance of patients to undergo a second surgical procedure, better adaptation due to constancy of optical correction, or that patients were selected for monovision surgical correction following a successful monovision contact lens trial (Miranda and Krueger, 2004, Reilly et al., 2006).

### 2.5.3 Ocular Dominance and Monovision

Correction of the dominant eye for distance is the most commonly used modality. A review of the literature revealed that 95% of patients had their dominant eye corrected for distance (Jain et al., 1996). Other suggested modalities include correcting the most myopic eye for near (Ghormley, 1989), correcting the right eye for near vision (for ease of reading from left to right, Sanchez, 1988), and correcting the eye depending on visual demands of the patient, for example correcting the dominant eye for near if the patient regularly does prolonged close work (McMonnies, 1974, Sanchez, 1988).

It was shown by McGill and Erickson (1991) that correction of the non-dominant eye for distance led to a greater esophoric shift and reduction in the vergence fusional reserves, compared to correction of the dominant eye for distance. It is assumed that corrected patients will be better able to suppress a blurred image from the non-dominant eye. However no difference was found in blur suppression ability (measured by asking subjects wearing monovision to adjust the brightness of a target light until they were able to suppress the blurred image) when either the dominant or non-dominant eye was blurred (Schor et al., 1989). Furthermore there was no correlation found between the sighting dominant eye and the sensory dominant eye; where sensory dominance was defined as the eye that could suppress the blurred image of the brightest target, using the same method as Schor et al (1989). Correction of the dominant or non-dominant eye for distance made no difference to binocular visual acuity and this remained the case for both sensory and sighting dominance (Robboy et al., 1990). In contrast, when a balance technique using binocular rivalry (sinusoidal gratings presented at differing orientations to either eye) was used, it was found that the dominant eye, determined by a sighting test, was the same eye as the dominant eye determined by the sensory binocular rivalry test (Handa et al., 2004b). Binocular summation was shown to occur (measured using contrast sensitivity) only when the non-dominant eye was corrected for near (Handa et al., 2005).

Despite the differences in study findings on the importance of ocular dominance in monovision correction it has been consistently reported that patients with strong ocular dominance are more likely to be dissatisfied with monovision correction (Jain et al., 1996, Wright et al., 1999, Handa et al., 2004a).

### 2.5.4 Visual Performance and Monovision

High contrast binocular acuity in patients wearing monovision contact lenses has been found to be reduced compared to patients wearing a binocular distance correction by an average of 0.06 logMAR or 3 letters (Back et al., 1992, Erickson and McGill, 1992, Harris et al., 1992, Collins et al., 1993, Back, 1995). In patients who had undergone LASIK monovision correction there was a trend of poorer high contrast binocular acuity compared to patients who had full distance correction but the difference between the two groups did not reach statistical significance (Wright et al., 1999). Of note, Collins et al (1993) found that the loss of binocular visual acuity in monovision patients was independent of level of blur and was not significantly different from the patients' best monocular visual acuity (Collins et al., 1993). Another study found that only 1 of 19 monovision patients had binocular acuity better than best corrected monocular acuity, and that the majority of monovision patients demonstrated suppression of the eye corrected for near (Kirschen et al., 1999). It appears that there is suppression of the eye corrected for near, leading to loss of binocular summation for distance viewing, but there is no evidence of binocular inhibition.

Binocular low contrast acuity was also significantly impaired in monovision conditions, compared to full distance correction (Back et al., 1992, Erickson and McGill, 1992, Back, 1995). Contrast sensitivity function was reduced in monovision contact lens correction compared to multifocal spectacle correction (Rajagopalan et al., 2007) although another study found that contrast sensitivity was significantly poorer in monovision correction for higher spatial frequencies (8 or 16 cycles per degree) but not lower spatial frequencies (0.5 to 4 cycles per degree, Collins et al., 1989). This is in agreement with findings that monocular refractive blur was found to cause loss of binocular summation of contrast sensitivity at spatial frequencies of 6 cycles per degree (Pardhan and Gilchrist, 1990).

Based on findings of impairment of stereoacuity in conditions of monocular refractive blur (Section 2.4) it is unsurprising that the majority of studies have found that stereoacuity is impaired in monovision patients (McGill and Erickson, 1988, Back et al., 1992, Back, 1995, du Toit et al., 1998, Kirschen et al., 1999, Levinger et al., 2006). Of particular interest is that stereoacuity was found to be worse when the dominant eye was corrected for near (McGill and Erickson, 1988). There is no evidence of adaptation to monocular blur as the level of stereoacuity did not improve from when subjects were first fitted with monovision correction compared to a second measurement two weeks later (du Toit et al., 1998). Furthermore it was found that stereoacuity in patients who had had surgical monovision correction, measured at a minimum of six months post-op (average 14.5 months) were found to have be reduced compared to age-match normals even when given full binocular correction, and patients with higher levels of induced anisometropia (≥ 1.50DS) demonstrated foveal suppression when wearing full binocular correction (Fawcett et al., 2001).

Unsuccessful monovision wear was found to be associated with poorer stereoacuity than successful monovision wear (Erickson and McGill, 1992, Back, 1995) as well as increased levels of reported ghosting of distance vision (Back, 1995) and worse high and low contrast visual acuity (Erickson and McGill, 1992). The strength of the near addition may also play a role in the success of monovision, as high levels of anisometropia were reported as a reason for unsuccessful monovision surgical outcome (Wright et al., 1999) and visual performance of monovision patients was reduced when reading additions were greater than 2.50DS (Johannsdottir and Stelmach, 2001).

#### 2.5.5 Task Performance and Monovision

In order to investigate if any impairment in visual function resulting from monovision correction affects patients' ability to perform every day tasks, studies have investigated performance of near tasks in monovision correction compared to full distance contact lens correction worn with reading spectacles (Sheedy et al., 1988, Harris et al., 1992) or compared to other lens modalities (Harris et al., 1992).

Subjects were assessed on their performance in three near tasks; 1) letter editing, where three paragraphs of random nonsense words were displayed on a video screen and subjects had to count the number of a certain letter in the middle paragraph, reporting the number verbally as quickly as possible; 2) filing cards into alphabetical order into a metal card file box and 3) placing sharp pointers into straws one at a time. Performance was assessed on the number of errors made and the time taken to do the tasks. Subjects made fewer mistakes when wearing full correction compared to monovision and were also 2-6% slower in the monovision condition (Sheedy et al., 1988, Harris et al., 1992). Subjects were assessed at initial monovision contact lens fitting and following regular monovision wear, two and eight weeks later. Subjects improved in both the filing cards and pointers and straws tasks, but improved equally in both visual conditions, suggesting that the results were due to learning of the tasks rather than any adaptation to monovision (Sheedy et al., 1988).

### 2.5.6 Alternative Presbyopic Contact Lens Correction

Bifocal and multifocal designs of contact lenses are available as an alternative to monovision. In 'soft' lenses the design is based on simultaneous vision, where subjects can perceive both distance and near in focus simultaneously and "choose" the image to be viewed. Simultaneous vision designs include diffractive, where distance and near images are focussed through zone echelettes; aspheric, where there is a gradual flattening towards the edge of the lens leading to increasing plus power towards the lens periphery, and concentric designs, where either the central portion of the lens corrects for distance (centre distance), surrounded by an outer zone which is focussed at near or a near correction central portion (centre near) surrounded by a distance peripheral zone (Bennett, 2008).

A number of studies have compared visual performance and success rates of simultaneous vision bifocal lenses compared to monovision correction (McGill and Erickson, 1988, Back et al., 1989, Back et al., 1992, Harris et al., 1992, Kirschen et al., 1999, Richdale et al., 2006). The earliest simultaneous vision contact lenses were found to give poorer high contrast acuity than monovision correction (McGill and Erickson, 1988, Back et al., 1992) regardless of design. Monovision also performed better than diffractive and centre near lenses for low contrast distance acuity (Back et al., 1992).

There was no difference found for near stereoacuity between monovision and simultaneous vision contact lenses, with all contact lens modalities significantly worse than measurements taken with spectacles (McGill and Erickson, 1988). In another study it was found that monovision correction led to poorer stereoacuity than diffractive and centre near simultaneous perception designs (Back et al., 1992).

Subjects were found to have performed worse at near tasks (as outlined in Sheedy et al, 1988, section 2.5.5) with a diffractive bifocal design compared to subjects wearing monovision (Harris et al., 1992). In terms of success, monovision was found to be better than simultaneous design lenses, principally due to the greater visual compromise with early designs of bifocal contact lenses (Back et al., 1989).

**Comment [j2]:** ?

More recent studies have found that visual acuity is not compromised with later designs of bifocal lenses. For example patients wearing the Bausch and Lomb multifocal performed the same as when wearing monovision correction for both binocular distance high and low contrast visual acuity, with monovision correction only scoring better for low contrast near visual acuity (Richdale et al., 2006). Monovision correction was found to impair stereoacuity to a significantly greater degree than bifocal designs (Kirschen et al., 1999, Richdale et al., 2006) with suppression at near found with monovision correction, but not with bifocal correction (Kirschen et al., 1999). As visual performance was not as compromised with the later designs, 76% of subjects chose a simultaneous design as the preferred correction modality, compared to only 24% who chose monovision correction (Richdale et al., 2006).

## 2.6 Stereopsis and Ageing

It has been found that stereoacuity declines with age, with stereoacuity declining in those aged over 60 years old (Jani, 1966, Greene and Madden, 1987, Wright and Wormald, 1992, Brown et al., 1993, Yap et al., 1994, Rubin et al., 1997, Haegerstrom-Portnoy et al., 1999, Schneck et al., 2000, Zaroff et al., 2003, Lee and Koo, 2005, Garnham and Sloper, 2006) with only one study finding no effect of age on stereoacuity (Yekta et al., 1989). However this study had relatively younger participants (maximum age 69 years) compared to the other studies and only had seven subjects in the oldest age group which may explain why the findings are in conflict with other studies. Different measurements of stereopsis were used for the studies, however findings of decline in stereopsis with age remains consistent whether the measurement is based on clinical stereotests (Jani, 1966, Greene and Madden, 1987, Wright and Wormald, 1992, Rubin et al., 1997, Haegerstrom-Portnoy et al., 1999, Schneck et al., 2000, Lee and Koo, 2005, Garnham and Sloper, 2006) or if measurements were laboratory based (Brown et al., 1993, Yap et al., 1994, Zaroff et al., 2003).

Some studies have measured stereopsis in the elderly population with no exclusion criteria applied (Greene and Madden, 1987, Wright and Wormald, 1992, Rubin et al., 1997, Haegerstrom-Portnoy et al., 1999, Schneck et al., 2000). However a decline in stereopsis can be secondary to eye disease (section 2.7) and consequently these studies may have measured a decline in stereopsis that was due to increasing incidence of eye disease with age (Sperduto and Hiller, 1984, Klein et al., 1992, Klein et al., 1998, Leske et al., 2000, McCarty et al., 2003, de Voogd et al., 2005). However other studies have excluded potential participants with any known history of eye disease or ocular abnormality found on screening, including any media opacity (Brown et al., 1993, Yap et al., 1994). Other studies based exclusion criteria on visual acuity score, excluding subjects with visual acuity of Snellen worse than 6/9 in either eye (Jani, 1966, Zaroff et al., 2003), or even more stringently, worse than 6/6 in either eye (Brown et al., 1993, Yap et al., 1994). Despite these exclusions the finding of decline of stereoacuity with age remained robust.

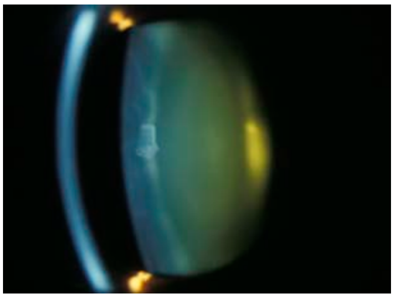
Studies have proposed explanations for the age-related decline in stereoacuity. Yap et al (1994) investigated whether a decline in retinal illumination, such as that caused by a age related decline in the transparency of ocular media may be a factor, however their results show that reducing the retinal illuminance using a neutral density filter in young adults did not have a significant effect on stereoacuity and did not reduce the level to that of elderly participants (Yap et al., 1994). Zaroff et al (2003) also found no effect of decreased retinal illuminance. Other suggestions include increased prevalence of heterophoria, with an increase found in fixation disparity with age (Yekta et al., 1989). However increased fixation disparity was not found to be related to poorer levels of stereoacuity (Zaroff et al., 2003). Rubin et al (1997) found that individuals with difference in visual function (visual acuity or contrast sensitivity) between eyes was associated with a much increased risk of having poor stereoacuity or classed as stereoblind (unable to detect 340 seconds of arc with Frisby stereotest) with 5 or more difference in lines on either test resulting in a huge increase in risk of being stereoblind; although this does not account for findings of impaired stereoacuity in studies with more stringent exclusion criteria.

The most commonly suggested reason for a decline in stereoacuity with age, is an age-related decline in neural cells in the retina and/or the visual cortex (Jani, 1966, Wright and Wormald, 1992, Yap et al., 1994, Zaroff et al., 2003, Lee and Koo, 2005). This is supported by evidence indicating the loss of stereopsis in glaucoma patients is due to a loss of retinal neural cells (section 2.6.3, Bassi and Galanis, 1991) and the high rate of poor or absent stereoacuity in patients with cortical cell loss such as patients with dementia (Poggio et al., 1985, Mittenberg et al., 2000). However Schneck et al (2000) measured other aspects of visual function including the reduction in contrast sensitivity due to the introduction of a glare source (disability glare) glare recovery and assessment of central visual fields using an Amsler chart. Disability glare highlights subtle ocular media opacites, and glare recovery or photostress represents a good test of retinal function as does the measurement of central visual field. Schneck et al (2000) found those with poor stereopsis performed poorly on at least one of the tests. In addition, although previously agreeing with other studies in finding age-related decline in stereoacuity, if the other visual measures were taken into account the effect of age disappeared (Schneck et al., 2000). Schneck et al (2000) therefore suggested that the decline in stereopsis is not due to loss of cortical function, but is more likely related to subtle changes in ocular function, not detected with visual acuity or contrast sensitivity measurements. This suggests that it may be possible to improve stereoacuity in elderly subjects, by providing optimal refractive correction and early cataract surgery.

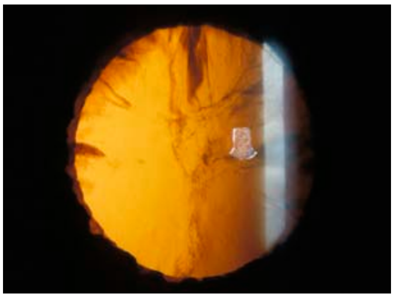
## 2.7 Stereopsis and Eye Disease

### 2.7.1 Age Related Cataract

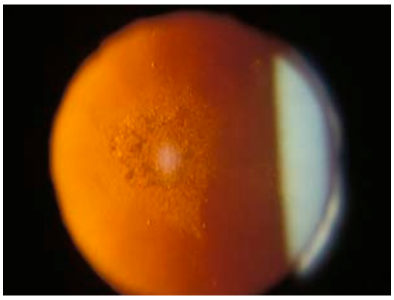
The definition of a cataract is the partial or complete loss of transparency of the crystalline lens substrate or its capsule (Millodot, 2002). The prevalence of cataract has been found to range from 38% to 59% (Sperduto and Hiller, 1984, Tsai et al., 2003), based on grading scales following slit lamp assessment. Both cross sectional and longitudinal data show that the prevalence of cataracts increases with age (Sperduto and Hiller, 1984, Klein et al., 1992, Klein et al., 1998, Leske et al., 2000, Klein et al., 2002, McCarty et al., 2003, Tsai et al., 2003). Prevalence also depends on gender, with women found to have a higher prevalence than men (Sperduto and Hiller, 1984, Tsai et al., 2003). The three most common types of cataracts are nuclear (Figure 9a) with prevalence ranging from 17 to 38%, cortical cataracts (Figure 9b) with prevalence of 14 to 22%, and posterior subcapsular cataracts (Figure 9c) with prevalence of 6 to 9% (Sperduto and Hiller, 1984, Klein et al., 1992, Tsai et al., 2003). Nuclear cataract is an extension of normal ageing, beginning as a yellowish hue in the nucleus of the lens and progressing to a brown appearing nucleus in advanced cataract. Cortical cataracts often begin as vacuoles between lens fibres which subsequently opacify and appear as spokes within the lens. Subcapsular cataracts lie centrally just in front of the lens capsule in the middle of the pupil, and can have a plaque like or granular appearance (Kanski, 2003). The type of cataract seen also varies with gender, with women more likely to have nuclear (Sperduto and Hiller, 1984, Klein et al., 1992) or cortical opacities (Klein et al., 1992) than men. The type of cataract can also vary with race, with cortical opacities more common than nuclear opacities in the black African population compared to the white population living in the same area (Leske et al., 2000). Risk factors also vary for different types of cataract, with smoking the chief risk factor for nuclear cataracts, increased blood pressure and diabetes for cortical cataracts, and increased blood pressure for posterior subcapsular cataract (Tsai et al., 2003).



a) Nuclear Cataract



b) Cortical Cataract



c) Posterior Subcapsular Cataract

Figure 9. Three most common types of age-related cataract a) Nuclear, b) Cortical and c) Posterior Subcapsular Cataract. Images courtesy of D.B Elliott.

Women are more likely to have undergone cataract surgery than men (Klein et al., 2002, Tsai et al., 2003) with overall incidence of cataract surgery found to be 5-13% (Klein et al., 2002, McCarty et al., 2003, Tsai et al., 2003). Again incidence of surgery increases with age with approximately 40% of an elderly population aged over 85 years over having undergone cataract surgery on at least one eye (Klein et al., 2002, Tsai et al., 2003).

Cataract was found to be the primary cause for the majority (75%) of visual impairment found in an elderly UK population, with prevalence of cataract found to be 10%. Prevalence was assessed on the basis that visual acuity was reduced by the presence of cataract to 6/18 or worse (Wormald et al., 1992) and hence cannot be directly compared to other studies reported above which assessed presence of cataract according to grading on slit lamp examination (Sperduto and Hiller, 1984, Klein et al., 1992, Tsai et al., 2003).

Cataract was found to adversely affect visual acuity, with Klein et al (1995) reporting Snellen visual acuity in eyes without cataract as 6/6, reducing on average to 6/7.5 with one type of cataract present and with two or more types of cataract reducing visual acuity on average to 6/12. Visual acuity was found to be worst with posterior subcapsular cataracts and best with cortical cataract (Klein et al., 1995). Unilateral cataract is shown to reduce both binocular visual acuity and contrast sensitivity, with high contrast acuity reduced due to the loss of binocular summation, and contrast sensitivity, measured on the Pelli Robson chart, reduced by binocular inhibition (Pardhan and Elliott, 1991). In early cataract, neither standard visual acuity or large letter contrast sensitivity (equivalent to Pelli Robson chart at 1 metre) were found to be sensitive to detect a decline in visual function, although small letter contrast sensitivity could detect changes related to the presence of early cataract (Elliott and Situ, 1998).

Cataract is associated with refractive change in the eye. Nuclear sclerosis is associated with a myopic shift of refractive error (Brown and Hill, 1987, Pesudovs and Elliott, 2003), with an average change between habitual and optimal refraction of 0.38DS in patients with nuclear sclerosis compared to age-match normals (Pesudovs and Elliott, 2003). In comparison, cortical cataracts were associated with a change of astigmatism, with an average change of 0.70DC, compared to age match normals (Pesudovs and Elliott, 2003). Refractive change due to cataract that is uncorrected will further contribute to loss of visual acuity due to the cataract. In addition refractive error related to cataract is likely to contribute to the increased level of anisometropia found in elderly subjects, compared to younger populations (Attebo et al., 1999, Qin et al., 2005).

Patients with bilateral cataracts have been found to have significantly impaired stereoacuity compared to age match normals (Elliott et al., 2000), with a finding of average stereoacuity of 800 seconds of arc in 137 elderly patients with bilateral cataract (Comas et al., 2007). Stereoacuity remains poor following first eye surgery (Laidlaw and Harrad, 1993, Laidlaw et al., 1998, Talbot and Perkins, 1998, Elliott et al., 2000, Castells et al., 2006, Comas et al., 2007), with 20-70% of subjects having no measurable stereoacuity, using clinical stereotests (Laidlaw and Harrad, 1993, Laidlaw et al., 1998, Castells et al., 2006), or average stereoacuity, measured as 152 seconds of arc (Elliott et al., 2000) or 282 seconds of arc (Comas et al., 2007). In addition there was no improvement in the level of anisometropia following first eye surgery (Laidlaw and Harrad, 1993, Elliott et al., 2000).

Following second eye surgery all studies found a significant improvement in stereoacuity (Laidlaw and Harrad, 1993, Laidlaw et al., 1998, Talbot and Perkins, 1998, Elliott et al., 2000, Castells et al., 2006, Comas et al., 2007), with all post-operative patients able to achieve a score on a clinical stereotest (Castells et al., 2006). Average stereoacuity ranged from 57 (Hayashi and Hayashi, 2004) to 70 seconds of arc (Comas et al., 2007) and was not statistically different from age matched normal data (Elliott et al., 2000). Levels of anisometropia also reduced following second eye surgery (Laidlaw and Harrad, 1993, Elliott et al., 2000), and again did not differ from age matched normal values (Elliott et al., 2000).

### 2.7.2 Age-Related Macular Degeneration

Early macular degeneration features discrete yellow spots (drusen) at the macular, along with hyperpigmentation and areas of depigmentation of the retinal pigment epithelium (RPE). Late macular degeneration (Figure 10) can feature geographic atrophy of the retinal pigment epithelium (dry AMD), pigment epithelial detachment, subretinal or sub-RPE neovascularisation, haemorrhage, exudates and fibroglial scarring (wet or exudative AMD, Kanski, 2003).

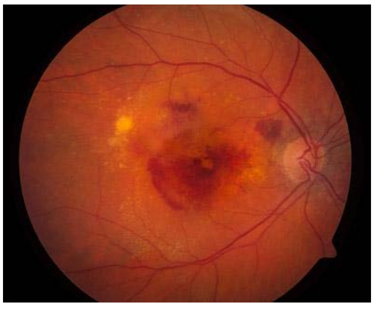


Figure 10. Exudative AMD. www.clevelandsightcenter.org (August 2008)

The prevalence of AMD was assessed by slit lamp and volk examination, looking for the presence of macular lesions including drusen, retinal pigment changes, exudative maculopathy and geographic atrophy. The prevalence of all types of lesion was found to increase with age. Early AMD was found in 12.1% and late AMD was found in 2.1% of the investigated population (Klein et al., 2002).

The presence of any type of gradable maculopathy was found on average to reduce acuity by two letters, compared to absence of any lesion (Klein et al., 1995). Late AMD reduced visual acuity by on average 7 lines (0.7 log score, Klein et al., 1995). The level of stereoacuity in AMD patients has not been reported, however, due to decline in visual acuity and likely asymmetry between the two eyes, it is highly likely to be impaired. Stereoacuity was shown to improve in 10 out of 91 patients with exudative AMD following photodynamic therapy of the affected eye (Suzuma et al., 2008). Of those the majority showed an improvement in monocular best corrected visual acuity and had good visual acuity in the contralateral eye (Suzuma et al., 2008).

### 2.7.3 Glaucoma

Open angle glaucoma is defined as glaucomatous optic neuropathy accompanied by glaucomatous visual field loss in eyes with open angles in the absence of history or signs of secondary glaucoma (Wolfs et al., 2000). Figure 11 shows an optic nerve head with advanced 'cupping'. Prevalence of open angle glaucoma in a white population has been found to be 0.8% (Bengtsson, 1981, Wolfs et al., 2000) but it was found that prevalence could vary from 0.1 to 1.2% if different definitions of glaucoma were applied; for example whether glaucoma was defined in terms of intraocular pressure or the presence of visual field defects (Wolfs et al., 2000). The prevalence of open angle glaucoma increases with age with bilateral glaucoma five times more likely over the age of 75 years, compared to under 75 years of age (de Voogd et al., 2005).

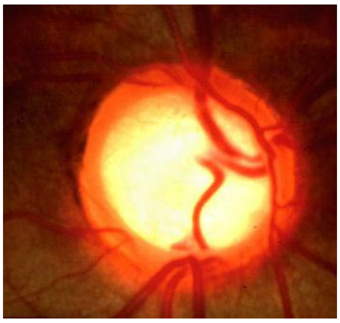


Figure 11. Optic Nerve Head with cupping characteristic of glaucomatous optic neuropathy. www.meded.ucsd.edu (Aug 2008)

The presence of glaucoma was not found to be related to any significant decrease in visual acuity (Klein et al., 1995). However, monocular and binocular contrast sensitivity, measured with the Pelli Robson chart at 1 metre was significantly reduced in patients with glaucoma compared to age match normals (Bassi and Galanis, 1991).

Stereoacuity was found to be reduced in patients diagnosed with glaucoma, compared to both age matched normals and ocular hypertensives (Bassi and Galanis, 1991). This may be due to loss of larger ganglion retinal cells in the magnocellular pathway, important to the mediation of stereopsis (Section 1.3.1). Based on their findings the authors suggest that measurement of stereoacuity be used to aid detection of the presence of early glaucomatous damage (Bassi and Galanis, 1991).

# Chapter 3

# Visual Control of Locomotion

## 3.1 Gait

Gait is the sequence of lower-limb movements describing the way in which locomotion is achieved. Three qualities are essential for locomotion; the maintenance of postural balance, the ability to adapt to the environment, and progression through the environment (Shumway-Cook and Woollacott, 2007). It is also important to minimise stress to the locomotor apparatus to ensure structural integrity of the apparatus over an entire lifespan (Patla and Vickers, 1997).

### 3.1.1 Postural Balance

Posture refers to the orientation of the body segments relative to gravity. It can be measured as an angular deviation from the vertical. Balance refers to dynamics of posture to prevent falling (Winter, 1995). In order to comprehend how postural balance is maintained two further terms need to be defined. Centre of mass (CM) of the body refers to a single point about which the body mass is evenly distributed. It is calculated from the weighted average of the CM position of all body segments (Winter, 1995). The centre of pressure (CP) is the point location of the ground reaction force, and represents the weighted average of all the pressures over the area in contact with the ground (Winter, 1995). To maintain balance during quiet standing (static postural stability) the horizontal position of the CM has to stay within the base of support, which, in quiet standing, is defined as the area defined by the outer edges of the feet, including the space between the feet (Trew and Everett, 2001). Balance is maintained by moving the CP in order to keep the horizontal position of the CM within the base of support.

### 3.1.2 Gait Initiation

In order to move from a relatively static and stable standing position to dynamic position the CM must move forward, out of the base of support (Winter, 1995). Prior to movement onset the CP is positioned midway between the feet, slightly anterior to the ankle. To initiate gait the CP moves posteriorly and laterally towards the intended swing (lead) limb. At lead limb heel-off the CP then shifts towards the stance limb heel region (Shumway-Cook and Woollacott, 2007). At toe off of the lead limb the CP shifts anteriorly under the stance foot. During single limb support the CM accelerates forward and medially from the stance limb (Winter, 1995). The movements of the CP and direction of the CM movement are shown in Figure 12.

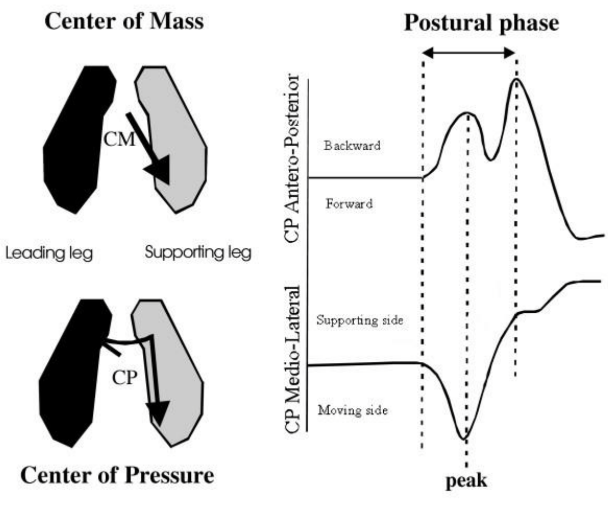



Figure 12. Movement of the CP and direction of the CM during gait initiation.

www.biomedcentral.com (July 2008)

### 3.1.3 Characteristics of Human Gait

This section refers to walking rather than other forms of human locomotion (running, hopping etc). Human gait varies according to many factors including age (section 2.5), gender, height and presence of any abnormalities, but despite this variability, human locomotion contains common patterns of movement. Walking can be defined as a method of progression involving rhythmical, reciprocal movements of the lower limb, in which at least one foot is always in contact with the floor (Trew and Everett, 2001). A gait cycle is defined as the time interval between two successive occurrences of one of the repetitive events, although it is conventional to start with initial contact of the right foot (Figure 13). The gait cycle can be divided into a swing phase, in which the foot moves through the air and makes up approximately 40% of the cycle and a stance phase (or support phase), in which the foot is in contact with the ground and makes up approximately 60% of the cycle (Whittle, 2002). Figure 13 shows the break down of a gait cycle.

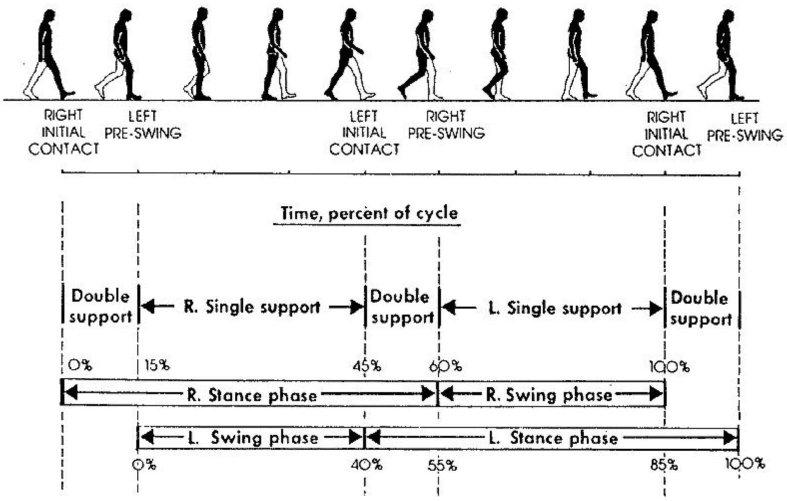



Figure 13. The Gait Cycle. www.laboratorium.dist.unige.it (July 2008)

Temporal and distance parameters can be used to describe gait and changes in gait. Walking velocity is defined as the average horizontal speed of the body CM measured over one or more strides, cadence is the number of steps per unit time, usually given as steps per minute (Shumway-Cook and Woollacott, 2007). In young adults cadence has been found to be just over 100 steps per minute (Winter, 1992, Sparrow et al., 1996). Step length refers to distance covered from one heel strike to the contralateral heel strike. Stride length refers to distance covered from one heel strike to the next heel strike of the ipsilateral foot (Shumway-Cook and Woollacott, 2007) and is typically around 1.5 metres in young adults (Winter, 1992, Sparrow et al., 1996). As long as gait is symmetrical then stride length will be twice that of the step length (Shumway-Cook and Woollacott, 2007).

Dynamic stability refers to how balance is maintained whilst the body is in locomotion; and it represents a different challenge from static balance control, particularly because there are periods when the CM is moved out of the base of support at which point it falls forward over the support limb (section 2.1.2). In order to avert a fall the lead limb needs to safely accept weight, initially on the heel, whilst the other foot pushes as the CM moves forward (Winter, 1995).

### 3.1.4 Adaptive Gait

The ability to adapt gait is important for the negotiation of uneven terrain; avoiding obstacles and negotiating a change in height (stepping up or stepping down). Gait parameters used to describe adaptations to gait include foot clearance (referring to heel or toe clearance) foot placement of the trail (support) and lead limb prior to or after an obstacle and walking velocity of a subject as they approach and step over an obstacle.

The trajectories of the lead and trail feet have been found to differ, with the lead foot trajectory rising steeply and descending gradually, whilst the trail foot trajectory shows a more symmetrical profile. The lead foot crosses the obstacle as it rises to the peak of its trajectory. Higher foot clearance has been found for the trail limb, compared to the lead limb (Sparrow et al., 1996), although this may be because the heel marker was used to measure clearance whilst it is the toe that it the lowest part of the trail limb during obstacle crossing (Sparrow et al., 1996).

Requirements for successful negotiation of stairs are similar to that of successful gait, being progression, stability; the CM must be kept within a changing base of support (dynamic stability) and there must be the capacity to adapt to changes in step height or width (Shumway-Cook and Woollacott, 2007). Stair climbing can be divided into two phases, a stance phase and a swing phase which last approximately two thirds and a third of the cycle respectively. During ascent the stance phase can be further divided into weight acceptance, pull up and forward continuance; the swing phase can be divided into foot clearance and foot placement phases (Zachazewski et al., 1993). The greatest instability occurs during trail leg toe off with subjects in single support and with the hip, knee and ankle joint all flexed (McFadyen and Winter, 1988). Toe clearance of the step is achieved with increased knee flexion, one and half times greater than when compared to normal gait on a flat surface (Andriacchi et al., 1980).

Stair descent can also be divided into stance and swing phases, with the stance phase divided into weight acceptance, forward continuance and controlled lowering and the swing phase divided into leg pull through and preparation for foot placement (Zachazewski et al., 1993). Weight acceptance involves energy absorption at the ankle and knee joints through muscle contraction. Such absorption is important as ground reaction force on landing can be two times the body weight (Shumway-Cook and Woollacott, 2007). The knee flexion moments during stair descent are over four times greater than determined for normal gait (Andriacchi et al., 1980)

Negotiation of a raised surface differs from obstacle avoidance in that obstacle avoidance returns the lower limb to its original state, whilst negotiation of a raised surface involves an adaptation which introduces the lower limb to a new end state (McFadyen and Carnahan, 1997). Comparison of adjustments to stride length and toe elevations in reaction to an obstacle, a raised surface or a set of three stairs show that when negotiating a raised surface subjects have the greatest toe elevation (McFadyen and Carnahan, 1997). Subjects shorten their stride length prior to the stair case compared to unobstructed gait, whilst stride length for negotiating a raised surface does not significantly differ from non-obstructed walking, with toe off not occurring any later within the stride cycle (McFadyen and Carnahan, 1997). In contrast when negotiating an obstacle, toe off occurs earlier in the stride cycle compared to non-obstructed walking and later in the stride cycle when negotiating a stair case. The differences seen between negotiating a raised surface and a stair case may be due to the constraints posed by the stairs in order to avoid awkward foot positioning for negotiation of the next step (McFadyen and Carnahan, 1997). In contrast to McFadyen and Carnahan’s findings, Crosbie (1996) found that when negotiating kerbs, subjects did increase their step length for one step prior to the kerb and for the step up on to the kerb, compared to the previous and subsequent step length, with decreased velocity during the step crossing (Crosbie, 1996). The difference in results may have been due to difference in methodology with McFadyen and Carnahan (1997) using a laboratory based set up with subjects undergoing each task repeatedly, whilst Crosbie (1996) used an outdoor environment and investigated subjects as they negotiated the kerb for a single time.

## 3.2 Vision and Control of Locomotion

There are three systems which control human locomotion: the visual system, the somatosensory system and the vestibular system. The somatosensory system controls balance and movement through proprioception. Proprioception can be divided into two sub modalities, the sense of position of the limbs (limb position sense) and the sense of limb movement (kinaesthesia), both of which are important for maintaining balance and controlling limb movement. Input into the proprioception system is from three different types of peripheral receptor, mechanoreceptors located in the joints, muscles spindle receptors, which detect the stretch of muscle, and cutaneous (skin) mechanoreceptors (Kandal et al., 1991). Proprioception is thought to be important in determining appropriate stepping frequency (Shumway-Cook and Woollacott, 2007).

The vestibular system helps maintain balance and posture and stabilise head and eye movements. The vestibular system is located in each ear canal and can be divided into two sections, the semicircular canals and the otolith organs; the utricle and the saccule. The three semicircular canals lie in different planes, perpendicular to each other, and due to the arrangement can detect angular acceleration of the head in these three directions. The otolith organs detect linear acceleration when the head moves and determine the position of the head with respect to gravity.

During head movements the semicircular canals detect the speed and direction of head movements. This signal is then used by the oculomotor system to move the eyes at the same velocity in the opposite direction in order to stabilize the eyes and hence the retinal image relative to the external world. This oculomotor response is called the Vestibulo-ocular reflex  (Kandal et al., 1991).

Both somatosensory and vestibular systems are able to respond to perturbations and therefore are important in reactive control of balance. However vision can identify static and dynamic features of the environment at both near and distance and therefore allows planning and anticipatory changes in reaction to the environment (Patla, 1997). The later experimental chapters in this thesis concentrate on vision and its effects on negotiation of a step or raised surface within the travel path and therefore the rest of this chapter will concentrate on aspects of vision and its role in adaptive gait.

### 3.2.1 Optic Flow

Optic flow has been identified as critical for successful locomotion (Gibson, 1958). The definition of optic flow is the apparent visual motion of objects on the retina and relates to head and eye movements through space. The visual images appear to expand on forward motion with the speed of flow increasing as speed of movement increases. The centre of the flow pattern during forward movement is the direction goal (Gibson, 1958). The expansion from the goal appears radial but in the far periphery appears to be parallel and is called lamellar flow (Cavanaugh, 2002).

Retinal flow refers to the distortions that occur to optic flow due to complex body movements, for example small involuntary eye movements during locomotion. Retinal flow contains motion parallax (Cutting et al., 1992) and it is argued that motion parallax, where distance objects are perceived as moving slower than closer objects (chapter 1, section 1.2.1), defines the perceived direction of heading rather than the information from optic flow (Cutting et al., 1992). However experiments which have presented manipulated scenes including optic flow and no motion parallax or vice versa have demonstrated that optic flow is more important that motion parallax in the control of heading (Kim et al., 1996).

### 3.2.2 Vision and Adaptive Gait

Vision is used in the control of adaptive gait, and it has been shown that subjects modulate aspects of adaptive gait in response to visually detected obstacle characteristics (Chen et al., 1991, Patla and Rietdyk, 1993, Sparrow et al., 1996). For example increased lead foot clearance is found when negotiating higher obstacles (Chen et al., 1991, Patla and Rietdyk, 1993, Sparrow et al., 1996) although obstacle height does not effect stride length (Chen et al., 1991, Patla and Rietdyk, 1993, Sparrow et al., 1996). Velocity of the lead limb decreased with height of the obstacle (Chen et al., 1991, Patla and Rietdyk, 1993, Sparrow et al., 1996) and subjects' lead foot landed with increased vertical velocity and decreased horizontal velocity for higher obstacles (Patla and Rietdyk, 1993). The width of the obstacle affects the trajectory of the lead limb only if the width of the obstacle forces a change in step length (Patla and Rietdyk, 1993) The change in gait according to obstacle property demonstrates a more cautious approach to taller obstacles, in order to prevent contact with the lead toe (Chen et al., 1991) and reduce the risk of tripping by reducing the speed of the toe in case it does make contact with the obstacle (Patla and Rietdyk, 1993). As well as height and width, other visually inferred obstacle properties have been found to modulate foot placement when negotiating an obstacle (Patla et al., 1996). Subjects increased lead limb toe clearance when negotiating an obstacle perceived as fragile, compared to one with similar dimensions perceived as robust (Patla et al., 1996).

When negotiating an obstacle whilst walking on a compliant surface lead limb toe clearance reduces, compared to toe clearance of the same obstacle on a non-compliant surface. This effect is because toe elevation remains unchanged as no account is taken of the compliant surface and depression of the surface during push off of the lead limb. This demonstrates that visual perception of the obstacle height modulates the toe elevation not toe clearance of the obstacle (Maclellan and Patla, 2006). Toe elevation had been found to increase with obstacle height (Mohagheghi et al., 2004).

### 3.2.3 Gaze Behaviour

Gaze behaviour patterns have been assessed in subjects asked to negotiate obstacles (Patla and Vickers, 1997) or precisely plan foot placement on to specific points (Patla and Vickers, 2003). Two types of gaze behaviour have been identified. The first is classified as dominant gaze pattern where the gaze is fixed in front of the subject and carried along with body motion, and not actively moved to any specific location. It is suggested that this is when information regarding optic flow and self motion are acquired (Patla and Vickers, 1997). The second type of gaze behaviour is fixation of the object of interest, with subjects found to fixate on the object one or two steps prior to reaching it but not during stepping over the obstacle (Patla and Vickers, 1997)or as the foot was swung forward on to the specified foot placement location (Patla and Vickers, 2003). The majority of gaze behaviour during the tasks was dominant gaze behaviour

(Patla and Vickers, 1997, Patla and Vickers, 2003) even in tasks where every footfall had to be placed precisely (Patla and Vickers, 2003). However type of fixation was modulated to obstacle size, with higher obstacles fixated on more frequently and for longer periods, presumably because higher obstacles are perceived as a greater risk of tripping (Patla and Vickers, 1997).

### 3.2.4 Feed Forward vs. On-line Control

Gaze behaviour reported above (section 3.2.3) suggests that visual control of locomotion occurs in a feedforward manner. Loss of visual information five steps prior to an obstacle results in a high failure rate when negotiating an obstacle, with up to 50% of trials resulting in failure, where there was foot contact with the obstacle (Patla, 1998). When subjects dynamically sampled the visual scene, prior to occlusion (five steps away whilst walking towards the obstacle) then this resulted in a much lower failure rate, compared to static sampling (from five step lengths away) of the scene prior to occlusion. The authors suggested that feed forward sampling of the visual environment using information from optic flow was important for control of adaptive gait (Patla, 1998). In a later study (Patla and Greig, 2006) type of vision sampling was analysed further. In this study subjects were asked to approach and step over an obstacle in the travel path in five different visual conditions, 1) full vision throughout, 2) static visual sampling, with occlusion for the duration of the trial, including walking 5 steps and stepping over the obstacle, 3) forward walking with vision for three steps then stopping, 4) forward walking for three steps but with no stopping prior to negotiating the obstacle, and 5) vision during backward walking for three steps (whilst viewing the obstacle) then stopping. Backward walking would have resulted in a decrease in retinal image size of the obstacle whilst still providing dynamic optic flow information. Again subjects performed better when they dynamically sampled the scene whilst walking, compared with static sampling, however there was no difference between static and dynamic sampling when the subjects stopped walking prior to occlusion (including the backward walking trials). Therefore it appears the difference in failure rates in negotiating the obstacle was not due to difference in sampling but due to the added task of initiating gait. Failure to negotiate the obstacle successfully was due to incorrect lead foot placement prior to the obstacle, with trials that involved a gait initiation following occlusion having greater variation in foot placement. Lead toe clearance of the obstacle increased for all conditions where vision was occluded; however failure to negotiate the obstacle was due to the foot being placed too close to the obstacle during approach so that maximum toe elevation during the crossing step occurred after the foot had crossed the obstacle. In contrast to their previous work the authors concluded that online visual control is important for adjustment of foot placement prior to the obstacle and therefore online visual information is important for successful adaptive gait (Patla and Greig, 2006).

Feedforward visual information is used to modulate the lead limb elevation and clearance of the obstacle, with loss of vision in the approach phase found to increase toe clearance in agreement with Patla and Greig's findings (Mohagheghi et al., 2004). On-line visual information was only used to modulate toe clearance if visual information was not available during the approach phase (two steps ahead, Mohagheghi et al., 2004).

### 3.2.5 Exteroceptive vs. Exproprioception in Control of Locomotion

Exteroceptive visual information describes feature of the environment and for example would refer to the height of an obstacle or step in the travel path. Exproprioception refers to the body's position relative to the environmental feature (Lee, 1978). It has been suggested that exteroceptive cues are used for planning movements (feed forward control) and that timing of movements are based on visual exproprioceptive cues (Lee, 1978). In addition the trailing limb, for which no visual exproprioceptive cues are available during obstacle crossing has been found to have more variable toe clearance values than the lead limb for which exproprioceptive cues are available in normal vision (Patla et al., 1996), suggesting that exproprioceptive cues are important for precision of foot clearance of an obstacle.

In order to investigate the relative importance and roles of exteroceptive and exproprioceptive cues in the control of locomotion, studies have occluded the lower visual field during obstacle crossing, as this prevents online visual feedback regarding the location of the lower limbs relative to the obstacle (Patla, 1998, Rietdyk and Rhea, 2006, Rhea and Rietdyk, 2007). When the lower visual field is occluded during obstacle crossing there is an increase in both variability (Patla, 1998, Rhea and Rietdyk, 2007) and maximum value of lead limb toe clearance (Patla, 1998, Rietdyk and Rhea, 2006, Rhea and Rietdyk, 2007) compared to no occlusion. There is also an increase in anterior position of the lead limb prior to the obstacle (Patla, 1998, Rietdyk and Rhea, 2006, Rhea and Rietdyk, 2007). Although lower visual field occlusion results in loss of both exteroceptive and exproprioceptive cues, if cues giving information regarding the obstacle position are provided by means of markers visible in the upper visual field then foot placement reverts to normal (no occlusion) values (Rietdyk and Rhea, 2006, Rhea and Rietdyk, 2007). Interestingly, providing online exteroceptive cues, by having a second, identical obstacle placed where subjects could see it during the approach to the first obstacle, toe clearance values or toe clearance variability do not return to normal (no occlusion) values. The authors concluded that this indicated that it is visual exproprioception, rather than exteroceptive cues that are important for controlling toe clearance over an obstacle (Rhea and Rietdyk, 2007).

## 3.3 Disruption to Vision and Locomotion

### 3.3.1 Effect of Binocular Blur

When asked to perform a single step up, in conditions of binocular blur (cataract simulating lenses) elderly subjects demonstrated increased vertical and horizontal lead limb toe clearance over the step edge compared to optimally corrected vision. In addition the subjects were slower to perform the stepping motion and demonstrated decreased medial lateral displacement of the CP and decreased the maximum distance in medial lateral position between their CM and CP when their vision was blurred (Heasley et al., 2004, Heasley et al., 2005). These changes meant that CM was kept closer to the base of support and was likely a strategy to improve dynamic stability.

When stepping down a flight of stairs, degraded binocular vision increased foot clearance over the step positioned midway down the staircase. The subjects foot was also placed farther back on the step and there was reduced cadence in blurred conditions compared to normal vision conditions (Simoneau et al., 1991). When stepping down from a single step subjects again decreased the medial lateral distance between CP and CM when vision was blurred in an attempt to increase dynamic stability however the change in CP and CM position did not increase dynamic stability and in fact there was decreased stability (measured as the SD in medial lateral displacement of the CP during single support) in blurred conditions possibly due to a longer time spent in single support (Buckley et al., 2005a, Buckley et al., 2005b).

In the above studies binocular blur was achieved through the use of light scattering lenses. The lenses degraded visual acuity by a small amount but caused a larger degradation in contrast sensitivity (Heasley et al., 2004, Heasley et al., 2005). In subjects with visual impairment, contrast sensitivity has been found to be a better predictor of mobility and orientation, measured as speed of gait and successful avoidance of obstacles along a mobility course, than visual acuity (Marron and Bailey, 1982, Haymes et al., 1996, Geruschat et al., 1998). In addition, although binocular refractive blur has been found to decrease postural stability during quiet standing, especially in the presence of disruption to somatosensory (by standing on a foam base) or vestibular (by tilting the head upwards) control of stability (Anand et al., 2002, Anand et al., 2003b) findings show that light scattering lenses reduce postural stability to a similar degree to a high level of refractive blur (8.00DS). These findings suggest it is the loss of contrast sensitivity, caused by refractive blur or light scattering lenses rather than visual acuity that causes the increase in postural stability (Anand et al., 2003a).

### 3.3.2 Loss of Visual Field

The importance of the visual field has been assessed in visually impaired subjects, using the ability to successfully negotiate around a mobility course that includes obstacles.

Mobility has been assessed using the speed of gait negotiating the course and number of mobility incidences, defined as contact with obstacles within the defined pathway (Lovie-Kitchin et al., 1990, Black et al., 1996, Haymes et al., 1996, Geruschat et al., 1998, Turano et al., 1999, Broman et al., 2004). When compared to age matched normals, subjects with impaired visual fields were found to have slower gait and made more mobility errors navigating the course (Lovie-Kitchin et al., 1990, Black et al., 1996, Geruschat et al., 1998, Turano et al., 1999). The average extent of remaining binocular visual field was found to be predictive of mobility performance (Lovie-Kitchin et al., 1990, Black et al., 1996, Haymes et al., 1996) with the central, superior central and inferior central areas (37º radius zone) and left, right and inferior mid-peripheral areas (37-58º radius) best at predicting mobility performance (Lovie-Kitchin et al., 1990).

The above studies showed that a full visual field is important for successful mobility but the results do not provide information regarding how kinematic factors differ for subjects with restricted visual fields during adaptive gait. In normal subjects, when the lower visual field is occluded prior to and during obstacle crossing, there is an increase in lead limb toe clearance of the obstacle (Patla, 1998, Rietdyk and Rhea, 2006) as well as increased variability in lead limb toe clearance (Patla, 1998) and increased anterior placement of the trail limb foot placement prior to the obstacle (Patla, 1998, Rietdyk and Rhea, 2006). Both the above studies demonstrated that loss of lower visual field results in loss of online visual information leading to uncertainty in the position and height of the obstacle and hence the use of a cautious strategy to decrease the likelihood of foot contact with the obstacle. In both studies the lower visual field was occluded using goggles but the extent of the visual field loss caused by the goggles was not objectively measured and the effect of loss of different areas or extent of the visual field were not examined.

Occlusion of the different areas of the visual field have been found to increase postural instability, with loss of central visual field was found to increase instability greater than loss of peripheral visual field (Paulus et al., 1984, Straube et al., 1994). It is suggested than the peripheral retina is not able to control posture to the same level displayed by the fovea (Paulus et al., 1984). Indeed, subjects who had central visual field loss showed a smaller contribution of visual stabilisation to postural control than subjects with normal vision (Turano et al., 1996). However no difference was found between the postural stabilisation of central and peripheral fields if magnification of the foveal cortical representation was considered (Straube et al., 1994) suggesting that there is no functional separation of peripheral and central visual field in control of postural stability.

### 3.3.3 Monocular Occlusion

To investigate the importance of binocular vision in control of gait, researchers have investigated the effect of occluding one eye on negotiation of an obstacle (Patla et al., 2002) and when performing a single step down (Cowie et al., 2008). When either eye was occluded subjects demonstrated increased lead limb toe clearance of the obstacle, but there was no change in lead foot placement prior to the obstacle (Patla et al., 2002). The authors suggested this was due to monocular vision not providing adequate visual exteroceptive information regarding the obstacle. As the lower limbs were still visible with one eye occluded the position of the lower limbs in relation to the obstacle (visual exproprioception) could still be seen and as a consequence there was no increase in variability in lead limb toe clearance. As there was no change in lead limb foot placement it appears that the position of the obstacle could still be judged accurately with one eye occluded. In addition Patla et al (2002) looked at when binocular vision is used in controlling adaptive gait during obstacle negotiation. Subjects still demonstrated increased toe clearance if one eye was occluded when approaching the obstacle, even if they had full binocular vision during obstacle crossing. In contrast toe clearance decreased to normal levels if subjects had binocular vision during the approach but subsequently had one eye occluded during obstacle crossing. This demonstrated that binocular vision is important when planning negotiation of the obstacle but is not required to make online adjustments (Patla et al., 2002).

Cowie et al (2008) used a measure of kneedrop, defined as the amount the knee dropped during the outward swing of the limb, to measures the effect of monocular occlusion on performance when stepping down. In normal conditions knee drop was scaled to the height of the step. However occlusion of one eye impaired this scaling, demonstrating that subjects had difficulty judging the height of the step when stepping down in monocular conditions (Cowie et al., 2008).

It is unclear whether binocular vision is important for the control of postural stability with studies presenting conflicting results. This may have been due to studies using dissimilar targets. For example where a visual target of a cross was used no difference was found between monocular and binocular conditions (Isotalo et al., 2004). However when the target was an array of LED lights presented at different distances from the subjects, postural stability in the fore-aft direction was better in binocular conditions compared to monocular occlusion for sway (Fox, 1990), suggesting that if there is a depth cue used in the control of standing posture. It appears therefore that binocular vision is important for adaptive gait. However to date, studies have investigated the effect of occlusion only, and the effect of monocular degradation is largely unknown.

## 3.4 Age Related Changes to Gait and Visual Control of Gait

### 3.4.1 Changes to Adaptive Gait

As stated in section 3.1.3 human gait varies with age. For example during unobstructed walking elderly subjects were found to have a shorter stride length than young subjects (Begg and Sparrow, 2000) and there is a trend for slower stride velocity in elderly subjects, although this did not reach statistical significance (Chen et al., 1991, Begg and Sparrow, 2000).

Changes in adaptive gait with age have also been investigated. When negotiating an obstacle in the travel path elderly subjects showed a  slower approach and crossing speed than younger subjects (Chen et al., 1991). Elderly subjects also demonstrated shorter step length and width during obstacle crossing with the lead heel landing closer to the obstacle following crossing although there was no difference in foot clearance of the obstacle between young and elderly subjects (Chen et al., 1991). When ascending on to a raised surface or a single step within the travel path elderly subjects shortened their step length prior to the raised surface, whilst young subjects showed no such adaptation (Lythgo et al., 2007). In addition, the crossing step length was relatively shorter compared to young subjects (Begg and Sparrow, 2000, Lythgo et al., 2007)  with the feet placed relatively closer to the platform edge prior to the platform (Lythgo et al., 2007) and with a shorter distance from heel to the platform edge when the foot was placed on the surface (Begg and Sparrow, 2000). Lead foot clearance of the step in elderly subjects was found to be the same (Heasley et al., 2005) or lower than young adults (Begg and Sparrow, 2000, Lythgo et al., 2007). Elderly adults did not take any longer to perform a step up than young subjects but did spend relatively longer in double support (Heasley et al., 2005, Benedetti et al., 2007) and relatively less time in trail leg single support (Benedetti et al., 2007).

When approaching the platform edge, prior to step descent, elderly subjects were seen to adjust their stride length five step lengths prior to stepping down. The crossing step length was shorter for elderly subjects and they placed their lead foot closer to the platform edge when landing. Again elderly subjects were found to be slower than young subjects when stepping down. In contrast to step ascent, during descent elderly subjects spent relatively less time in double support and more time in trail leg single support than young subjects (Lythgo et al., 2007).

When stepping down elderly subjects were found to have greater vertical heel clearance than young subjects (Begg and Sparrow, 2000). In contrast Hamel et al (2005) found no difference due to age in minimum foot clearance during step descent; again the differences may have been due to difference in how foot clearance was measured as Hamel et al (2005) measured from the mid foot to the step edge, rather than from the heel. During descent the lead foot was found to be orientated downwards, so the toe was lower than the heel (Lythgo et al., 2007), it therefore may be more pertinent to measure foot clearance from the toe during stair descent to have a more accurate measure of minimum foot clearance. Of note it was found that although no change was seen in foot clearance with age, elderly subjects showed more variability in foot clearance than young subjects, leading to 7% of foot clearances in elderly subjects being less than 5mm, representing a potentially hazardous strategy (Hamel et al., 2005). In addition during stepping up, elderly subjects demonstrated increased hip flexion, reduced knee flexion and decreased ankle dorsal flexion. The change in ankle dorsal flexion means that the toe was positioned lower and this was thought to increase risk of tripping (Benedetti et al., 2007).

### 3.4.2 Gaze Behaviour

When asked to step onto targets during a walking task, older adults demonstrated different gaze behaviour to younger adults, fixating the target at an earlier point in the approach (by about 1 second) and for longer periods, although both young and elderly adults fixate the target prior to toe off of the lead limb to step on to the target. The reason for the earlier fixation does not appear to be related to walking velocity (Chapman and Hollands, 2007).

### 3.4.3 Response to Visual Disruption

When vision was blurred, both young and elderly subjects have been found to increase toe clearance when stepping up, compared to full vision conditions (Heasley et al., 2005). Elderly subjects were found to decrease the medio-lateral divergence of the CP and CM to a greater degree than young subjects, suggesting that elderly subjects see medio-lateral instability as a greater risk than young subjects. In contrast to Heasley et al’s findings, when walking down stairs, under conditions of poor illumination, elderly adults did not increase foot clearance of the step edge, whilst younger subjects did increase foot clearance, compared to well lit conditions (Hamel et al., 2005). It appears that elderly adults did not make appropriate adaptations to conditions where the edge of the step could not be clearly detected, resulting in increased risk of a trip.

It has been found that when maintaining postural stability, elderly subjects had greater sway velocity than younger subjects in unperturbed conditions and were found to be more reliant on visual control of postural stability i.e. the ratio of sway in eyes open condition compared to eyes closed condition (the Romberg quotient) was greater. This demonstrated reduced somatosensory and vestibular input and hence a greater reliance on vision (Pyykko et al., 1990).

## 3.5 Ocular Disease and Adaptive Gait

### 3.5.1 Cataracts

Patients with cataracts were found to be slower at negotiating an obstacle course and made more errors, defined as hitting obstacles in the travel path, straying away from the defined travel path and stopping, compared to age-match normals (Elliott et al., 2000). Cataract patients were also much slower when asked to negotiate obstacles (measured as toe and hip velocity) and had significantly higher lead limb toe clearance than age match normals (Elliott et al., 2000). Following first eye cataract surgery there were improvements in binocular visual acuity and contrast sensitivity, but not stereopsis. First eye surgery patients performed better when negotiating the travel pathway and were quicker when negotiating obstacles, although there was no reduction in toe clearance of the obstacle. Following second eye cataract surgery there were further improvements in binocular visual acuity and contrast sensitivity and in addition stereoacuity improved to age match normal levels. There were further improvements in mobility and toe clearance of the obstacles reduced to age match normal levels. Of note is that the change in lead limb toe clearance following surgery was significantly correlated with the improvement in stereoacuity resulting from second eye surgery (Elliott et al., 2000).

### 3.5.2 Age-related Macular Degeneration (AMD)

Brown et al (1986) showed that patients with AMD demonstrated no difficulties in negotiating a mobility course, judged by speed of gait and any deviation from the travel path compared to age match normals in normal (bright) lighting conditions, however, at lower luminance, AMD patients demonstrated mobility difficulties (Brown et al., 1986). In contrast, Spaulding et al (1995) found that AMD patients had slower gait than age match normals but that there was no further difficulties resulting from lower light levels (5 lux, Spaulding et al., 1995). The differences between these studies may be due to the task subjects undertook; as Spaulding et al (1995) asked subjects to walk along a straight travel path, whilst Brown et al (1986) used a variety of pathways, including a slalom course. Hassan et al (2002) asked patients with AMD to negotiate an obstacle course with good illumination (300-500 lux). AMD patients did not demonstrate any decline in walking speed compared to age match normals and did not make any more obstacle contacts than normally sighted subjects. When tested in dimmer conditions (52 lux) that included a single glare source, there was again no difference between AMD and normally sighted subjects. Despite there being no difference between the two groups a correlation was found between poor contrast sensitivity and extent of binocular scotoma and mobility performance (Hassan et al., 2002).

### 3.5.3 Glaucoma

Glaucoma patients who were assessed on a mobility course demonstrated slower walking speed than visual normals and were found to have a twice as many “bumps” (defined as body contact above the knee, excluding the hands) or stumbles (defined as change in posture or gait due to contact with an object below the knee) but this did not reach statistical significance (Turano et al., 1999). Friedman et al (2007) found that patients with bilateral glaucoma were found to be statistically slower walking along a 4 metre mobility course than age match normals. In addition they were found to be slower at negotiating an obstacle course, and were statistically more likely to “bump” into objects (Friedman et al., 2007). The difference in findings between the two studies may be due to how glaucoma was defined. Friedman et al (2007) divided the glaucoma cohort into bilateral and unilateral glaucoma, with the decline in mobility performance found only in the bilateral glaucoma group. Turano et al (1999) defined glaucoma subjects as those having glaucoma in at least one eye and hence would have included subjects with both unilateral or bilateral glaucoma in the same cohort. Both studies found visual field loss to be a predictor of poor mobility performance (Turano et al., 1999, Friedman et al., 2007).

### 3.5.4 Retinitis Pigmentosa

Subjects with retinitis pigmentosa were found to have a slower walking speed around a mobility course (500lux) and were more likely to make errors, with performance worsening further in darkened conditions (50 lux, Black et al., 1996). Visual field extent was a significant predictor of mobility performance rather than visual acuity or contrast sensitivity (Black et al., 1996). In contrast, Haymes et al (1996) found that contrast sensitivity and visual field extent predicted mobility performance, although the task was not comparable to that in the Black et al (1996) study, as Haymes et al (1996) judged mobility on walking speed over three outdoor courses where there was no control of light level (Haymes et al., 1996).

In summary, the presence of eye disease of different types causes difficulties with mobility. However most studies have analysed mobility performance in terms of speed of walking along a flat surface or avoidance of obstacles and only one study has investigated how eye disease affected the ability to walk up stairs (Friedman et al., 2007). It may be pertinent to assess how subjects manage everyday mobility tasks, including ascending or descending stairs and negotiation of a single step such as a roadside kerb. In addition although contrast sensitivity and visual field loss were found to be good predictors of mobility performance, stereoacuity was also found to be important in mobility performance (Elliott et al., 2000) and as stereoacuity has been found to be impaired in patients with eye disease (section 2.6) including glaucoma (Bassi and Galanis, 1991), retinitis pigmentosa (Vingolo et al., 2006) and AMD (Suzuma et al., 2008), as well as cataract (Talbot and Perkins, 1998, Elliott et al., 2000) it may be pertinent to include a measurement of stereopsis in future studies investigating the impact of eye disease on mobility tasks.

# Chapter 4

# Falls and Fracture in the Elderly

## 4.1 Falls in the Elderly

### 4.1.1 Definition of a Fall

In almost half of fall intervention randomised controlled trials no definition is given for a fall (Hauer et al., 2006). In studies that do give a definition of a fall there is much variation between definitions. The Frailties and Injuries: Cooperative Studies of intervention techniques (FICSIT) definition "unintentionally coming to rest on the ground or floor or other lower level" (Masud and Morris, 2001) is the most frequently used but still was only used in 10% of recent studies (Hauer et al., 2006).

Similarly, the Prevention of Falls Network Europe (ProFaNE) identify the variation in fall definition as a major cause of difference between studies in fall rates in similar populations and recommended that a simple definition is appropriate unless looking at particular subtypes of fall. They have advised the following definition, which is similar to the one used by the FICSIT:

"an unexpected event in which the participants come to rest on the ground, floor or lower level" (Lamb et al., 2005).

The importance of defining falls has been highlighted by a randomised controlled trial investigating the effect of two different exercise programs on occurrence of falls in the community based elderly. Using the FICSIT definition the interventions were found to make a significant difference but when using a modified version (that excluded stumbles and was therefore more rigid) no significant reduction in falls was found with the intervention (Wolf et al., 1996). Any difference in fall definitions should therefore be taken into consideration when comparing outcomes of studies.

**4.1.2 Types of Study**

Cohort studies follow groups of subjects over a period of time to identify risk factors and outcomes. Prospective cohort studies identify the sample and take measurements before any outcome has occurred. In retrospective studies the sample is identified and variables measured after the outcome has occurred. Prospective studies allow the researcher control over the initial measures but unfortunately are expensive and inefficient, as large numbers of participants are needed for the study to have enough statistical power, especially if the outcome is rare. Retrospective studies are easier as the sample is already in place and the data collected, but relies on the initial measurements being appropriate and complete (Hulley and Cummings, 1988).

Case controlled studies are usually retrospective in nature. They identify subjects with (cases) and without (controls) the outcome measure present and then investigate difference in variables between the two groups. Case controlled studies need far fewer "normals" than cohort studies and are suited for investigating rare outcomes such as hip fracture, but it can be challenging to control selection bias of both cases and controls. Case controlled studies can investigate risk factors but not incidence. Incidence is defined as the number of new cases per year divided by the number at risk (Bland, 1994).

Cohort and case controlled studies can tell us about the change in risk caused by variables within the population. Relative risk measures increased risk or change in risk for a list of variables and is simply the ratio of the risks between the case and control groups. When logistic regression is used in a case-control study or to adjust for confounding factors in cohort studies then odds ratios must be used to measure the change in risk (Zhang and Yu, 1998). Odds ratios are calculated from the ratio of the odds in the two groups and show a larger effect than relative risk. An odds ratio will always overestimate the relative risk, although odds ratios can be used as an approximation of the relative risk providing the initial risk is low (20% or less) as serious divergence between relative risk and odds ratios only occurs with large effects on groups at high initial risk (Davies et al., 1998). Applying this to the falls literature, as the risk of hip fracture is low then odd ratios are a good approximation of relative risk, but the risk of falls is much higher and in this case odds ratios may overstate the effect of a risk factor. Whether the risk is given as odd ratios or relative risk should be taken into account when looking at the magnitude of risk factors.

When investigating incidence of falls in the elderly, both retrospective and prospective studies may underestimate falls. A prospective study by Cummings et al (1988) compared the incidence of falls over a 12 month period based on elderly subjects' recall at the end of that period with falls recorded by weekly postcards filled in by the participants. Subjects' 1-year recall underestimated the incidence of falls by 13%. As subjects had prior knowledge they were participants in a falls study this value is applicable to prospective studies using long term recall of falls to measure outcome. Interestingly the study found that the recall error increased if subject were asked to remember shorter periods with recall error increasing to 32% for the proceeding 3 months (Cummings et al., 1988). To minimise error in prospective studies ProFaNE recommend study participants use daily falls records with monthly or weekly telephone follow up (Lamb et al., 2005). A good example of falls data collection is shown by Berg et al (1997). Individuals completed and returned a report card every 2 weeks and if a report card was not returned the participant was telephoned and reminded. Reports of falls were followed by telephone and a postal questionnaire. One hundred percent of report cards were returned and the paper reported a falls incidence of 52% (Berg et al., 1997). Retrospective studies that rely on recall of falls (rather than hospital records of injurious falls) may be subject to a greater error as participants will not have any prior knowledge of the study. For example a retrospective study on a similar population to that of Berg et al reported a rate of falls of only 35% (Blake et al., 1988). The differences in study type and methodology help to explain differences in incidence of falls and risk factors found by studies investigating similar populations.

#### 4.1.3 Incidence of Falls

Both prospective and retrospective studies have investigated the annual incidence of falls. Differences in findings are related not just to study type and methodology but also population studied. For example community based elderly have a lower rate of falls than elderly based in care or nursing homes (Rubenstein, 2006). The incidence of falls in community based elderly 65 years and older ranges from 15 to 52% (Campbell et al., 1981, Prudham and Evans, 1981, Gabell et al., 1985, Blake et al., 1988, Lord et al., 1993, Yasumura et al., 1996, Berg et al., 1997, Morris et al., 2004). However the 15% figure was derived from a "healthy" population and had exclusion criteria of major disorders that may affect gait including arthritis, stroke, disabling foot conditions, blindness or the need for walking aid (Gabell et al., 1985) and therefore cannot be

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compared directly to other studies which do not have such stringent criteria. Also the highest incidence (52%) is from a study with 100% response rate from participants (Berg et al., 1997) and therefore, although accurate, appears much higher than the majority of studies, which have found that approximately one third of adults over 65 years fall at least once a year (Campbell et al., 1981, Blake et al., 1988, Ivers et al., 1998, Friedman et al., 2002, Morris et al., 2004, Freeman et al., 2007). The rate of falls has been consistently found to increase with age and studies using older populations report a higher rate of falls than those including a younger age group. In studies using populations aged 75 years of age and over the rate of falls were found to be 32% (Tinetti et al., 1988), 42% (Downton and Andrews, 1991) and 51% (Bergland and Wyller, 2004). Differences in incidence between the three studies may be due to difference in fall definition, as both Downton and Andrews (1991) and Bergland and Wyller (2004) use difference definitions, whilst Tinetti et al (1988) does not define falls, or due to difference in type of study, both Tinetti et al (1988) and Bergland and Wyller (2004) are prospective studies, whilst Downton and Andrews (1991) is retrospective.

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## 4.2 Risk factors

Risk factors for falls can be extrinsic (environmental) or intrinsic. Intrinsic factors can be due to chronic illness and therefore can lead to multiple falls or may be short-term. e.g. short term use of medication. Most falls are a result of a combination of extrinsic and intrinsic risk factors (Tinetti and Speechley, 1989). Studies have identified elderly people who only fall once or occasionally as having different risk factors than those who fall multiple times (Campbell et al., 1981, Nevitt et al., 1989, Hill et al., 1999). For example Campbell et al (1981) found that occasional fallers had better mobility and did not rely on mobility aids as much as multiple fallers.

### 4.2.1 Extrinsic Factors

Over 50% of falls occur away from the home (Hill et al., 1999, Sherwin and Gilhotra, 2006) with the percentage of falls occurring at home increases with age (Tinetti et al., 1988, Sherwin and Gilhotra, 2006). The majority of falls occur when walking (Yasumura et al., 1996) and are due to trips associated with negotiation of obstacles or uneven surfaces or steps/kerbs (Lord et al., 1993). Falls are more likely to occur with environmental constraints such as reduced lighting (Nevitt et al., 1989, Lord et al., 1993) or wet or slippery surfaces (Tinetti et al., 1988, Nevitt et al., 1989, Lord et al., 1993).

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### 4.2.2 Intrinsic Factors

Common intrinsic risk factors for falls are age (section 3.1.3), due to age related changes in postural control and muscle strength and tone which can impair reaction to a trip or slip (Rubenstein, 2006), and gender. More women fall than men (Prudham and Evans, 1981, Blake et al., 1988, Downton and Andrews, 1991, Friedman et al., 2002) although differences between the sexes reduces with advancing age (particularly over 80 years, Prudham and Evans, 1981, Blake et al., 1988). Increased body sway (Campbell et al., 1989, Lord et al., 1994, Bergland and Wyller, 2004), reduced lower limb muscle strength (Campbell et al., 1989, Lord et al., 1994), problems with mobility (Prudham and Evans, 1981, Blake et al., 1988) and impaired gait (Tinetti et al., 1988, Campbell et al., 1989, Lord et al., 1994, Hausdorff et al., 2001) are all linked with falls. Impaired gait is defined as abnormal scores on tests of walking speed and/or stride length variability. Prescribed medication has been consistently linked with increased risk of falls, either through increased number of medications overall (Blake et al., 1988, Campbell et al., 1989) or certain types of medication including sedatives, (Benzodiazepenes, phenothiazipines and antidepressants, Prudham and Evans, 1981, Blake et al., 1988, Tinetti et al., 1988), psychotropic drugs (Campbell et al., 1989, Lord et al., 1993) and diuretics (Prudham and Evans, 1981). Co-morbidity increases the likelihood of falls with risk increasing with increasing number of co-morbidities present (Friedman et al., 2002). Chronic illnesses that have been identified as independent risk factors include Parkinson's disease (Nevitt et al., 1989), history of stroke (Prudham and Evans, 1981, Downton and Andrews, 1991, Friedman et al., 2002) and arthritis (Blake et al., 1988, Nevitt et al., 1989). Cognitive impairment has been found to be a risk factor though this is more likely to be underreported than other factors as elderly with cognitive impairment are more likely to forget falls (Cummings et al., 1988).

## 4.3 Consequences of Falls

### 4.3.1 Morbidity

During 1999 there were 647,721 A&E attendances related to falls in persons over 60 years, the majority of these (66%) were over 75 years and 31% of these attendances resulted in admission to hospital (Scuffham et al., 2003). In a prospective study of 96 healthy, community based women, Hill et al (1999) reported 9% of those who fell experienced a fracture, 10% suffered strain or moderate injuries and 26% had bruises or other minor injuries. Similar rates of fall related injuries were found in a retrospective study by Lord et al (1993) of 704 community based women. To investigate the effect of age on the proportion of falls leading to injury the subjects were divided into 3 age groups. Injuries were found to increase with age, from 23% in women aged 65-74 years to 30% in women aged 74-85 years. The proportion increased again to 35% in women aged over 85 years. The type of injury also changed with age, with more women over 85 years reporting a fracture compared to those aged 65-74 years (19% vs. 6%). The most frequently reported fractures were to the wrist, rib and hip (Lord et al., 1993).

Hip fractures are associated with higher mortality and morbidity than all other fractures combined (Cummings et al., 1985) with hip fracture associated with a mortality rate of 33% at 12 months (Keene et al., 1993). White women are most at risk of hip fracture due to loss of bone mass following menopause (Cummings et al., 1985) with 1 in 6 experiencing a hip fracture during her lifetime (Cummings et al., 1995) and therefore studies investigating risk of hip fracture often look only at this group (Cummings et al., 1995, DargentMolina et al., 1996, Wainwright et al., 2005). The length of the studies varied from 1.9 years to up to 5 years but all found hip fracture to have occurred in 2-3% of participants. Unfortunately although concentrating on white, elderly women gives the studies better power to identify risk factors it means outcomes are not generalizable to males or other races. Identified risk factors for hip fracture are similar to those found for falls but also include reduced femoral bone mineral density.(Keene et al., 1993, Cummings et al., 1995, DargentMolina et al., 1996, Wainwright et al., 2005). Analysis of the causes of hip fractures show that 97% result from falls (Grisso et al., 1991).

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Falls are a strong predictor of long term admission to nursing homes. Subjects who have had a single serious injury resulting from a fall are most likely to be admitted but even fallers who have non-injurious falls are also more likely to be admitted than elderly people that experienced no falls (Tinetti and Williams, 1997).

### 4.3.2 Mortality

Mortality rates have been calculated from International Classification of Diseases (ICD) codes. To avoid underestimating falls data, deaths classified as due to osteoporosis have been included in falls mortality analysis as in many cases deaths resulting from pathological fracture following a fall are classed as due to osteoporosis and over 80% of deaths coded as due to osteoporosis in 2004 involved a fall. In 2004, falls and fractures were the most common causes of injury related mortality (Griffiths et al., 2006). In the age group 55-74 years, 26% of injury related deaths in females and 23% in males were accounted for by falls and this increased to 33 and 35% respectively for the 75 years and over age group (Griffiths et al., 2006).

### 4.3.3 Cost of Falls

There are two types of cost; the first is direct or accounting costs associated with a fall, which includes immediate medical costs and the cost of long term care. The second type of cost is the economic cost, consisting of the direct cost plus the loss of contribution to the economy that the person would have made either during the period of rehabilitation (morbidity cost) or if the fall resulted in death, the contribution the person would have made over the rest of their lifetime (mortality cost). For the population over 65 years the morbidity and mortality costs are small compared to the direct costs (Englander et al., 1996). The Department of Trade and Industry (DTI) in the UK calculated direct costs for unintentional falls in the over 60s. The costs were calculated from Accident and

Emergency department data and Hospital Episode Statistics. Ten thousand cases of falls were randomly selected and examined to estimate proportions of patients who incurred additional expenses after hospital treatment, such as long term nursing care (assumed to be for a 6 month period). The total cost was estimated as £981 million (UK pound in year 2000).  £578 million of the total were NHS costs and the remaining was cost of long term care provided by Personal Social Services. This figure is likely to be a conservative estimation of cost of falls in the UK, as it does not include patients who attended their general practitioner for initial treatment and long term nursing care will often be provided for a period longer than 6 months (Scuffham et al., 2003).

## 4.4 Vision and Falls

Poor vision, both self reported or where aspects of visual function have been measured has been found to be a significant risk factor for falls (Campbell et al., 1981, Nevitt et al., 1989, Lord et al., 1991, Lord et al., 1993, Lord et al., 1994, Berg et al., 1997, Ivers et al., 1998, Lord and Dayhew, 2001, Tromp et al., 2001, Klein et al., 2003, Coleman et al., 2004, de Boer et al., 2004, Morris et al., 2004, Freeman et al., 2007) and hip fracture (Felson et al., 1989, Grisso et al., 1991, Cummings et al., 1995, DargentMolina et al., 1996, Ivers et al., 2000, Ivers et al., 2003, Klein et al., 2003, Wainwright et al., 2005).

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### 4.4.1 Definition of Visual Impairment

As with falls there is no singular definition of visual impairment. Impairment can be defined in terms of function, for example an inability to perform domestic tasks or read a newspaper. More frequently though it is defined as an inability to reach a visual standard, most commonly spatial resolution, measured as Snellen visual acuity (Dickinson, 2001). In the United States visual impairment is defined as binocular visual acuity worse than 6/12 but better than 6/60 and legal blindness defined as worse than 6/60 (Rubin et al., 1997).

The World Health Organisation (WHO) has defined that visual impairment includes low vision and blindness and gives definitions which are widely used, and used in the UK. Low vision is defined as "visual acuity of less than 6/18 but equal to or better than 3/60 in the better eye, or a corresponding visual field loss to less than 20 degrees in the better eye with best possible correction". Blindness is defined as "visual acuity of less than 3/60 in the better eye, or a corresponding visual field loss to less than 10 degrees in the better eye with best possible correction".

Leat et al (1999) recommended that low vision be defined as visual impairment sufficient to cause visual disability, advising the definition to be visual acuity worse than 6/12. They recommended that other measures of visual function should also be considered and suggested visual disability cut off criteria as Pelli Robson contrast sensitivity worse than 1.05 log units and a visual field less than 120º (measured with Goldmann target III-3e).

**4.4.2 Visual Impairment in the Elderly**

Data on prevalence and incidence of visual impairment globally has been reported by WHO. The majority (82%) of people defined as visually impaired were over the age of 50. The leading causes of visual impairment were cataract (47.8%), glaucoma (12.3%) and age-related macular degeneration (8.7%) (Resnikoff et ak., 2004).

Data taken from blind and partially sighted registration in the UK reports that 87% of the visually impaired population are aged over 50 years, 65% of which are over the age of 75. The main causes of visual impairment are macular degeneration (49.3%) and glaucoma (11.8%). Cataract is only a primary cause for 3.4% reflecting the availability of surgical intervention in the UK (Dickinson, 2001). However registration data underestimates the prevalence of visual impairment, as registration is voluntary and does not include any data on undetected visual impairment (Dickinson, 2001). Wormald et al (1992) investigated the prevalence of visual impairment in elderly people aged over 65 years in London. Using WHO definitions of low vision of VA worse than 6/18, 7.7% of subjects were found to have low vision. Of these, 75% had cataract, 13% had optic atrophy and 13% had age related maculopathy. The prevalence of low vision increased with age with only 1% of 65-74 year olds having low vision, increasing to 14.2% of elderly 75 years and older (Wormald et al., 1992). A study of 14,600 GP registered elderly across the UK found 12.4% of elderly 75 years or over had visual impairment (VA 6/18 or worse). This increased to 36.9% for those over 90 years (Evans et al., 2002). Both studies measured habitual visual acuity and so included visual impairment due to uncorrected refractive error. Wormald et al (1992) measured pinhole acuity in subjects identified as visual impaired and from this concluded that 11% of visual impairment was due to uncorrected refractive error. Evans et al (2002) found that measuring pinhole acuity reduced prevalence from 12.4% to 10.2%, but found that 38% of subjects with vision of 6/18 or worse could not do the pinhole test satisfactorily, and therefore did not accurately reflect the prevalence of low vision due to uncorrected refractive error. A study in Australia looking at a community based population aged 49 years and over found a prevalence of visual impairment (VA 6/12 or worse) of 11.1%

(Foran et al., 2002). Following subjective refraction, prevalence reduced to 4% (Foran et al., 2002). These studies suggest that even in developed countries the leading causes of visual impairment in the elderly are treatable, either through cataract surgery or updating spectacles.

Other measures of visual function also decline with age. A survey of 2520 community based elderly people measured EDTRS visual acuity, Pelli Robson contrast sensitivity, glare sensitivity, Humphrey screening visual fields and Randot stereoacuity. For all measures of visual function there was a linear decrease with age, apart from stereoacuity which remained constant for subjects up to the mid-seventies at which point it declined rapidly. All visual function measures apart from glare sensitivity were moderately correlated with the highest correlation between visual acuity and contrast sensitivity (Rubin et al., 1997). Similar findings were found between visual acuity and contrast sensitivity as measured by the Melbourne edge test in an elderly population (Lord et al., 1991). Despite findings of good correlation between visual acuity and other measures of visual function, including contrast sensitivity and glare recovery, visual acuity was found to be a poor predictor of other aspects of visual function (Haegerstrom-Portnoy et al., 2000) and underestimates loss of visual function in older people (Haegerstrom-Portnoy et al., 1999).

### 4.4.3 Cost of Falls due to Visual Impairment

Using national data from Accident and Emergency (A&E) and hospital inpatient admission the medical cost of falls related to visual impairment has been calculated. The population with visual impairment was based on the prevalence of age-specific visual impairment and relative risks reported in the literature. In 1999, there were

189,000 accidental falls that required treatment in individuals with visual impairment. 89,500 of these were directly related to the visual impairment itself. The cost of these falls were estimated at £269million and £128 million respectively (Scuffham et al., 2002). These values do not include economic cost (section 3.3.3) or cost of long term nursing care required following a fall and hence are an underestimation of the total costs.

### 4.4.4 Visual Acuity and Falls

High contrast visual acuity is the most widely used measure of visual function in cohort studies as visual acuity charts are widely available and easy to use, and as outlined in section 3.4.1 visual impairment is usually defined in terms of visual acuity. In addition there is evidence to link reduced acuity and falls (Jack et al., 1995, Close et al., 1999). In patients admitted to an Acute Geriatric ward following an injurious fall 76% had habitual binocular Snellen acuity of 6/18 or worse (Jack et al., 1995). In a separate study of patients attending Accident and emergency, following a fall 59% were found to have impaired vision (defined as 6/12 or worse in either eye, Close et al., 1999).

As outlined previously (sections 4.1.2 and 4.1.3), comparison of cohort studies can be difficult due to differences in methodology. A well designed study would be prospective in nature, with large number of participants given daily falls records and results collected regularly, weekly or monthly as recommended by ProFaNE (section 4.1.2). A number of studies have used this method to collect falls data (Campbell et al., 1989, Nevitt et al., 1989, Lord et al., 1991, Lord and Dayhew, 2001, Freeman et al., 2007) although many studies investigating visual acuity as a risk factors for falls have used longer recall periods (Tinetti et al., 1988, Lord et al., 1994, Friedman et al., 2002, Stalenhoef et al., 2002, Klein et al., 2003) and therefore may have underestimated the number of falls (Cummings et al., 1988). In addition some studies are retrospective in nature (Campbell et al., 1981, Downton and Andrews, 1991, Ivers et al., 1998) and therefore may further underestimate incident of falls due to poor recall in participants. In order to overcome the problem of poor participant recall of falls, studies have instead investigated hip fracture as an outcome measure (Felson et al., 1989, DargentMolina et al., 1996, Koski et al., 1998, Ivers et al., 2000, Ivers et al., 2003, Klein et al., 2003). When a hip fracture occurs medical intervention is required, and therefore a record exists, making it a more reliable outcome measure than falls. It is also important that confounding factors, for example age, are corrected for in data analysis to demonstrate whether visual acuity is an independent risk factor. A positive link between falls and reduced acuity may be as a result of the correlations between decline in visual acuity with age and increase in incidence of falls with age.

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Ideally measurement of visual acuity should be performed on a chart using Bailey Lovie logMAR design principles (Bailey and Lovie, 1976) as opposed to a Snellen chart because although Snellen visual acuity is widely used, it has shortcomings when quantifying visual acuity. A misread letter on one line is not quantifiably the same on another line due to difference in the number of letters per line and an irregular progression in letter size on Snellen charts. LogMAR charts have been designed to overcome these difficulties and provide reproducible visual acuity information (Ferris et al., 1982). Unfortunately the Snellen chart is still widely in use outside of vision research and has been used in many epidemiological studies (Campbell et al., 1981, Tinetti et al., 1988, Campbell et al., 1989, Felson et al., 1989, Downton and Andrews, 1991, DargentMolina et al., 1996, Berg et al., 1997, Ivers et al., 2000, Stalenhoef et al., 2002), although it appears that later studies are more likely to use LogMAR charts

(Koski et al., 1998, Lord and Dayhew, 2001, Friedman et al., 2002, Ivers et al., 2003, Klein et al., 2003, Freeman et al., 2007). Most studies have measured habitual binocular visual acuity rather than optimal visual acuity (Ivers et al., 1998, Ivers et al., 2000, Lord and Dayhew, 2001, Friedman et al., 2002, Stalenhoef et al., 2002, Ivers et al., 2003, Klein et al., 2003, Freeman et al., 2007). Many elderly people have been found to have impaired vision through not wearing an up to date or appropriate refractive correction (Wormald et al., 1992, Foran et al., 2002) and therefore habitual acuity is a more appropriate measure than best corrected visual acuity. Of note, Klein et al (2003) found that impaired habitual acuity was a risk factor for falls whilst impaired optimal visual acuity was not, although this was not the case for hip fracture as an outcome measure where both optimal and habitual acuity were significant risk factors (Klein et al., 2003). Unfortunately it is not always made clear in the methodology what correction has been used, some studies have only specified “corrected” visual acuity which suggests subjects wore their own spectacles (Campbell et al., 1981, Nevitt et al., 1989, Cummings et al., 1995, DargentMolina et al., 1996), or no information is provided on whether spectacles were worn at all (Tinetti et al., 1988, Downton and Andrews, 1991, Berg et al., 1997). In other studies “best corrected” has been specified (Felson et al., 1989, Lord et al., 1991, Lord et al., 1994, Ivers et al., 1998, Koski et al., 1998, Ivers et al., 2003, Klein et al., 2003). However this again may refer to habitual rather than optimal acuity. For the purpose of comparison it has been assumed that best corrected refers to optimal correction only if it is stated in the methodology that subjects underwent a subjective refraction (Felson et al., 1989, Ivers et al., 1998, Ivers et al., 2003, Klein et al., 2003). Comparison of studies is made more difficult by the use of different definitions of visual impairment and therefore the cut-off point used in statistical analysis. The majority of studies use a definition of 6/12 (0.3 LogMAR) or

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worse, whereas other studies have used differing levels including 6/10 (0.2 LogMAR) or worse (Lord and Dayhew, 2001), 6/15 (0.4 LogMAR) or worse (Nevitt et al., 1989), worse than 6/18 (Lord et al., 1994), one line of visual loss (Freeman et al., 2007), a twenty percent loss (Tinetti et al., 1988) or one standard deviation decline in visual acuity (Cummings et al., 1995). In addition some studies have provided no information on what level was used to define poor or impaired visual acuity (Campbell et al., 1989, Ivers et al., 1998, Koski et al., 1998, Stalenhoef et al., 2002, Ivers et al., 2003, Klein et al., 2003). Table 1. summarises studies that have investigated visual acuity as a risk factor for falls or hip fracture, providing odd ratios (OR) where this was given by the studies. Despite the variations in methodology, the majority of studies have not found impaired visual acuity to be a risk factor for falls (Campbell et al., 1981, Tinetti et al., 1988, Campbell et al., 1989, Nevitt et al., 1989, Downton and Andrews, 1991, Lord et al., 1991, Cummings et al., 1995, Berg et al., 1997, Lord and Dayhew, 2001, Friedman et al., 2002, Stalenhoef et al., 2002, Lord et al., 2003, Freeman et al., 2007), including the well-designed prospective studies which used appropriate measures for visual acuity. In contrast, studies that have investigated self-reported impaired vision as a risk factor have mostly shown impaired vision to be a risk factor for falls (Tromp et al., 2001, Morris et al., 2004) or hip fracture (Grisso et al., 1991, de Boer et al., 2004). This perhaps suggests that it is not visual acuity but other aspects of visual function that are more important as risk factors for falls.

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#### 4.4.5 Low Contrast Visual Acuity

In the previous section all results refer to high contrast visual acuity. However, although not widely investigated, a study that has measured low contrast acuity (10% contrast) have found it to be a risk factor for falls (adjusted Relative Risk 2.08 95% CI 1.17-3.71, Lord and Dayhew, 2001). Indeed, low contrast acuity was found to be significantly poorer in participants classed as multiple fallers, compared to non-fallers (Lord et al., 1994). Low contrast acuity declines with age to a greater extent than high contrast acuity and cannot be predicted from the high contrast acuity score (Haegerstrom-Portnoy et al., 1999).

### 4.4.6 Contrast Sensitivity

Evidence suggests than contrast sensitivity may be more important than visual acuity in predicting falls. For example visual stabilization of posture (as measured by the ratio of sway with eyes open and sway with eyes closed) is closely associated with contrast sensitivity (CS), measured using the Pelli Robson chart (Turano et al., 1994, Anand et al., 2003a) and on the Melbourne edge test (MET) contrast test (Lord et al., 1991, Lord and Menz, 2000). In addition postural stability was correlated with contrast sensitivity in subjects with age-related macular degeneration (Elliott et al., 1995a). Orientation mobility, the ability to recognize one’s position with respect to the immediate environment and travel safely is also correlated with peak contrast sensitivity rather than visual acuity (Marron and Bailey, 1982).

Epidemiological studies have investigated contrast sensitivity as a potential risk factor for falls although there are difficulties in comparing results across studies as there is no single test that has been used consistently. Contrast sensitivity varies with spatial frequency (Ginsburg, 1984) and unlike visual acuity there is no accepted normal standard or definition of impairment (Leat et al., 1999), although there are normal values for the different clinical tests (Ginsburg, 1984, Elliott and Whitaker, 1992, Mantyjarvi and Laitinen, 2001, Haymes and Chen, 2004). The most widely used test within falls epidemiological studies is the Vistech test (Ginsburg, 1984) which assesses contrast sensitivity at 5 different spatial frequencies ranging from 1.5 to 18 cycles/deg. Most studies using the test have found that increased risk of hip fracture occurs when there is loss of contrast sensitivity at low spatial frequency (average of the scores for 1.5 and 3 cycles/degree, Cummings et al., 1995, de Boer et al., 2004, Wainwright et al., 2005). No link was found between contrast sensitivity and fracture when the spatial frequencies were assessed individually (DargentMolina et al., 1996). However the test-retest reliability of this test is very poor (coefficient of repeatability or COR, 1.96 times the standard deviation of the test-retest reliability, 0.4 log contrast, Pesudovs et al., 2004). A test of a similar design, the Vector vision CSV-1000 chart was used for the Blue Mountains Eye Study for investigating falls in a retrospective study (Ivers et al., 1998) and hip fracture in a prospective study (Ivers et al., 2003). This test assesses contrast sensitivity at four spatial frequencies (3, 6, 12 and 18 cycles/deg) and may have better repeatability than the Vistech (COR 0.2 log contrast, Pomerance and Evans, 1994) although both tests have poorer reliability when compared to the Pelli Robson (COR 0.1 log contrast, Elliott et al., 1991). Following adjustment for age and gender poor contrast sensitivity was associated with multiple falls in the previous year at all spatial frequencies (Prevalence Ratio 1.1, 95% CI 1.0-1.2, Ivers et al., 1998) and poor contrast sensitivity (worse than 1.55 log units) at 6 cycles/degree increased risk of hip fracture over a period of 2 years (Hazard Ratio 5.8, 95% CI 1.1-31.8, Ivers et al., 2003).

**Field Code Changed**

The Melbourne Edge test does not utilize gratings to measure contrast but instead asks the subject to identify the orientation of an edge within a disc. The discs are arranged in rows of 5 of decreasing contrast difference. When assessed with this test, reduced contrast sensitivity almost doubles the risk of multiple falls (RR 1.93, 95% CI 1.01-3.68) (Lord and Dayhew, 2001). Edge detection is considered to be related to peak contrast sensitivity (Haymes and Chen, 2004), which was found to be important for orientation mobility (Marron and Bailey, 1982) and stair negotiation (Tiedemann et al., 2007). Similar results may be expected with the Pelli-Robson chart as, in low vision patients, a good correlation has been found between the Melbourne Edge test and the Pelli-Robson chart (Haymes and Chen, 2004). Poor performance on the Pelli Robson chart was found to be predictive of falls in one study (worse than 1.55 log units, OR 1.63, 95% CI 1.11-2.39, Klein et al., 2003) but not in others (Friedman et al., 2002, Freeman et al., 2007). Again the differences between the studies may have been the cut-off used to define poor contrast sensitivity, with Friedman et al (2002) providing no definition of poor contrast and Freeman et al (2007), calculating odd ratios for every 0.3 log units seen correctly. Both studies measured CS at 1 metre when using the Pelli Robson chart at 3 metres is more sensitive to changes in visual function in visually normal subjects (Elliott and Situ, 1998). In addition, all three studies took measurements from the best eye, rather than the binocular score (Friedman et al., 2002, Klein et al., 2003, Freeman et al., 2007) and thus, due to the effects of summation or inhibition (Pardhan and Elliott, 1991) may not accurately reflect the patients' contrast sensitivity.

Overall the evidence for impaired CS appears to suggest that it is a significant risk factor for falls, however, due to different methodology in measuring CS and difference in study design there is inevitably some disagreement between studies.

Table 1. Summary of studies investigating visual acuity as a risk factor for falls or hip fracture.

| **Study** | **Type** | **No. subjects** | **Assessment of acuity** | **definition VI** | **Time period (fall data coll)** | **Outcome measure** | **Adj con-founders** | **Link** | **OR (95% CI)** |
|---|---|---|---|---|---|---|---|---|---|
| Campbell et al (1981) | Retrospective | 533 | Best eye habitual Snellen | Not defined | Prev 12 months | Falls | NO | NO | Not given |
| Tinetti et al (1988) | Prospective | 336 | Binocular Snellen | 20% drop | 12 month (8 weekly) | Falls | NO | NO | 1.4 (0.9-2.0) |
| Campbell et al (1989) | Prospective | 761 | Binocular habitual Snellen | ≤ 6/12 | 12 months (monthly) | Falls | YES | NO | 1.3 (0.8-2.2) |
| Felson et al (1989) | Prospective | 2633 | Either eye optimal Snellen | ≤ 6/7.5 either eye | 10 years | Hip fracture | YES | YES | 1.7 (1.1-2.7) |
| Nevitt et al (1989) | Prospective | 325 | Binocular habitual LogMAR | ≤ 6/15 | 12 month (weekly) | Falls | YES | NO | Not given |
| Downton and Andrews (1991) | Retrospective | 203 | Binocular Snellen | Not defined | Prev 12 months | Falls | NO | NO | Not given |
| Lord et al (1991) | Prospective | 95 | Binocular habitual LogMAR | Not defined | 12 months (monthly) | Falls | NO | NO | Not given |
| Lord et al (1994) | Prospective | 414 | Binocular habitual LogMAR | <6/15 | 12 months (8 weekly) | Falls | NO | NO | Not given |
| Cummings et al (1995) | Prospective | 9516 | Binocular habitual, LogMAR | 1 SD | Mean 4.1 years | Hip fracture | YES | NO | 1.1 (1.0-1.2) |
| Dargent-Molina et al (1996) | Prospective | 7575 | Binocular habitual Snellen | 6/15-6/20<br>≤ 6/30 | Mean 1.9 years | Hip fracture | YES | YES | 1.9 (1.1-3.1)<br>2.0 (1.1-3.7) |
| Berg et al (1997) | Prospective | 96 | Binocular Snellen | Not defined | 12 month (2 weekly) | Falls | NO | NO | 0.8 (0.3-2.1) |
| Koski et al (1997) | Prospective | 979 | Binocular habitual LogMAR | <6/12 | 2 years | Injurious falls | YES | YES | 2.3 (1.2-4.6) |
| Ivers et al (1998) | Retrospective | 3654 | Habitual binocular LogMAR | ≤ 6/12 | Prev 12 months | Falls | YES | YES | 1.4 (1.1-2.0) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Ivers et al (2000) | Case control | 911 | Binocular habitual Snellen | ≤ 6/12 | 30 months | Hip fracture | YES | YES | 1.6 (1.1-2.2) |
| Lord and Dayhew (2001) | Prospective | 156 | Binocular habitual LogMAR | ≤ 6/10 | 12 month (monthly) | Falls | YES | NO | 1.6 (0.9-3.0) |
| Friedman et al (2002) | Prospective | 2212 | Habitual, binocular, logMAR | Not defined | 20 month (at end of period) | Falls | NO | NO | Not given |
| Stalenhoef et al (2002) | Prospective | 311 | Habitual binocular Snellen | ≤ 6/12 | 36 weeks (6 weekly) | Falls | NO | NO | 1.6 (0.8-3.1) |
| Ivers et al (2003) | Prospective | 3654 | best eye habitual LogMAR | <6/18 | 2 years | Hip fracture | YES | YES | 4.0 (1.2-13.6) |
| Klein et al (2003) | Prospective | 2962 | Binocular habitual LogMAR | ≤ 6/12 | Prev 12 month | Falls | YES | YES | 2.0 (1.1-3.6) |
| | | | | | 5 years | Fracture | YES | YES | 1.8 (0.9-3.0) |
| Freeman et al (2007) | Prospective | 2375 | Binocular habitual logMAR | Per line missed | 20 months (monthly) | Falls | YES | NO | 1.0 (1.0-1.1) |

#### 4.4.7 Visual Field Loss

As with contrast sensitivity, the main difficulty in ascertaining if visual field loss increases the likelihood of a fall is how to define visual field loss. Loss can be defined in terms of the extent of the visual field, as determined by kinetic testing, or by loss of central visual field or presence of scotomas, found by static tests. The extent of the visual field has been found to an independent predictor of subjects ability to negotiate a travel path whilst avoiding obstacles, with subjects who missed at least 10 points in their binocular visual field (as measured on a Humphrey visual field analyser) more likely to hit at least one obstacle (Broman et al., 2004) and the extent of the lower visual field has been found to be significantly reduced in recurrent fallers (Berg et al., 1997, Lord and Dayhew, 2001).

Loss in central visual fields has been found to increase postural instability (Turano et al., 1996) and the increase in postural instability is greater for central field loss than for peripheral field loss (Paulus et al., 1984, Straube et al., 1994). Indeed Berg et al (1997) found no correlation between peripheral visual field constriction and either static or dynamic stability (Berg et al., 1997). Central field loss was not found to be a risk factor for falls when defined as more than 5 missed points on a central 30º suprathreshold test on the Humphrey visual field analyser (Friedman et al., 2002). However if the losses on edge points are excluded (Ivers et al., 1998, Ivers et al., 2003) or only the central 24º tested (Ramrattan et al., 2001) in order to avoid artefactual losses due to lens edge or physiological features, then a loss of more than 5 points was found to increase the risk of falling (Ivers et al., 1998, Ramrattan et al., 2001) or hip fracture (Ivers et al., 2003). A study of binocular visual field (calculated from the most sensitive points from either eye using a Humphrey visual field analyser) divided the visual field into central and peripheral visual field and losses in both were found to be significant risk factors for multiple falls following adjustment for age and health (Freeman et al., 2007).

Both central and peripheral visual field loss appears to be a significant factor for increased risk of falling or hip fracture, however it appears that there are two separate mechanisms with the loss of lower peripheral visual field increasing the risk of tripping on uneven surfaces and loss of central field increasing postural instability.

**4.4.8 Stereopsis**

A number of studies have investigated whether impaired depth perception may increase the likelihood of falls, either using a stereopsis test to assess depth perception (Nevitt et al., 1989, Cummings et al., 1995, DargentMolina et al., 1996, Lord and Dayhew, 2001, Friedman et al., 2002, Ivers et al., 2003, Wainwright et al., 2005, Freeman et al., 2007) or by assuming that depth perception is impaired by poor vision in one eye and therefore using asymmetry of visual function as a surrogate measure for stereoacuity (Felson et al., 1989, Klein et al., 2003). Of elderly attendees of an Accident and Emergency department following a fall, 62% were found to have impaired binocular vision (defined as disparity in acuity between eyes of two lines or more on the Snellen chart, Close et al., 1999). Felson et al (1989) found that risk of hip fracture increased in patients who had poor vision in one eye (6/30 or worse, adjusted RR 2.17, 95% CI 1.24-3.80) or moderately impaired vision in one eye (6/9 to 6/24, adjusted RR 1.94 95% CI 1.13-3.32) but not in patients who had impaired vision in both eyes (Felson et al., 1989). However Klein et al (2003) did not find asymmetry of visual function (VA, CS or visual field) to be associated with increased risk of multiple falls or hip fracture, although the definition of asymmetry of vision differed from that of Felson et al (1989) as asymmetry was defined as either one, two or three lines difference on a logMAR chart (Klein et al., 2003), which is equivalent to less asymmetry between the two eyes than investigated by Felson et al (1989), which is equivalent to 2 to 5 lines (moderately impaired) or more than 6 lines difference (poor vision).

Studies that have directly measured stereoacuity have used a variety of stereotests, including Frisby (Lord and Dayhew, 2001), Randot (Nevitt et al., 1989, DargentMolina et al., 1996, Ivers et al., 2000, Friedman et al., 2002, Freeman et al., 2007) and the Howard Dolman (HD) apparatus (Cummings et al., 1995, Lord and Dayhew, 2001, Wainwright et al., 2005). The HD apparatus requires subjects to align vertical rods in depth, but it is not a commercially available test and hence there is no standardisation between designs, including rod diameter and positioning. The gap between the rods can influence stereo threshold measured (Simons, 1981). In addition there is variation between how stereoacuity is measured. Lord and Dayhew (2001) use mean alignment error of six trials as a measure of stereopsis whilst other studies have used the standard deviation of four trials (Cummings et al., 1995, Wainwright et al., 2005), whilst it has been suggested than neither mean error or standard deviation accurately measure stereoacuity (Larson, 1985). Lord and Dayhew (2001) found that poor performance on the HD apparatus increased risk of falling (adjusted RR 2.26, 95% CI 1.24-4.14) and Cummings et al (1995) found that poor depth perception increased risk of hip fracture (RR 1.5, 95% CI 1.1-2.0) whilst Wainwright et al (2005) found no increase in risk of hip fracture.

The most frequently used stereotest in epidemiological studies has been the Randot circles test, and a score of poorer than 50 seconds of arc has been found to increase risk of hip fracture threefold (Ivers et al., 2000) and a score of worse than 120 secs of arc associated with experiencing 3 or more falls in a year (Nevitt et al., 1989). Unfortunately no information regarding whether appropriate near spectacle correction for the test was used in either study so the measures may not have been accurate. In contrast other studies have found no link between stereoacuity measured on the Randot test and increased risk of falls (Friedman et al., 2002, Freeman et al., 2007). Freeman et al (2002) suggested this may be because the Randot stereotest is not an appropriate test for an elderly population because of the random dot background used in the test. This is based on poor reported performance of elderly subjects on another random dot stereogram test, the TNO (Garnham and Sloper, 2006) which has no monocular contours, unlike the Randot test which contains such contours.

Elderly people with stereoacuity worse than 215 seconds or arc, measured on a Frisby test were found to be at higher risk of multiple falls (RR 1.99, 95% CI 1.11-3.59, Lord and Dayhew, 2001). The Frisby test has been found to have excellent test-retest repeatability (Situ and Elliott, 2000) and is suitable for an elderly population (Haegerstrom-Portnoy et al., 1999, Garnham and Sloper, 2006), however the number of participants taking part in Lord and Dayhew (2001) was low (n = 156) compared to other epidemiological studies cited previously.

**4.4.9 Type of Spectacles**

Multifocal spectacles (bi/trifocals and varifocals) have been linked to increase risk of falls (Davies et al., 2001, Lord et al., 2002) and multifocal wearers suffer more trips when stepping up, compared to when wearing distance single vision spectacles (Johnson et al., 2007). These findings are most likely due to impaired visual function at critical distances when gazing through the near addition segment of the lens (Lord et al., 2002, Johnson et al., 2007, Johnson et al., 2008). Therefore multifocal wearers who achieve good scores on vision tests, as they could use the appropriate segment of their spectacles during assessment, would still be at higher risk of falls.

#### 4.4.10 Change in Vision

A change in vision may also increase the risk of falls with one study finding that elderly women experiencing a decline in visual acuity (defined as one line or more on the LogMAR chart) were significantly more likely to have a fall than women with stable poor acuity (Coleman et al., 2004). In addition, Cumming et al (2007) found that subjects who were provided with optimal refractive correction were more likely to fall in the following year than those who received no vision intervention (Cumming et al., 2007), suggesting that not only a decline in visual function but even a positive change in visual function can increase risk of falls. Of note is that the subjects who underwent visual intervention were more likely to fall in the first 6 months following the intervention and following a major change in refractive correction (0.75D or more change in either eye). This suggests subjects take time to adapt to a new prescription, especially of a large magnitude, possibly due to change in spectacle magnification or a change in prismatic lens effects when looking away from the lens optical centre.

In addition to the previous difficulties discussed when comparing studies (poor collection of falls data, variations in methodology and definition of impairment), the large variation in findings regarding whether poor stereopsis is a risk factor for falls may be partly due to none of the studies separating out those participants who have had poor or absent stereopsis due to longstanding strabismus or amblyopia. These individuals may have adapted to utilise monocular cues better than participants whose impaired stereopsis may be due to ocular disease or decline of vision with age. To date there is no evidence that poor or absent stereopsis from a young age is likely to cause falls later in life. As a result some study participants who are defined as having impaired stereopsis may be well adapted and therefore unlikely to trip thus these individuals may mask the effects of deterioration of stereopsis in falls.

The above findings may explain why there is such variation in findings of epidemiological studies investigating visual function as risk factors for falls, as outcome will depend on when subjects last updated spectacles or if there has been a recent change in visual function in relation to visual assessment and the collection of falls data. In order to overcome these difficulties visual function should be measured both at the beginning and end of the study period. Ocular history should be noted including presence of strabismus or amblyopia as well as other ocular disease. Type of spectacle should be noted in order to identify multifocal wearers, as well as when (and if) spectacles are worn. Not wearing prescribed spectacles has been identified as a risk factor for falls (Gabell et al., 1985). Subjects should also be asked about any recent eye examinations prior to the study and eye examinations during the study period along with consequent change in refractive correction (and asked to supply the refractive correction details), as well as any other visual intervention, for example cataract surgery during the study period. In addition in order to reliably identify participants who have had a change in visual function then tests with excellent test- retest reliability need to be used, for example LogMAR acuity, Pelli Robson contrast sensitivity and the Frisby stereotest. These recommendations will enable future epidemiological studies to fully investigate which visual functions are most important for predicting falls in an elderly population.

# Chapter 5

# General Methodology

The following chapter provides information regarding general methods. Specific detail for each experiment will be provided in the relevant chapters.

## 5.1 Subjects

Only individuals without a history of neurological, muscoskeletal or cardiovascular disorders which could affect their balance or gait were invited to take part in the mobility based studies. This is to ensure all participants would be able to do the locomotion tasks safely and with no difficulty and secondly to exclude any variability in the gait and balance due to the condition. Potential participants were also excluded if they had any history of eye disorders including amblyopia, strabismus or cataract so that all subjects had normal levels of stereoacuity. Written informed consent was obtained from all subjects who participated in the studies.

### 5.1.1 Young subjects

Subjects were recruited from University of Bradford student population. Medical and ophthalmic histories were self reported. Subjects were excluded if best corrected visual acuity was worse than 0.0 logMAR (6/6 Snellen equivalent) in either eye or if they failed to achieve 60 seconds of arc on the TNO stereoacuity test (section 5.2.3a). This level was chosen as it has been found that majority of young adults with normal binocular vision could achieve 60 seconds of arc or better when tested with the TNO

(Simons, 1981, Hall, 1982). This therefore excluded any participants who were not classed as visually normal for their age.

### 5.1.2 Elderly Subjects

Subjects aged 60 years or over were recruited from the University of Bradford Eye Clinic. Subjects were excluded if they used any mobility aids or had best corrected visual acuity worse than 0.2 log MAR (6/9.5 Snellen equivalent) in either eye, the presence of comitant or incomitant strabismus or if visible ocular disease was seen on ocular screening using slit lamp biomicroscopy, direct ophthalmoscopy, central visual field testing and non-contact tonometry. As stereoacuity has been found to be worse in the elderly population (Brown et al., 1993, Lee and Koo, 2005, Garnham and Sloper, 2006) subjects were excluded if they could not achieve 240 seconds or arc on the Frisby stereotest. This level was chosen as it was achieved by all elderly subjects over 70 years with good acuity (6/9 or better) in both eyes (Garnham and Sloper, 2006). Subjects all had undergone subjective refraction and binocular vision assessment including cover/uncover test, alternating cover test and ocular motility within the past year. Prior to data collection for mobility studies, each subject’s balance and mobility were assessed using the Functional Reach Test (which measures forward reach ability from a bilateral stance) and the Timed Up and Go test (which measures the time taken to stand up from a chair, walk 3 metres, turn-around walk back to the chair and sit down). These tests the elderly subjects’ functional ability to be assessed in relation to normative data (Rosemary et al., 2004) and in the case of Timed Up and Go can distinguish fallers and non-fallers (Shumway-Cook et al., 2000). Both tests show good test-retest reliability in healthy subjects and the Timed Up and Go test correlates closely to the Berg balance scale (Rosemary et al., 2004).

### 5.1.3 Monovision Contact Lens Patients

Subjects were recruited from the University of Bradford Eye clinic and from the student and staff population of the University of Bradford. Inclusion criteria included being presbyopic and having worn monovision correction on a regular basis for a minimum of three months. Monovision correction was defined as having one eye (usually but not necessarily the dominant eye) corrected for distance and the other eye corrected for near tasks. All medical and ophthalmic histories were self reported. Subjects were excluded if they failed to achieve a visual acuity of 0.2 log MAR (6/9.5 Snellen) in either eye or they had any history of strabismus, amblyopia or ocular disease. This ensured any impairment of stereoacuity was due to the monovision correction rather than to other factors.

## 5.2 Vision Assessment

### 5.2.1 Visual Acuity

Visual acuity was assessed using the Early Treatment Diabetic Retinopathy (ETDRS) LogMAR chart and the Test Chart 2000.

#### 5.2.1a ETDRS chart:

The Early Treatment Diabetic Retinopathy (ETDRS) log MAR chart (luminance 160cd/m$^2$, Figure 14).


Figure 14. ETDRS Chart (Chart R). www.precision-vision.com (June 2008)

A log MAR chart was chosen because as stated previously, in chapter 4 (section 4.4.4), Snellen charts have a number of shortcomings when making visual acuity measurements (Ferris et al., 1982). The ETDRS chart has been designed using recommendations of the Committee on Vision of National Academy of Sciences-National research council (Ferris et al., 1982). The chart has a geometric progression of letter size, with each line containing 5 Sloan letters. The selection of letters for each line was chosen so that each line had approximately equal difficulty. Each line has a value of 0.1 log of the minimum angle of resolution (MAR), scoring of logMAR acuity was scored per letter (Bailey and Lovie, 1976), with each letter being worth 0.02 log (0.1 line divided by 5 letters). The final acuity was determined when subjects made four or more errors on a line which optimises test reliability and prevents the outcome being influences by the subject's own criterion (Carkeet, 2001). Three ETDRS charts with different letter sequences were used for repetition of visual acuity measurements in order to prevent subjects memorising the letter sequences.

### 5.2.1b Test Chart 2000

Visual acuity measurements were also taken using a PC-based chart system (www.thomson-software-solutions.com), using the ETDRS logMAR chart design and Sloan letters as well as the same scoring system and termination rule as above. As the chart is PC based it allows the chart letters to be randomised between every measurement and hence stops subjects memorising any letter sequences during repeated measures. The chart was set at 100% contrast for high contrast acuity measurements and then adjusted to 25% contrast to measure low contrast visual acuity. The contrast was set according to the Test Chart 2000 standard Gamma function.

### 5.2.2 Contrast Sensitivity

Contrast sensitivity was assessed because, as stated in chapter 4 (section 4.4.6), poor contrast sensitivity has been found to be a significant risk factor for falls (Lord and Dayhew, 2001, de Boer et al., 2004) and good contrast sensitivity is important for mobility orientation tasks (Marron and Bailey, 1982) and stair negotiation (Tiedemann et al., 2007). Furthermore binocular contrast sensitivity has also been found to be impaired by monocular refractive blur (Pardhan and Gilchrist, 1990). Contrast sensitivity measures were taken using the Pelli-Robson chart (luminance 200cd/m$^2$, Figure 15).


Figure 15. Pelli Robson Chart. www.psych.nyu.edu (June 2008)

There are a range of clinical contrast sensitivity tests available which include those that measure contrast sensitivity through detection of orientation of sine wave gratings of different contrast and spatial frequency (Vistech contrast sensitivity chart, Ginsburg, 1984, Functional acuity contrast test, Pesudovs et al., 2004) or the detection of the orientation of edges of different contrasts (Verbaken and Johnston, 1986). Instead of these the Pelli Robson is a letter based chart, designed to be quick, a familiar task to the patient and easy to score (Pelli et al., 1988). The letter chart design utilised 10 letters and therefore gives a 10 forced choice alternative whilst tests based on orientation only provide 3 or 4 forced choice alternative. The test-retest reliability is better for the Pelli Robson chart compared to the Vistech contrast sensitivity test (Elliott and Whitaker, 1992) and Melbourne edge test (Haymes and Chen, 2004). In addition the Vistech Contrast Sensitivity test has been found to have considerable redundancy in information at higher spatial frequencies in normal subjects if used in conjunction with a high contrast visual acuity measurement (Kennedy and Dunlap, 1990, Elliott and Whitaker, 1992). In addition measurements using only lower spatial frequency gratings have the poorest test-retest reliability (Kennedy and Dunlap, 1990). Both the Melbourne Edge Test (Haymes and Chen, 2004) and the Functional Acuity Contrast Test (Pesudovs et al., 2004) have also been found to have upper limitation of scale for normal subjects whilst the Pelli-Robson chart has no upper or lower limitation of scale for either visually normal or visually impaired subjects (Haymes and Chen, 2004).

The chart consists of 16 Sloan letter triplets of equal contrast and size (4.9 x 4.9cm). With each successive triplet there is a decrease in contrast of 0.15 log units. The letters are constructed from a square-wave grating with the fundamental spatial frequency of the letters varying with test distance. Outcome scores were determined using a by-letter scoring system, which has been shown to improve test-retest reliability compared to the standard scoring (Elliott et al., 1991). There is a large variation in letter legibility at threshold level for some letters and in order to overcome this, the miscalling of the letter "C" as the letter "O" or vice versa was accepted as correct (Elliott et al., 1990). Two versions of the chart with different letter sequences are available and both were used in order to minimise subjects memorising letter sequences. Subjects were given plenty of time for each measurement and were encouraged to guess letters as they approached their end point.

### 5.2.3 Stereoacuity

#### 5.2.3a TNO Test for Stereoscopic Vision

The TNO (Institute of Perception, National Organisation for Applied Scientific Research in The Netherlands, 1974) consists of random dot stereograms in the form of red/green anaglyphic plates viewed with red/green goggles (Figure 16).

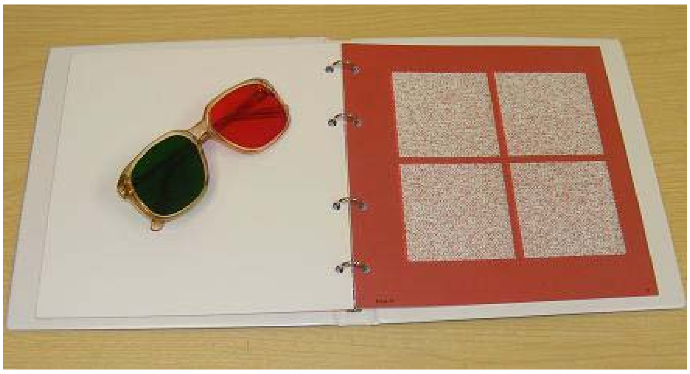


Figure 16. TNO Stereotest.

It consists of three screening plates which contain at least one test figure (visible without stereopsis) and one concealed figure with disparity of 33 minutes of arc (1980 seconds of arc) and three grading plates. Each grading plate contains two pairs of equal disparity. The figures are concealed circles with 60° sectors missing. The task is to identify the location of the missing sector within each target with a four alternative forced choice (top, bottom, left or right). To pass each level subjects had to correctly identify the orientation of the missing sector for both targets of each pair. Stereoacuities measured with the grading plates are 480, 240, 120, 60, 30 and 15 seconds of arc. The TNO test contains no monocular cues (Walraven, 1975). As a result the test has been found to be more reliable in detecting the presence of amblyopia when screening children than other stereotests for which monocular cues are present and in which children with poor or absent stereopsis can utilise the monocular cues to identify the target (Walraven, 1975, Okuda et al., 1977). Test-retest reliability of the TNO has been found to be excellent (correlation coefficient of 0.91, Jenkins and Curran, 1978). However in comparison to other stereotests it has been found that poorer stereoacuity scores are obtained with the TNO across all age groups (Hall, 1982, Garnham and

Sloper, 2006). There are a number of reasons why this may be the case. Firstly as previously stated, the TNO contains no monocular cues, in addition the TNO requires form discrimination rather than just the perception of depth (Hall, 1982) and finally that the TNO measures global stereopsis whilst other tests measure local stereopsis (Harwerth and Rawlings, 1977). In elderly patients the difference in stereoacuity measured by TNO and other stereotests appears to be more pronounced than in young subjects (Garnham and Sloper, 2006). The authors suggest this is due to difficulty with motor alignment of the eyes in the absence of monocular contours and the disassociative nature of the test. As a consequence Garnham and Sloper (2006) recommend that this test should not be used for measurement of stereopsis in older adults.

For repeated measures of stereopsis the grading plates were removed from the booklet and presented in a randomised order, to prevent subjects learning the orientation of the missing sector. All measurements were carried out at the recommended test distance of 40cm and using crossed disparity (target in front of background).

**5.2.3b Frisby Stereotest**

The Frisby stereotest is real depth test consisting of a clear Perspex plate with four random texture patterns printed on one side. Within one of the texture patterns a circular shape is printed on the other side of the perplex (Figure 17).

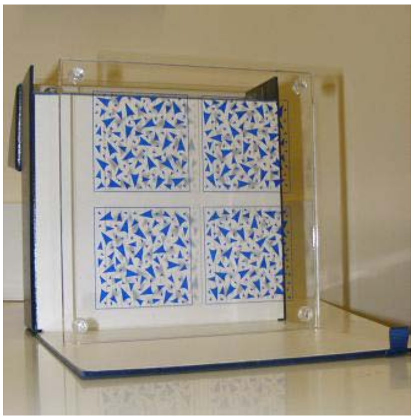


Figure 17. Frisby Stereotest.

The hidden circle can be identified if stereopsis is present and can discriminate the difference in position of the circle and the background. The degree of stereoacuity that can be measured is varied by using different thicknesses of Perspex plate (6, 3 and 1.5mm) and by changing test distance. For the purpose of these experiments a series of test distances (20 to 120cm) was calculated to give a range of acuities with the three Frisby plates from 0.95 to 3.03 log seconds of arc (9 to 1070") in 0.16 log steps (Table 2). At each test distance appropriate working lenses were used. Subjects first viewed a stereo level of 2.23 log secs of arc (170"). If subjects correctly identified the stereoscopic target in at least 2 of the possible 4 presentations, the stereothreshold was decreased to the next level.

Table 2. Range of log stereoacuity measured using the modified Frisby stereotest.

| LEVEL | PLATE (mm) | DISTANCE (cm) | Log Stereopsis | Secs of arc |
|---|---|---|---|---|
| **1** | 6 | 22 | 3.03 | 1071 |
| **2** | 3 | 19 | 2.87 | 741 |
| **3** | 6 | 33 | 2.71 | 513 |
| **4** | 6 | 40 | 2.55 | 355 |
| **5** | 3 | 33 | 2.39 | 245 |
| **6** | 3 | 40 | 2.23 | 170 |
| **7** | 1.5 | 33 | 2.07 | 117 |
| **8** | 1.5 | 40 | 1.91 | 81 |
| **9** | 6 | 100 | 1.75 | 56 |
| **10** | 1.5 | 60 | 1.59 | 39 |
| **11** | 3 | 100 | 1.43 | 27 |
| **12** | 3 | 120 | 1.27 | 19 |
| **13** | 1.5 | 100 | 1.11 | 13 |
| **14** | 1.5 | 120 | 0.95 | 9 |

Measurements were completed when either none or only 1 of the 4 presentations were correctly identified. As each step was an equal perceptual size, stereothresholds were scored per presentation (giving 0.04 log secs of arc per presentation with four presentations per level) similar to the by-letter scoring system used on the logMAR acuity chart (Bailey and Lovie, 1976). In all cases a crossed disparity was presented. The Frisby test was utilised as it has been found to have excellent test-retest reliability, comparable to the TNO (correlation coefficient 0.91, Situ and Elliott, 2000) and the design allows a large range of stereoacuity to be measured in small steps. In addition the drop in stereoacuity measured with the TNO in elderly subjects has not been found with the Frisby stereotest (Garnham and Sloper, 2006). A disadvantage of the Frisby test is the presence of a motion parallax as a monocular cue if the test is moved during assessment or if the patient makes excessive head movements. However this can be overcome through careful administration of the test and clear instructions to the patient (Hinchcliffe, 1978). In addition, in presbyopic patients the working distance lenses need to be changed for each change in test distance.

### 5.2.4 Kay Dominant Eye Test Box

Ocular dominance was tested using the Kay Dominant eye test box (Figure 18). The box (dimension length 152 x width 102 x height 100mm) contains a diamond printed in the middle of one of the inner sides of the box. On the opposite side is a circular aperture through which the diamond can be viewed. The subject is asked to hold the box with both hands at arm's length and line up the diamond so it appears within the circular aperture. This cannot be done with both eyes simultaneously and therefore forces the subjects to choose one eye for the task.

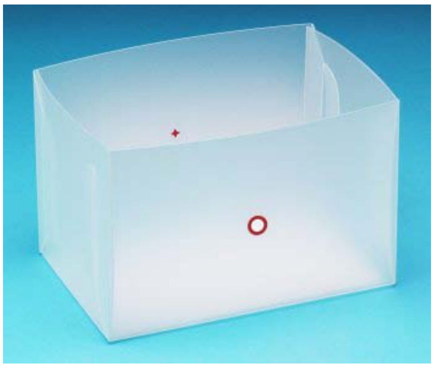


Figure 18. Kay Dominant Eye Test Box. www.kaypictures.co.uk (June 2008)

This type of ocular dominance is classed as sighting dominance (Chapter 1, section 1.5) and has been selected as the majority of ocular dominance tests determine sighting dominance (Coren and Kaplan, 1973). Sighting dominance is frequently used to determine the dominant eye in patients being fitted with monovision contact lenses (Jain et al., 1996). The test was administered three times to each subject.  The dominant eye was defined as the eye used for sighting in 3 out of 3 presentations. Subjects not using an eye consistently in these measurements were defined as having no clear preference.

## 5.3 Laboratory

The five mobility based studies were all undertaken in the Vision and Mobility Laboratory of the University of Bradford. The laboratory contains a multi-camera 3D motion capture system (Section 5.3.3) and two centrally placed force platforms (Section 5.3.5). The dimensions of the laboratory are width 5.77 x length 7 x height 2.77m. In order to control room illumination black out blinds have been fitted to the windows to keep out sunlight. The room illumination is provided by six fluorescent tubes within the ceiling, giving an average illumination of 400 lux at eye level in the area over the force platforms. The floor is covered in green vinyl (approximately 2mm thick) including the surfaces of the force platforms which are flush with the surrounding floor.

### 5.3.1 Step

The step was made from layers of medium density fibreboard, bonded together to form a solid block (dimensions length 508 x width 464 x height 142mm, Figure 19). The width and length of the step were chosen so that the step would fit exactly on to one force platform (Section 5.3.6), without overlap. The height was chosen to represent a typical step height that might be encountered within daily life e.g. stepping on to road side kerb. There are no regulations regarding kerb heights; although they typically can vary between 100 and 150mm. A single step in a domestic dwelling can be a maximum height of 220mm or in a commercial building 180mm (Billington et al., 2007). One or two additional sheets of MDF (thickness 5mm) could be added (fixed in position with metal pegs) in order to vary the height of the step. Height was varied in order to prevent subjects learning the height of the step during multiple trial repetitions. In addition variation in riser height has been linked to incidence of falls on stairs (Jackson and Cohen, 1995). US building regulations state that within a stair case the maximum difference in height between the largest and smallest riser should not exceed 3/8 inch (9.5mm) and a maximum difference between adjacent risers of 3/16 inch (4.8mm, BOCA, 1994). UK building regulations recommend that risers within a stair case should be the same height although there are no stated values to which stairs risers must comply (Billington et al., 2007). Therefore the variation in the height of the step was thought to reflect that likely found within a stair case. Subjects were informed that the height of the step may vary between trials.

#### 5.3.2 Raised Platform

A platform (dimensions length 3m x width 1m x 142mm) fitted around the step (Figure 19). The platform height matched the height of the step and was adjusted using MDF slats that slid underneath the platform and were therefore hidden from view. In addition, to disguise how much the platform was raised from the floor and to hide when additional MDF layers were added to the top of the step, a panel was attached to the front of the platform. Three different front panels were used, corresponding to the step and platform height and raised heights of the platform and step when the MDF layers were added (142, 152 and 157mm). All visible surfaces were covered in a layer of green vinyl to match the floor.

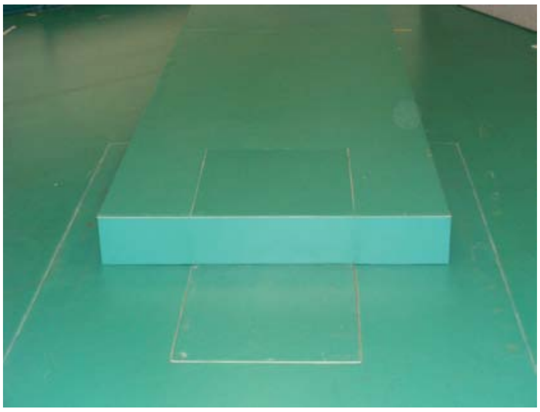


Figure 19. The Step and Raised Platform.

### 5.3.3 Motion Capture System

Motion capture was undertaken using a 6 or 8 camera Vicon MX three dimensional (3D) optical motion analysis system. The cameras used digitally controlled strobes that emit infrared beams; 6 of the 8 cameras had a resolution of 3 million pixels (MX-3, Figure 20) and 2 had a resolution of 13 million pixels (MX-13).


Figure 20. Vicon MX3 Camera. www.inition.com (June 2008)

**Formatted:** Italian (Italy)

Retro reflective markers were attached to subjects (section 5.3.4.), which interrupt and reflect back the infrared light. The cameras were wall mounted at a height of approximately 2.3m and were positioned evenly around the laboratory in order to have at least two cameras able to see each body marker throughout the trials, allowing the three-dimensional co-ordinates of the body markers to be calculated.

Prior to any data collection the camera system was calibrated. This involved using an L-frame placed at the coordinate origin of the laboratory and then using the wand (390mm wand), with markers placed at fixed distances, which was waved within the workspace utilised during the trial. This procedure allowed the cameras to identify their relative position and orientation to other cameras and to the workspace origin. This information was then used to calculate the 3D position and trajectory of the reflective markers during data collection. The mean error in reconstructing marker positions within the calibrated volume was less than 0.5mm for all cameras.

### 5.3.4 Helen Hayes Marker Set

A standard link-segment model (Plug in Gait, Oxford Metrics, UK) that utilises the Helen Hayes marker set was used (Kadaba et al., 1990). Reflective markers (14mm) were attached to each subject in the following locations (Figure 21); lateral malleoli, posterior aspect of the calcenei, lateral aspects of each shank and thigh, lateral femoral condyles, anterior superior iliac spines, sacrum, medial and lateral sides of wrists, lateral humeral epicondyles, acromions and inferior tip of the sternum, jugular notch, spinous processes of the $7^{th}$ cervical and $10^{th}$ thoracic vertebrae and antero-lateral and postero-lateral aspects of the head and a 6mm marker at the head of both 2nd metatarsals. Markers were attached with double sided tape, or in the case of head and wrist markers, were attached to sports bands which were then worn in the appropriate place. Wherever possible, markers were placed directly on the skin. Where markers were placed on to clothing the clothing was taped down to avoid excessive movement. Measurements were taken of the subjects' height and mass (kg), shoulder offset, defined as the distance from the acromion marker to centre of rotation of the shoulder joint, inter anterior superior iliac spine and leg length, defined as the length from anterior superior iliac spine marker to the medial malleoli. Elbow width, wrist width, hand thickness, knee width and ankle width were measured in the frontal plane, using an anthropometer. The measurements were entered into the Plug-in-Gait model so that a 3D segment linked model could be created for each subject (section 5.3.5).

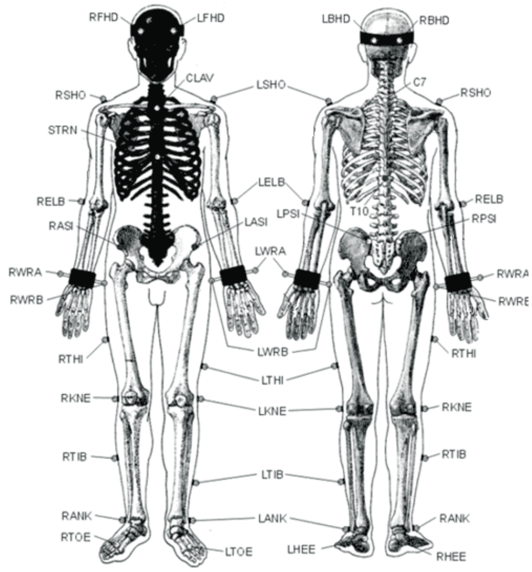



Figure 21. Helen Hayes Marker Set. Modified from www.lifemodeler.com (June 2008) Abbreviations listed in Appendix 8.

In addition to the standard marker set, reflective markers (6mm diameter) were placed onto the subjects' shoes in the following forefoot locations; 5$^{th}$ metatarsal heads and end of 2$^{nd}$ toe to make up the forefoot markers (Figure 22). A measurement of the distance (horizontal and vertical) from the 2nd toe marker to the bottom tip of the subject's shoe, was taken, from which a virtual marker, representing the shoe tip was created (right and left AIT). A virtual marker was used because an actual marker placed on the shoe tip would have been a hindrance to normal gait and would have been likely to have been knocked out of position during trials.

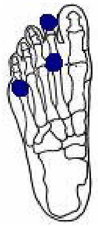


Figure 22. Forefoot Markers.

**5.3.5 Centre of Mass Calculation**

To determine the point location of the whole body centre of mass (CM) the position of the body marker along with measurements taken (outlined in section 5.3.4) were entered into the Plug-in-gait model. The CM location for each segment was then calculated from standard regression equations (Dempster, 1955) and the weighted sum of all segment CM locations was used to calculated whole body CM.

**5.3.6 Force Platforms**

Two adjacent force platforms (AMTI OR6-7-000, Advanced Medical Technology Inc) were used to sample (at 100Hz) the contact forces between the subjects' feet and the ground (Figure 23).

Figure 23. AMTI Model OR6-7 Force Platform. www.amtiweb.com (June 2008)

The force platforms sat flush with the laboratory floor, with a gap between the edge of each force platform and the surrounding floor of 0.32cm and were covered in the same green vinyl as the surrounding floor. Each platform consisted of a rigid upper plate mounted on a base, which contained four strain gauge transducers, mounted at each corner. The force platforms measured the ground reaction forces along X, Y and Z axes, along with moments along the three axes, providing a total of six outputs for each platform (Figure 24). The strain gauge transducers produced an electrical output when they were deformed under loading due to change in resistance. The signal was amplified and converted from an analogue to a digital output (16 bit analogue to digital converter).

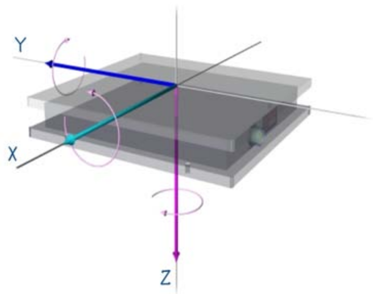



Figure 24. The Force and Moments Reference System. www.summitmedsci.co.uk (June 2008)

The step was placed on to the second force plate so that it did not overlap onto the floor. Prior to any data collection a zero-level calibration was carried out, which was used in conjunction with the amplifiers auto zero-function. The platform was re-zeroed when there was any change made to the step height to maintain accuracy throughout data collection.

### 5.3.7 Centre of Pressure

The centre of pressure is the point of application of ground reaction force under the feet. The co-ordinate of the centre of pressure is calculated from the moments applied to the force platforms. The centre of pressure is the point on the floor about which the moments are zero. The calculation for M-L (x axis) centre of pressure is below

$$\sum M = 0$$
$$M_Y - xF_Z - zF_X = 0$$
$$xF_z = zF_X - M_Y$$
$$x = \frac{zF_X - M_Y}{F_Z}$$

$\chi$ = CP coordinate

$F_\chi$, $F_y$, $F_z$ = Forces active along X, Y and Z axis

$M_y$ = Moment about the Y axis

z = Constant (Equating to the distance of the transducers below surface)

The centre of pressure in then normalised to the origin of the laboratory co-ordinate system. CP calculations can also be performed for the Y co-ordinates based on the moment about the X axis and the forces acting about the Z and Y axes. However within the following study (Chapter 5) only displacement of the CP in the M-L direction is investigated.

### 5.3.8 Data Processing and Treatment

Using Plug in Gait software (Oxford metrics) marker trajectory data were filtered using the Woltring Spline smoothing routine, a general cross validation method (studies 1 and 2) or using a predicted MSE value of 10 (studies 3, 4 and 6). The MSE value of 10 was chosen as pilot data suggested it gave an appropriate level of smoothing. Missing data for marker trajectories were filled using linear interpolation for gaps of 10 frames or less, or by copying trajectories from adjacent markers on the same body segment for gaps of over 10 frames. The 3D coordinate data of the left and right virtual shoe tip markers, forefoot, ankle, heel, knee, sternum and head markers, markers positioned on the platform edge and the centre of mass and centre of pressure data were exported into ASCII format for further analysis.

# Chapter 6

## Study 1: Step up from a standing start under conditions of acute monocular blur

### 6.1 Introduction and Aim

Approximately one third of community based elderly fall each year, with 25% of falls resulting in some form of injury (Lord et al., 1993) (Chapter 4). Poor or absent stereoacuity may be more pertinent as a risk factor than poor binocular high contrast acuity for falls (Close et al., 1999) or fall related injury, (Felson et al., 1989, Ivers et al., 2000) (Chapter 4) but there are very few experimental studies investigating how loss of stereopsis affects negotiation of raised surface or obstacles. Studies investigating how binocular visual impairment affects subjects when negotiating a step found that subjects adopted a two-fold safety driven strategy. Firstly subjects increased both vertical and horizontal lead limb toe clearance of the step. Secondly the subjects demonstrated reduced divergence of centre of mass (CM) and centre of pressure (CP) in the medial-lateral direction (Heasley et al., 2004, Heasley et al., 2005). Increasing toe clearance of the step when the position of the step edge is unclear can help avoid a trip. Reducing the divergence of CM and CP, although needed to initiate a step from standing, increases dynamic stability. If the divergence is too large then a fall may result (Zachazewski et al., 1993). In addition CP displacement in the medial-lateral direction was reduced. The displacement of the CP demonstrates the response to movements of the CM to keep the CM within the base of support in order to prevent a fall. Both reduced divergence of

CM-CP and CP displacement show subjects increasing dynamic stability in conditions of binocular blur

The effect of monocular refractive blur on negotiation of a step has previously not been investigated, although monocular occlusion has shown to increase lead limb vertical toe clearance when subjects negotiate an obstacle in the travel path (Patla et al., 2002), as did the presence of unilateral cataract (Elliott et al., 2000). This suggests that loss of binocular vision causes subjects to increase safety margins when negotiating obstacles (Section 3.3.3). Furthermore, following 2nd eye cataract surgery, subjects reduced lead limb toe clearance to that of age-match normals and the change in stereoacuity and change in toe clearance due to surgery was significantly correlated (Elliott et al., 2000).

The aim of this study was to determine whether the negotiation of a single step would be affected by impaired stereopsis caused by acute monocular refractive blur, and whether subjects would employ a similar safety driven strategy as seen in conditions of binocular blur. We chose a level of blur that is typically induced in monovision correction and hence may be found in a presbyopic population and chose the protocol of a single step up to allow comparison to the effects of binocular blur investigated previously (Heasley et al., 2004). We hypothesised that this level of monocular refractive blur would cause a significant decline in stereoacuity that would lead to less accurate visual information regarding the step’s height and position and thus subjects would adapt a gait strategy to increase lead limb toe clearance. We hypothesised that subjects would also demonstrate changes to the displacement of the CP in order to improve dynamic stability. We further hypothesised that blurring the dominant eye would have a greater effect than blur in the non-dominant as it would likely cause a larger decline in stereoacuity (Erickson and McGill, 1992). To judge the extent that monocular blur affected stepping strategy and toe clearance, we compared the monocular blur conditions to conditions where one eye was occluded.

## 6.2 Method

Eleven young subjects (two males and nine females, mean age 25.6 ± 6.5 years; height 169 ± 11cm; mass 64.8 ± 12.8kg) were recruited and screened as described in Chapter 5 (section 5.1.1)

### 6.2.1 Visual Assessment

All subjects underwent a subjective refraction to determine optimal refractive correction. Visual acuity was measured using the ETDRS chart (Section 5.2.1a). The test distance was determined from the subjects' eye height and the horizontal distance of two walking step lengths, determined by age and gender matched normal data (Auvinet et al., 2002). This testing distance was chosen as the majority of fixations of obstacles within the travel path typically occur at two walking step lengths prior to the obstacle (Patla and Vickers, 1997). This viewing distance averaged 2.08 ± 0.1m for the subject group. Contrast sensitivity was assessed using the Pelli Robson chart (Section 5.2.2). An individualised test distance could not be used as this would alter the fundamental spatial frequency of the chart, making measurements between subjects non comparable. Instead a fixed distance of 2m, similar to the average individualised distance was used. Stereoacuity was assessed using the TNO chart at the standard 40cm test distance (Section 5.2.3a) as the range of stereaocuities would be significantly reduced if used at other distances, such as 2 metres. Ocular dominance was determined using the Kay eye dominance test (Section 5.2.4).

All visual assessments were undertaken with optimal refractive correction (binocular), +2.00DS blur in front of the non-dominant eye (2NDom), and +2.00DS blur in front of the dominant eye (2Dom) and visual acuity and contrast sensitivity were also measured with the dominant eye occluded (occluded). Full aperture lenses in a trial frame were used throughout.

**6.2.2 Protocol**

Trials were recorded using the 3D motion capture system (Section 5.3.2) with subjects wearing the Helen Hayes marker set and additional foot markers, with markers also placed on the step edge (Section 5.3.3). Subjects started two step lengths away from the step (Section 5.3.1), which was positioned on the second force platform (Section 5.3.5). The subjects were then asked to approach the step and stop with their feet just behind a white line (positioned half a foot length away from the front of the step) on the first force platform. The subjects remained stationary behind the white line for approximately 5 seconds. They then performed a single step up and then remained stationary on top of the step for a few seconds, until informed to step off. Walking up to the white line at the start of the trial allowed subjects to fixate the step as they normally would as they approached a step or stairs (Patla and Vickers, 1997, 2003) and allowed the cameras (Section 5.3.3) to start tracking all the markers. Trials were arranged in nine blocks of four trials so that all four visual conditions outlined above occurred in each block in a randomised order. The nine blocks consisted of three repetitions of each step height (142, 152 and 157mm) outlined in chapter 5 (section 5.3.2) giving 36 trials in total. Blocks were randomised with the condition that the same step height did not occur consecutively.

### 6.2.3 Investigated Parameters

#### 6.2.3a Foot clearance

The following foot clearance parameters were analysed.

- Maximum toe elevation: the maximum vertical height reached by the lead limb during the single step up. Toe elevation was examined because it has been demonstrated that the central nervous system controls toe elevation rather than toe clearance in response to visual cues regarding the height of the step (Maclellan and Patla, 2006).
- Vertical toe clearance: the vertical distance between the upper edge of the step and virtual shoe tip as the foot crossed over the front edge of the step (Figure 25)
- Horizontal toe clearance: the horizontal distance between the front edge of the step and virtual shoe tip when it reached the same height as the top edge of the step (Figure 25).

Both horizontal and vertical toe clearance were included because both measurements showed significant increases in conditions of acute binocular blur, compared to optimally corrected binocular vision (Heasley et al., 2004, Heasley et al., 2005).

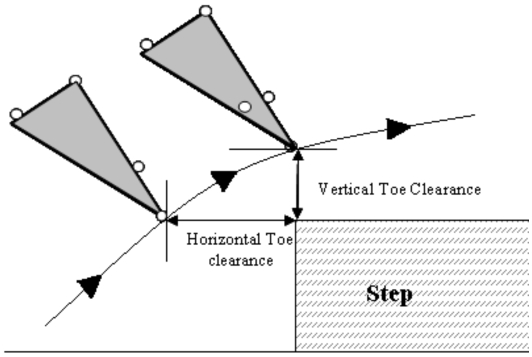



Figure 25. Vertical and horizontal lead limb toe clearance.

**6.2.3b Temporal parameters**

The step time was broken down into the following phases

- Time spent in double support: the period between initial movement and toe off of the lead limb (can also be defined as the anticipatory postural adjustment phase, Heasley et al., 2004, Heasley et al., 2005).
- Time spent in single support: the period when only the trailing limb was in contact with the ground while the lead limb was swung forwards and up onto the step (i.e. from instance of lead limb toe-off to lead limb foot contact with the raised surface).
- Time taken for weight transfer: the time from foot contact of the lead limb on to the top of the step to the instant of toe off of the trail limb.

Initial movement was defined as the instance the CP moved laterally by 10mm from the average location when standing stationary. Toe off of the lead limb was defined as the moment when the toe moves 1mm in the anterior-posterior plane for five consecutive frames. Foot contact of the lead limb was defined at the instant where the second force platform registered a ground reaction force (GRF) above 20N. Toe off of the trail limb was defined as the instant that force platform 1 registers a GRF of less than 20N.

**6.2.3c Centre of Mass dynamics**

- Root mean square (RMS) M-L CP displacement: The RMS of the centre of pressure (Chapter 5, section 5.3.7) displacement during the period the subjects spent in trail limb single support, in the medial-lateral (x-axis) direction. This has previously been shown to be a measure of dynamic stability (Zachazewski et al., 1993).
- Average CM-CP: The separation of the centre of mass (Chapter 4, section 4.3.7) and centre of pressure in the medial-lateral (x-axis) direction during the period subjects spent in trail limb single support. Previously used by Heasley et al (2004) to demonstrate an attempt to improve dynamic stability.

**6.2.4 Data Analysis**

Data were tested using the Shapiro-Wilk test for normality. Normally distributed data were analysed using a repeated measures ANOVA with level of significance set at $p < 0.05$. Post-Hoc analyses were performed using Bonferroni adjusted pair wise comparisons. Non-normally distributed data were analysed using the Wilcoxon signed rank test. Variability of vertical toe clearance was analysed, using the standard deviation of toe clearance across the three repetition and heights for each visual condition.

## 6.3 Results

### 6.3.1 Vision Results

Seven subjects were right eye dominant and four subjects were left eye dominant. Visual acuity and contrast sensitivity data were normally distributed, but stereoacuity data were skewed (Shapiro-Wilk p=0.01). Group mean ± 1SE visual acuity and contrast sensitivity and median and range stereoacuity are presented for the different visual conditions in Table 3. 60% of subjects had 60secs of arc on the TNO in the binocular condition.

Table 3. Group mean ± 1 SE visual acuity (VA in logMAR), contrast sensitivity (log CS) and median (range) TNO stereoacuity (seconds of arc) under binocular, 2NDom (+2.00DS blur of the non-dominant eye), 2Dom (+2.00DS blur of the dominant eye) and occluded conditions for 11 young subjects.

| Test | Binocular | 2NDom | 2Dom | Occluded |
|---|---|---|---|---|
| **Log MAR Acuity** | -0.02 ±0.01 | -0.01 ± 0.01 | -0.01 ± 0.01 | -0.01 ± 0.01 |
| **Log CS** | 1.92 ± 0.01 | 1.77 ± 0.04* | 1.82 ± 0.04 | 1.76 ± 0.04* |
| **Stereoacuity** | 60 (15-60) | 120 (60-240)* | 240 (120-480)*[†] | |

*significantly different from binocular score (p<0.01)
[†] significantly different from 2NDom score (p<0.05)

Contrast sensitivity was significantly affected by vision condition (p = 0.002) but log MAR acuity was unaffected (p = 0.18). Post hoc analysis using pair wise Bonferroni adjusted comparisons indicated that CS under 2NDom (p = 0.02) and occluded (p = 0.004) conditions were significantly different to the binocular condition. No significant difference was found between CS with 2Dom and 2NDom (p = 0.99) or 2Dom and occluded (p = 0.99) conditions. Stereoacuity data were analysed using the Wilcoxon Signed-rank test, which showed significant differences between binocular vision and

2Dom ($p = 0.001$) and 2NDom ($p = 0.03$) and between 2Dom and 2NDom conditions ($p = 0.049$).

Group mean ± 1SE for the different visual conditions for all investigated parameters are shown in Table 4.

### 6.3.3 Foot clearance parameters

There was a main effect for maximum toe elevation of vision ($p = 0.03$), step height ($p<0.001$) and repetition ($p = 0.02$). Post hoc analysis showed no difference between individual vision conditions but a significant difference between low (mean 231 ± 6mm) and medium step height (239 ± 6mm, $p <0.001$) and low and high step heights (244 ± 7mm, $p<0.001$) and between first (243 ± 6mm) and second repetition (236 ± 7mm, $p = 0.02$). There was a main effect of vision for vertical toe clearance ($p = 0.02$) with subjects showing an increase in vertical toe clearance in conditions of blur or occlusion though post hoc analysis did not reveal any significant differences between the individual vision conditions. Vertical toe clearance also decreased with repetition ($p = 0.04$) and decreased as the height of the step increased ($p = 0.03$), though there were no within height effects. There was no change in variability of vertical toe clearance across visual conditions ($p = 0.88$).

There was a main effect for vision for horizontal toe clearance ($p = 0.001$) with significant differences between Binocular and 2NDom conditions ($p = 0.05$) and Binocular and 2Dom conditions ($p = 0.05$).There were no effects on horizontal toe clearance for either height ($p = 0.24$) or repetition ($p = 0.26$).

### 6.3.4 Temporal parameters

There was no effect of vision or repetition for time spent in double or single support or for time taken to transfer weight ($p>0.05$). However, for all temporal parameters there was a main effect of step height ($p<0.05$). In double support there was a significant difference between low (mean 1.01 ± 0.03 secs) and high step height (mean 1.07 ± 0.04 secs, $p=0.04$). For time spent in single support there was a significant difference between low (mean 0.89 ± 0.03 secs) and high step heights (mean 0.85 ± 0.03 secs, $p=0.005$) and approached significant between high and medium step heights (0.88 ± 0.03 secs, $p=0.07$). For weight transfer there was a significant difference between low (mean 0.47 ± 0.02 secs) and medium step height (mean 0.52 ± 0.03 secs, $p=0.01$) and medium and high steps (mean 0.51 ± 0.02 secs, $p=0.02$).

### 6.3.5 Centre of mass dynamics

There were no significant effects of vision, repetition or step height on either RMS CM-CP divergence of M-L CP displacement ($p>0.1$).

Table 4. Group mean ± 1 SE for parameters investigated across visual condition of binocular, 2NDom (+2.00DS blur of the non-dominant eye), 2Dom (+2.00DS blur of the dominant eye) and occluded conditions for 11 young subjects.

| | **Binocular** | **2NDom** | **2Dom** | **Occluded** |
|---|---|---|---|---|
| **Vertical toe clearance (mm)*** | 53 ± 4 | 60 ± 4 | 58 ± 3 | 61 ± 4 |
| **Horizontal toe clearance (mm)*** | 96 ± 6 | 104 ± 6 | 106 ± 6 | 107 ± 6 |
| **Toe Elevation (mm) *** | 235 ± 6 | 239 ± 7 | 236 ± 7 | 241 ± 7 |
| **Time spent in double support (s)** | 1.02 ± 0.03 | 1.05 ± 0.04 | 1.05 ± 0.03 | 1.06 ± 0.03 |
| **Time spent in single support (s)** | 0.86 ± 0.02 | 0.89 ± 0.03 | 0.87 ± 0.03 | 0.88 ± 0.03 |
| **Weight transfer (s)** | 0.50 ± 0.03 | 0.50 ± 0.03 | 0.51 ± 0.03 | 0.49 ± 0.03 |
| **Av CM-CP divergence (mm)** | 41.2 ± 2.6 | 42.6 ± 3.0 | 43.7 ± 3.2 | 42.1 ± 2.6 |
| **RMS CP (mm)** | 4.19 ± 0.47 | 3.94 ± 0.44 | 3.92 ± 0.37 | 3.89 ± 0.40 |

* Main effect of vision ($p<0.05$)

## 6.4 Discussion

Stereoacuity got significantly worse when one eye was blurred, with blur over the dominant eye causing a greater decline in stereoacuity, supporting previous findings investigating stereoacuity in monovision contact lens patients (Erickson and McGill, 1992). A disadvantage of the TNO is that the contrast of the green half of the images has been found to be twice the contrast of the red half image, and, in amblyopic patients, there can be a marked difference in stereoacuity measurements if the red and green lenses are reversed (Simons and Elhatton, 1994). However this does not account for the different findings between 2Dom and 2NDom conditions as subjects who were dominant in the left eye showed the same pattern i.e. better stereoacuity was recorded when blur was over the non-dominant eye compared to blur over the dominant eye as subjects who were right eye dominant. Therefore the difference in stereoacuity appears to be genuine finding and not an artefact of the TNO stereotest.

There was no effect of visual condition for visual acuity, but a small and significant effect on contrast sensitivity. However, the mean loss of 0.15 log CS in monocular blur and occluded conditions is less than the reduction of 0.30 log CS that has been reported as the level likely to cause difficulty with mobility (Rubin et al., 1994). In addition, the reduced level of CS in blur and occluded conditions (1.75-1.85 log) was much greater than the level of CS identified as causing visual disability (1.05 log, Leat et al., 1999). Although there may have been greater losses of CS at other spatial frequencies, the peak of the CSF, as measured by the Pelli-Robson at 2m, and edge CS of the Melbourne edge test has been identified as the most important to the control of locomotion (Marron and Bailey, 1982, Tiedemann et al., 2007).

When one eye was blurred or occluded, vertical and horizontal toe clearance of the lead limb was significantly increased as subjects stepped up. This finding is similar to the adaptations shown by subjects under conditions of binocular blur undertaking the same task (Heasley et al., 2005). An increase in toe clearance has also been found when subjects were asked to step over obstacles in the travel path with one eye occluded, compared to binocular visual conditions (Patla et al., 2002). As hitting the front edge of the step with the toe of the lead limb (rather than the heel or plantar aspect of the foot) would likely cause a trip (Chen et al., 1991) then raising the lead limb to avoid the front edge was a clear safety strategy used to avoid tripping. This suggests that subjects were unable to accurately judge the height and the position of the step and as a consequence increased clearance safety margins.

Vertical toe clearance decreased with repetition, which suggested that although the surface height was varied throughout the experiment, the subjects were able to learn the height of the surface through somatosensory feedback of the lead limb when it was placed on top of the surface in preceding trials. Such learning has been reported in previous studies investigating the effect of binocular blur on stepping up to a new level and is assumed to be an energy conservation strategy (Heasley et al., 2004). However there is no effect of repetition on horizontal toe clearance. No somatosensory information regarding the horizontal position of the step is available to the subject, as long as the foot does not make contact with the front of the step, which did not occur for any subject during this particular study. Therefore subjects could not learn the position of the step through repeated trials and hence there was no effect on repetition for horizontal toe clearance.

Vertical toe clearance of the step decreased for the highest step, this is contrary to previous findings where toe clearance has been found to be increase for higher steps (Heasley et al., 2004) or obstacles (Patla and Rietdyk, 1993). Subjects increased toe elevation for the medium and high step, compared to the low step, however the increase in toe elevation was not enough to compensate for the increase in step height. As a consequence the vertical toe clearance of the step edge decreased for the higher steps, rather than remaining the same or increasing. The reasons for this are unclear, it may be biomechanical constraint of the lead limb, although young subjects have demonstrated increased toe clearance of a much higher obstacle (268mm) than the step used in this particular study (Patla and Rietdyk, 1993) so it appears more likely than the small variation in step height was not fully perceived. This may help explain why variation in riser height within a stair case appears to increase the likelihood of falls on stairs (Jackson and Cohen, 1995), as the small change in step height may not be perceived and vertical toe clearance not increased accordingly, leading to a potential trip. In addition Cavanagh and colleagues have shown that minimum foot clearance becomes progressively smaller as elderly subjects descend stairs (Simoneau et al., 1991, Hamel et al., 2005) and in this study vertical toe clearance decreased with repetition, decreasing safety margins and increasing the risk of a trip on a step edge as stairs are ascended or descended.

There was no effect of vision on the time spent in double or single support or weight transfer. There was also no effect on the medial-lateral movement of the CP or the divergence of CM and CP. Previously it has been found in conditions of binocular blur that subjects increased the time of all phases of the step up (Heasley et al., 2004), subjects also decreased CM-CP divergence and during single support movement of CP in the medial lateral direction decreased (Heasley et al., 2004, Heasley et al., 2005). The difference between previous studies and this study may be due to the difference in binocular compared to monocular visual disruption or it may be due to the age of subjects as the changes in dynamic stability have been found to be greater in elderly compared to younger subjects (Heasley et al., 2005).

Limitations of this study will be discussed in the following chapter along with limitations of study 2 (Chapter 7, section 7.4.)

To summarise monocular blur caused a significant decline in stereoacuity. Under conditions of monocular blur or monocular occlusion subjects increased vertical and horizontal toe clearance of the step, demonstrating a safety strategy in order to avoid tripping on the edge of the step. This indicated than monocular blur impairs the ability to judge the position and height of the step.

# Chapter 7

## Study 2: Walk and Step Up Under Conditions of Acute Monocular Blur

A version of this study has been published as Vale A, Scally A, Buckley J. G and Elliott D. B. (2008). The effects of monocular refractive blur on gait parameters when negotiating a raised surface. *Ophthalmic Physiol. Opt., 28: 135-142*

### 7.1 Introduction and Aim

In the previous study (chapter 6) the effects of monocular blur on stepping up from a stationary position were investigated in young subjects. However falls frequently occur through tripping on kerbs (Gallagher and Scott, 1997) when individuals are negotiating a change in height whilst walking. It has previously been reported that for successful negotiation of an obstacle in the travel path, precise foot placement prior to the obstacle is a key factor to successful negotiation of the obstacle (Chen et al., 1991, Patla and Greig, 2006) rather than solely increasing toe clearance. In the previous study (chapter 6) there was a change in horizontal toe clearance as well as vertical suggesting that the perception of the position of the step as well as the height was impaired by monocular blur. Previous studies looking at the effect of monocular occlusion or impairment on negotiation of an obstacle in the travel path have not investigated foot placement (Elliott et al., 2000) or only looked at the lead foot placement (Patla et al., 2002). The aim of this study was to assess how monocular refractive blur affects the negotiation of a raised surface in the travel path, looking at foot placement and step length prior to the raised surface as well as toe elevation and toe clearance parameters.

## 7.2 Methods

Fourteen young subjects (four males and ten females, mean age 25.4 ± 6.1 years; height 168 ± 10cm; mass 65.3 ± 12.2kg) were recruited and screened as described in Chapter 5 (section 5.1.1)

#### 7.2.1 Visual Assessment

All subjects underwent the same visual assessment as in Chapter 6 (Section 6.2.1) after subjective refractive to determine optimal refractive correction. Visual acuity was measured using the EDTRS chart (Section 5.2.1a) and the test distance was determined from the subjects' eye height and the horizontal distance of two walking step lengths, determined by age and gender matched normal data (Auvinet et al., 2002). This viewing distance averaged 2.08 ± 0.08m for the group. Contrast sensitivity was assessed using the Pelli Robson chart (Section 5.2.2) at 2 metres as in Chapter 6 (Section 6.2.1). Stereoacuity was assessed using the TNO chart at the standard 40cm test distance (Section 5.2.3a) and ocular dominance was determined using the Kay eye dominance test (Section 5.2.4).

All visual assessments were undertaken with optimal refractive correction (binocular), +2.00DS blur in front of the non-dominant eye (2NDom), and +2.00DS blur in front of the dominant eye (2Dom) and visual acuity and contrast sensitivity were also measured with the dominant eye occluded (occluded). Full aperture lenses were used, placed in a trial frame.

### 7.2.2 Protocol

Trials were recorded using the motion capture system (Section 5.3.2) with subjects wearing the Helen Hayes marker set and additional foot markers (Section 5.3.3). Subjects walked from four or five step lengths away to the raised surface (Section 5.3.1). This distance was the limit allowed by the size of the laboratory. The starting point was marked with a chalk line on the floor so subjects started consistently from the same place for each trial. Trials were arranged in nine blocks of four trials so that all four visual conditions outlined above occurred in each block in a randomised order. The nine blocks consisted of three repetitions of each platform height outlined in chapter 5 (Section 5.3.2). Blocks were randomised with the condition that the same platform height did not occur consecutively.

### 7.2.3 Data Analysis

The analyses focused on determining foot placement parameters during the approach and toe clearance parameters during the step up (see Figure 26).

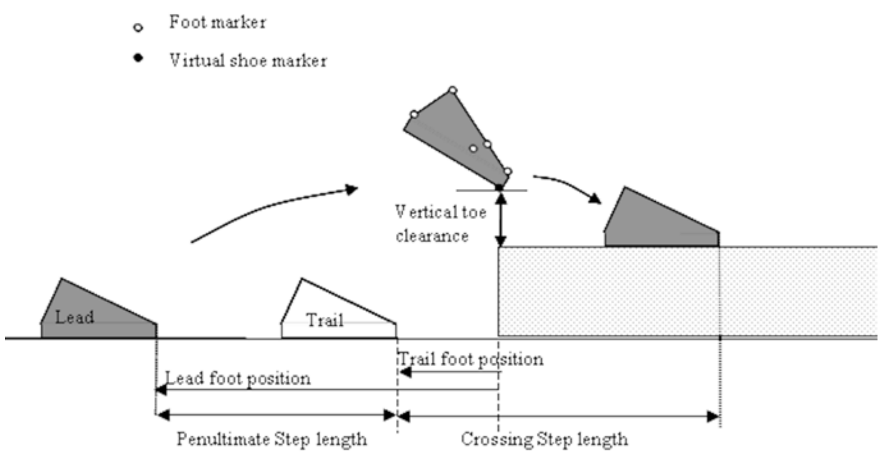



Figure 26. Foot position parameters investigated.

The following parameters were examined: (1) lead foot position, the horizontal position between the virtual shoe tip of the lead limb foot and the front edge of the raised surface; (2) trail foot position, the horizontal distance between the virtual shoe tip of the trail limb foot and the front edge of the raised surface; (3) maximum toe elevation, the maximum height the virtual shoe tip was lifted during stepping onto the raised surface; (4) vertical toe clearance, the vertical distance between the upper edge of the raised surface and virtual shoe tip as the foot crossed over the front edge of the surface (5) penultimate and (6) crossing step lengths, the horizontal distance between the virtual shoe tips of each foot for the step prior to, and the step on to the raised surface; (7) average walking velocity during the crossing step (from instance of trail limb foot contact, up to lead limb contact with the raised surface), estimated by determining the time derivative of the anterior-posterior coordinate data of the sternum marker ; (8) time in single support, the period when only the trailing limb was in contact with the ground while the lead limb was swung forwards and up onto the raised surface (i.e. from instance of lead limb toe-off to lead limb foot contact with the raised surface).

Instances of toe-off and foot contact were determined by evaluating when the vertical velocity of the toe and heel markers respectively increased/decreased for five consecutive frames above/below ± 50mm/s.

Vision data were tested using the Shapiro-Wilk test for normality. Normally distributed data were analysed using a repeated measure ANOVA and non-normally distributed data were analysed using the Wilcoxon signed rank test. Kinematic data were analysed using a random effects population averaged model using the Stata version 8.0 statistical program (StataCorp, College Station, TX, USA) with statistical support from Mr Andy Scally (Institute of Health Research, University of Bradford). The generalised linear model for longitudinal data takes into account that repeated measures for individuals are likely to be correlated. Factors of interest were incorporated sequentially and their statistical significance assessed. Level of significance was set at $p < 0.05$ and all factors reaching that level were retained in the final model. $p$ values quoted are those associated with specific terms in the final regression model, which were (1) vision: a fixed factor with four levels, binocular, 2NDom, 2Dom, and occluded; (2) raised surface height: a fixed factor with three levels, low, medium and high and (3) repetition: a fixed factor with three levels, trials one, two and three. Main effects of these multiple-level factors were determined using the likelihood ratio ($\chi^2$) test after dropping individual factors from the model.

Linear regression was used to investigate correlation between maximum toe elevation and vertical lead toe clearance and change in vertical lead toe clearance and change in stereoacuity (between binocular and blur conditions).

## 7.3 Results

### 7.3.1 Visual Assessments

Ten subjects were right eye dominant and four subjects were left eye dominant. Visual acuity and contrast sensitivity were normally distributed, but stereoacuity data were skewed (Shapiro-Wilk p=0.01). Mean ±1 SE visual acuity and contrast sensitivity and median and range stereoacuity are presented for the different visual conditions in Table 5. 60% of subjects had 60secs of arc on the TNO in the binocular condition.

Table 5. Group mean ± 1 SE binocular visual acuity (logMAR), binocular contrast sensitivity (log CS) and median (range) TNO stereoacuity binocular, 2NDom (+2.00DS blur of the non-dominant eye), 2Dom (+2.00DS blur of the dominant eye) and occluded conditions for 14 young subjects.

| Test | Binocular | 2NDom | 2Dom | Occluded |
|---|---|---|---|---|
| **Log MAR Acuity** | -0.02 ± 0.01 | -0.02 ± 0.01 | -0.01 ± 0.01 | -0.01 ± 0.01 |
| **Log CS** | 1.93 ± 0.01 | 1.79 ± 0.03* | 1.83 ± 0.03* | 1.75 ± 0.03* |
| **Stereoacuity** | 60 (15-60) | 120 (60-240)* | 240 (120-480)*† | |

*significantly different from binocular score (p<0.01)
† significantly different from 2NDom score (p<0.05)

Binocular contrast sensitivity was significantly affected by vision condition (p<0.01) but binocular visual acuity was unaffected (p=0.15). Post hoc analysis using pair wise

Bonferroni adjusted comparisons indicated CS for 2Dom (p=0.04), 2NDom (p=0.03) and occluded (p<0.001) vision conditions were significantly different to binocular vision. No significant difference was found between CS with 2Dom and 2NDom (p=0.99) or 2Dom and occluded (p=0.39) conditions. Stereoacuity data were analysed using the Wilcoxon Signed-rank test, which showed significant differences between binocular vision and 2Dom (p=0.001) and 2NDom (p= 0.03) and between 2Dom and 2NDom conditions (p=0.049).

### 7.3.2 Foot clearance parameters

Eleven subjects stepped up onto the raised surface leading with their right foot and three with their left foot. There was no correlation between ocular dominance and lead foot ($R^2$ = 0.003, p = 0.85).

Group mean ± 1SE data for foot placement and kinematic parameters is shown in Table 6. The distance the lead foot was placed before the step was unaffected by visual condition ($\chi^2_3$ = 3.14; p = 0.37). However, compared to the binocular vision condition there was a significant increase in the distance the trail foot was placed before the step in all monocular visual conditions (p<0.01), but there was no significant difference between the monocular conditions ($\chi^2_2$ = 4.23; p = 0.12) and no effect of repetition ($\chi^2_3$ = 2.63; p= 0.15). There was no increase in variability of trail foot position across visual conditions (p= 0.88).

Compared to binocular conditions, maximum toe elevation was significantly increased in occluded (p<0.01) and 2Dom conditions (p<0.01), but only approached significance in the

2NDom condition (p=0.07). Between monocular conditions there was only a significant difference between 2NDom and occluded (p=0.04). Maximum toe elevation decreased significantly with repetition (p<0.01) and increased significantly as the height of the step was increased (p<0.01)

Vertical toe clearance of the lead limb increased significantly in all monocular visual conditions compared to when vision was binocular (p<0.01). There was no significant difference between 2Dom and occluded ($\chi^2_1$ = 0.31; p = 0.16), but 2NDom was significantly different to occluded ($\chi^2_2$ = 5.19; p = 0.02) and 2Dom ($\chi^2_1$ = 5.99; p <0.01). Vertical toe clearance decreased with repetition, though this was only significant between the first and last repetition (p <0.01). Vertical toe clearance decreased as the height of the step was increased (p <0.01) with a decrease of 4.9 mm for medium and 5.6 mm decrease for high. There were no significant interactions between repetition and vision ($\chi^2_6$ = 10.18; p = 0.12) or repetition and height ($\chi^2_4$ = 6.71; p = 0.15) for vertical toe clearance. There was no increase in variability of toe clearance across visual conditions (p = 0.21). Time of trail limb single support was longer for all monocular compared to binocular conditions (p<0.05). In addition, subjects spent longer in trail limb single support in the occluded compared to blur conditions ($\chi^2_1$ = 6.30; p = 0.01).

Vertical toe clearance was significantly correlated, across all visual conditions, with maximum toe elevation ($R^2$ = 0.42, p = 0.01). No correlation was found between change in stereoacuity and change in vertical toe clearance for either 2Dom ($R^2$ = 0.02, p = 0.98) or 2NDom ($R^2$= 0.17 p = 0.66) conditions.

Table 6. Group mean ± 1 SE foot placement and kinematic data, collapsed across step height and repetitions for visual conditions of binocular, 2NDom (+2.00DS blur of the non-dominant eye), 2Dom (+2.00DS blur of the dominant eye) and occluded conditions for 14 young subjects.

| | **Binocular** | **2NDom** | **2Dom** | **Occluded** |
|---|---|---|---|---|
| **Lead foot position (mm)** | 886 ± 27 | 892 ± 24 | 899 ± 27 | 896 ± 25 |
| **Trail foot position (mm)** | 186 ± 15 | 204 ± 14* | 213 ± 14* | 202 ± 14* |
| **Maximum toe elevation (mm)** | 248 ± 7 | 250 ± 7 | 253 ± 8 * | 254 ± 8 *† |
| **Vertical toe clearance (mm)** | 49 ± 5 | 54 ± 5* | 58 ± 5* † | 57 ± 6* † |
| **Penultimate Step length (mm)** | 701 ± 20 | 688 ± 18 | 689 ± 21 | 695 ± 19 |
| **Crossing Step length (mm)** | 622 ± 19 | 631 ± 15 | 613 ± 15 | 626 ± 16 |
| **Average velocity ($m.s^{-1}$)** | 1.13 ± 0.03 | 1.12 ± 0.03 | 1.11 ± 0.03* | 1.11 ± 0.03* |
| **Time spent in single support (s)** | 0.45 ± 0.01 | 0.47 ± 0.01* | 0.46 ± 0.01* | 0.47 ± 0.01* |

*significantly different from binocular value ($p<0.05$)
† significant difference from 2NDom ($p<0.05$)

## 7.4 Discussion

Lead limb maximum toe elevation increased in conditions of monocular blur and occlusion. In response to visual perception of obstacles or steps within the travel path the central nervous system controls toe elevation rather than toe clearance (Maclellan and Patla, 2006) and as a consequence the toe clearance changes. In support of this we have found a significant correlation between toe elevation and toe clearance. As found in study 1 (Chapter 6) when one eye is blurred there is an increase in vertical toe clearance as subjects stepped up on to the raised surface. Elliott et al (2000) found a similar adaptation during obstacle crossing in patients with unilateral cataract as did Patla et al (2002) for obstacle crossing in subjects with one eye occluded (which was also the case in the occluded condition of this study). Of particular interest in the present study is that the magnitude of the effect was less when the blur was over the non-dominant eye and that the effect from a relatively small amount of refractive blur (2.00DS) over the dominant eye was no different from the effect when that eye was occluded.

As in study 1 (Chapter 6) toe elevation and, as a consequence vertical toe clearance decreased with repetition, which suggested that although the surface height was varied throughout the experiment, the subjects were able to learn the height of the surface through somatosensory feedback of the lead limb when it was placed on top of the surface in preceding trials. Such learning appears to be consistent across experiments where there is repetition of step height, and appears to be an energy conservation strategy (Heasley et al., 2004). Toe elevation increased with step height, however as in study 1, the toe clearance actually decreased with increasing step height. Previously toe clearance has been found to be greater over taller obstacles in the travel path (Patla and Rietdyk, 1993). A decrease in toe clearance suggests that the response in toe elevation is not accurate to that change in height and may because the height change was only small and not correctly identified and therefore responded to.

There was no change due to visual condition for lead foot position prior to the step or either penultimate or crossing step length, agreeing with previous findings comparing binocular and monocular occlusion conditions (Patla et al., 2002). There was, however an increase in the distance the trail foot was placed from the platform in monocular and blur conditions.  Placement of the foot farther from the platform allows more time for lead limb flexion to increase vertical toe clearance and findings indicate that subjects did indeed spend more time in single support in blur and monocular conditions. Additionally, placing the trail foot too close to the edge of the step increases risk of tripping (Chou and Draganich, 1998) and therefore the increase in trail foot distance from the raised surface was seen as indicative of a more cautious approach. These findings suggest that monocular blur affects the ability to accurately judge not only the height of the raised surface but also the position of the raised surface within the travel path.

Monocular blur caused a significant decline in stereoacuity. Blur in front of the dominant eye caused a significantly greater decline in stereoacuity than blur in front of the non-dominant eye. This supports the results found in contact lens patients fitted with monovision correction (Erickson and McGill, 1992) in which stereoacuity (Randot stereotest at near) was significantly worse when the dominant eye was corrected for near. No correlation was found between vertical toe clearance and stereoacuity, although this may be due to the small range of values obtained for change in stereoacuity due to only one level of blur being used: a small range is less likely to give rise to a significant correlation (Haegerstrom-Portnoy et al., 2000). In addition, the TNO has relatively large steps (especially at poorer stereoacuity levels) and this limited the sensitivity of the measurements. Contrast sensitivity was also significantly worse under monocular conditions. However, the mean loss of 0.15 log CS in monocular blur and occluded conditions is less than the reduction of 0.30 log CS that has been reported as the level likely to cause difficulty with mobility (Rubin et al., 1994). In addition, the reduced level of CS in blur and occluded conditions (1.75-1.85 log) was much greater than the level of CS identified as causing visual disability (1.05 log, Leat et al., 1999). Although there may have been greater losses of CS at other spatial frequencies, the peak of the CSF, as measured by the Pelli-Robson at 2m, has been identified as the most important to the control of locomotion (Marron and Bailey, 1982) and negotiation of stairs (Tiedemann et al., 2007). We therefore argue that, despite not finding a correlation between stereopsis and toe clearance, the principal changes to adaptive locomotion reported here are likely due to reductions in stereoacuity rather than CS or VA. This is supported by an earlier study that did find a correlation between changes in stereoacuity and toe clearance due to second eye cataract surgery (Elliott et al., 2000).

In monovision patients the non-dominant eye is commonly corrected for near vision and hence is blurred for distance, but some authors have suggested other strategies such as correcting the most myopic eye for near (Ghormley, 1989) or correcting the eyes according to what everyday tasks are typically undertaken by the patient (McMonnies, 1974, Sanchez, 1988). The findings of the current study support retaining as much stereopsis as possible during monovision, which likely means correcting the dominant eye for distance and the non-dominant eye for near. This would allow patients to maintain better levels of stereoacuity and consequently would have less effect on gait. Although monovision correction is commonly used for contact lens patients it is becoming a choice for presbyopes undergoing laser refractive surgery (Jain et al., 2001) or as a desired outcome following cataract surgery (Greenbaum, 2002). The present study demonstrates that using monovision correction may impair the ability to judge the height and position of an approaching raised surface. Therefore the present study suggests that the more permanent monovision correction provided by cataract surgery may not be a suitable method of vision correction in the elderly (i.e. over 65 years of age), particularly for those at high risk of falling. However, further research is required in this regard as this study evaluated the effect of acute monocular blur and it may be that patients may subsequently adapt to these changes.

Limitations of the present study and of Study 1 (chapter 6) include the learning effect demonstrated by the reduction of toe elevation and hence toe clearance with repetition, which may have masked the effect of the visual disruption. In addition there was a truncation effect for measurement of logMAR acuity with the majority of subjects able to read the lowest line of the chart in full at the shorter test distance. As a consequence visual acuity may have been underestimated and a small decline in visual acuity caused by monocular blur or occlusion may have been missed. The working distance used for measurement of visual acuity, was based on individual eye height but relied on age and gender matched normal values for step length. This was because of practical difficulties in measuring step length accurately as vision data were collected in advance of mobility data. However this does mean that the test distance was not truly individualized for each subject. Finally for studies 1 and 2, young subjects were used to find any effect of monocular blur on negotiation of a step or raised surface. To further investigate if monocular blur and the resultant loss in stereoacuity can affect safe negotiation of a step or raised surface in an elderly population then elderly subjects should also be tested. This will be addressed in the following chapter.

In summary, when one eye was blurred (or occluded) subjects used a safety strategy of increasing vertical lead limb clearance over the step of the raised surface to reduce risk of tripping. This was mainly facilitated by increasing maximum lead toe elevation. Monocular blur caused a large decline in stereoacuity but had no effect on binocular high contrast visual acuity and only a minimal effect on binocular contrast sensitivity.

# Chapter 8

## Study 3: Elderly Subjects Negotiating a Raised Surface Under Conditions of Acute Monocular Blur

A version of this study has been published as Vale A, Buckley J. G., Elliott D. B. (2008) Gait alterations negotiating a raised surface induced by monocular blur. *Optometry & Vision Science* **85** (12) 1128-1134

### 8.1 Introduction and Aim

In the present study we expand on our previous work, examining how monocular blur affects negotiation of a raised surface by using elderly subjects and a greater range in levels of monocular refractive blur. Specifically, we investigated the effect of small amounts of monocular refractive blur (0.50D and 1.00D) that is prevalent amongst elderly people, primarily due to cataract related ametropia (Guzowski et al., 2003). In addition, we investigated the effects of  monovision correction, as monovision has become a widely used approach for  presbyopic contact lens wearers and is becoming used for presbyopic patients undergoing refractive (Jain et al., 2001) or cataract surgery (Greenbaum, 2002). We hypothesised that elderly subjects with monovision correction will use a similar safety strategy as seen in the previous study involving young subjects (Chapter 6), whereby subjects increased lead limb toe clearance when negotiating a raised surface by increasing their maximum toe elevation. We further hypothesised that the smaller amounts of monocular blur would have a reduced effect on gait, compared to the largest level of blur, with possibly no effect with the 0.50DS level of monocular blur.

## 8.2 Method

Eleven subjects (2 males and 9 females, mean age 73.3 ± 3.6 years; height, 160 ± 12cm; mass, 67 ± 12kg) were recruited and screened as described in Chapter 5 (Section 5.1.2)

### 8.2.1 Visual Assessment

Ocular dominance was determined by the Kay eye dominance test (Section 5.2.4). High (100%) and low (25%) contrast visual acuity were measured using the Test Chart 2000 (Section 5.1.1b) at 3 metres. Low contrast acuity was used rather than contrast sensitivity as only two different versions of the Pelli-Robson chart are available (Section 5.1.2) leading to possible memorisation effects. Low contrast log MAR acuity has been found to be reliable with good test-retest reliability, and shows good correlation with Pelli-Robson CS in low vision patients (Pearson Correlation Coefficent 0.67, Haymes and Chen, 2004). The Test Chart 2000 was chosen in order to allow randomisation between every presentation as a greater number of visual conditions were measured. The test distance of 3 metres was used. Although an individualised distance could have been used (section 7.2.1) and the truncation effect found in studies 1 and 2 (Chapters 6 and 7) avoided by calibrating the letter size on the Test Chart 2000, test distances of less than 3 metres are not advised due to difficulty in reproducing the smaller letters accurately (www.thomson-software-solutions.com, June 2008). Stereoacuity was assessed with a Frisby near test (Section 5.2.3b). The Frisby test allowed a greater range of stereoacuity to be measured with a higher number of steps than the TNO stereotest, used for studies 1 and 2 (Chapters 6 and 7). In addition it has been reported the TNO test is unsuitable for older patients (Garnham and Sloper, 2006). All measurements of visual function were carried out with the subject's optimal refractive correction and under conditions of binocular vision (BIN) and repeated under the following conditions: 0.50NDom (0.50D blur over non-dominant eye), 0.50Dom (0.50D blur over dominant eye), 1.00NDom (1.00D blur over non-dominant eye), 1.00Dom (1.00D blur over dominant eye), MonovisionNDom (blur equal to the subject's near addition over non-dominant eye, mean +2.50 ± 0.20D, to simulate monovision), MonovisionDom (blur equal to the subject's near addition blur over dominant eye). Near addition was defined as the power of the reading addition prescribed at the subjects' last eye examination.

High contrast and low contrast acuity were also measured with the visual conditions OCCNDom (non dominant eye occluded), OCCDom (dominant eye occluded). The order of testing was randomised and the letters on the Test Chart 2000 were randomised between every presentation.

### 8.2.2 Protocol

Each subject walked from 4 or 5 walking steps away to the raised surface (Section 5.3.1) stepped up to the new level and continued walking to the end of the platform. Subjects completed each trial wearing trial frames with full aperture trial lenses, using the visual conditions outlined above. Each visual condition was repeated four times, giving 36 trials. The order of the trials was determined by computer generated random numbers and was different for each subject. A member of the research team was positioned near the front edge of the raised surface to ensure that if subjects should trip or stumble they didn't fall.  If a subject caught their foot on the platform or tripped a note was made and the trial repeated. In order to reduce learning effects with repetition, the starting position was varied. Subjects were instructed to start walking from behind one of 7 lines marked on the floor; the position of the central line having been determined as that which allowed subjects to reach, from 4 or 5 step lengths away, the raised surface at their comfortable walking speed without under or over striding. Three lines in front and 3 lines behind this central line, each 10cm apart, were then marked on the floor, giving a range of ± 30 cm. Starting position was randomised between the trials. The height of the platform was not varied as in Study 2 (Chapter 7) as the previous studies showed that despite varying the height there was still an effect of repetition (Section 7.4). All trials were recorded using the Vicon MX system (Section 5.3.2) using reflective markers placed as in the Helen Hayes marker set with additional foot markers (section 5.3.3).

#### 8.2.3 Data Analysis

Analysis focussed on foot placement parameters during the approach and toe clearance parameters during the step up (Section 7.2.3) including horizontal toe clearance (Section 6.2.3a).

Data were analysed using repeated measures ANOVA (SPSS 15.0). Level of significance was set at $p < 0.05$. Post-Hoc analyses were performed using Bonferroni adjusted pair wise comparisons.

## 8.3 Results

Subjects scored (mean ± 1 SE) 26.5 ± 2.8 cm for the functional reach test and 9.55 ± 0.9 seconds for the Timed Up and Go test classifying all subjects as having a low risk of falling (Shumway-Cook et al., 2000).

Three subjects were right eye dominant and three were left eye dominant. Five subjects were found to have no clear preference. For the purpose of analysis, their dominant eye was assumed to be the eye used for sighting for two out of the three presentations of the eye dominance test. There was no effect of eye dominance on any vision or gait parameters analysed ($p>0.1$) so data were averaged, giving just one category for each level of blur. The new categories were defined as

- 0.50DBlur – Averaged data of 0.50DS blur over the dominant eye and 0.50DS blur over the non-dominant eye.
- 1.00DBlur – Averaged data of 1.00DS blur over the dominant eye and 1.00DS blur over the non-dominant eye.
- Monovision – Averaged data of blur equal to subjects' near addition over the dominant eye and blur equal to subjects' near addition over the non-dominant eye.
- OCC – Averaged data of dominant eye occluded and non-dominant eye occluded

Group mean ± 1 SE high contrast visual acuity, low contrast visual acuity and log stereoacuity are presented for the different visual conditions in Table 7.

Table 7. Group mean ± 1 SE high contrast visual acuity (LogMAR), low contrast acuity (LogMAR) and log stereoacuity for BIN (binocular), 0.50DBlur, 1.00DBlur, Monovision and OCC (occluded) conditions for 11 elderly subjects.

| | **BIN** | **0.50DBlur** | **1.00DBlur** | **Monovision** | **OCC** |
|---|---|---|---|---|---|
| **High Contrast VA*** | -0.04 ±0.03 | 0.00 ± 0.02 | 0.04 ± 0.02 | 0.05 ± 0.03 | 0.03 ± 0.02 |
| **Low Contrast VA*** | 0.11 ± 0.03 | 0.15 ± 0.03 | 0.18 ± 0.02 | 0.20 ± 0.02 | 0.19 ± 0.02 |
| **Log Stereo * (secs of arc)** | 1.69 ± 0.12 (49) | 1.80 ± 0.13 (63) | 1.98 ± 0.10 (95) | 2.36 ± 0.11 (229) | |

* main effect ($p<0.05$)

There was a main effect of visual condition for high contrast acuity ($p<0.001$). Post hoc analysis revealed a significant difference between binocular vision and all other visual conditions ($p<0.05$) and between 0.50D monocular blur and occlusion ($p=0.023$). The effect of visual condition on low contrast acuity was also significant ($p<0.001$), with post hoc analysis showing a significant difference between binocular vision and all other visual conditions except for 0.50D monocular blur and a significant difference between 0.50D monocular blur and monovision ($p=0.003$).

There was a main effect of visual conditions for stereoacuity ($p<0.002$) with post hoc analysis showing differences between binocular and 1.00D monocular blur ($p=0.024$), between binocular and monovision ($p=0.002$), 0.50D monocular blur and monovision ($p=0.003$) and 1.00D monocular blur and monovision ($p=0.003$).

There was no effect of vision for lead foot position ($p = 0.18$). Similarly trail foot position did not change across visual condition ($p = 0.21$). There was a main effect of maximum toe elevation ($p<0.001$) for vision but not repetition ($p=0.24$) and there was no interaction between vision and repetition ($p=0.09$). Post hoc analysis revealed a significant difference between binocular and occluded conditions ($p = 0.009$).
There were main effects for visual condition for vertical toe clearance ($p<0.001$) as well as for repetition ($p=0.008$), with a mean decrease from 62mm for the first repetition to 53mm for the fourth repetition. Post hoc analysis revealed significant differences between binocular vision and 1.00D monocular blur ($p=0.018$), binocular and monovision ($p=0.012$), binocular vision and monocular occlusion ($p=0.001$), and 0.50D monocular blur and monocular occlusion ($p=0.002$). In addition, differences approached significance between 0.50D monocular blur and binocular ($p = 0.08$). There was a

significant increase in horizontal toe clearance across vision conditions ($p<0.001$) and post hoc analysis indicated a significant difference between binocular vision and all other visual conditions ($p<0.05$). There was also a significant effect for repetition ($p = 0.03$), indicating clearance was reduced with repetition from 267mm for the first repetition to 230mm for the fourth repetition. There were no interactions between vision and repetition for vertical ($p = 0.25$) or horizontal ($p = 0.66$) lead limb toe clearance. There was no effect of vision condition for trail toe clearance ($p = 0.12$).

Subjects walked slower under monocular blur and occlusion conditions, indicated by a main effect of vision condition for average walking velocity ($p = 0.04$). Subjects also spent longer in single support under monocular blur and occlusion conditions ($p = 0.002$). Table 8 shows group mean ± 1 SE for all visual conditions for foot placement and temporal factors. The effect of visual condition on lead limb vertical and horizontal toe clearance are shown in figure 27.

Table 8. Group mean ± 1 SE for foot placement and temporal parameters for BIN (binocular), 0.50DBlur, 1.00DBlur, Monovision and OCC (occluded) conditions for 11 elderly subjects.

| | **BIN** | **0.50DBlur** | **1.00DBlur** | **Monovision** | **OCC** |
|---|---|---|---|---|---|
| **Max lead limb Toe Elev (mm)*** | 243 ± 8 | 245 ± 7 | 247 ± 8 | 246 ± 5 | 253 ± 8 |
| **Trail limb toe clear (mm)** | 30 ± 5 | 36 ± 5 | 35 ± 4.0 | 37 ± 5 | 36 ± 6 |
| **Trail limb foot Pos (mm)** | 201 ± 44 | 215 ± 37 | 225 ± 47 | 202 ± 31 | 225 ± 47 |
| **Lead limb foot Pos (mm)** | 766 ± 46 | 779 ± 39 | 776 ± 43 | 776 ± 39 | 753 ± 39 |
| **Average vel ($m.s^{-1}$) *** | 0.997±0.05 | 0.995±0.05 | 0.997±0.05 | 0.970±0.04 | 0.979±0.05 |
| **Single support (secs) *** | 0.46 ± 0.02 | 0.46 ± 0.02 | 0.47 ± 0.01 | 0.48 ± 0.01 | 0.49 ± 0.01 |

* main effect ($p<0.05$)

Four trips were recorded by two subjects; in three cases the trail-limb foot hit the front edge of the platform and in the other the lead-limb foot hit the top edge of the platform. Three of the trips occurred when one eye was occluded and the other occurred under 0.50DS of monocular blur.

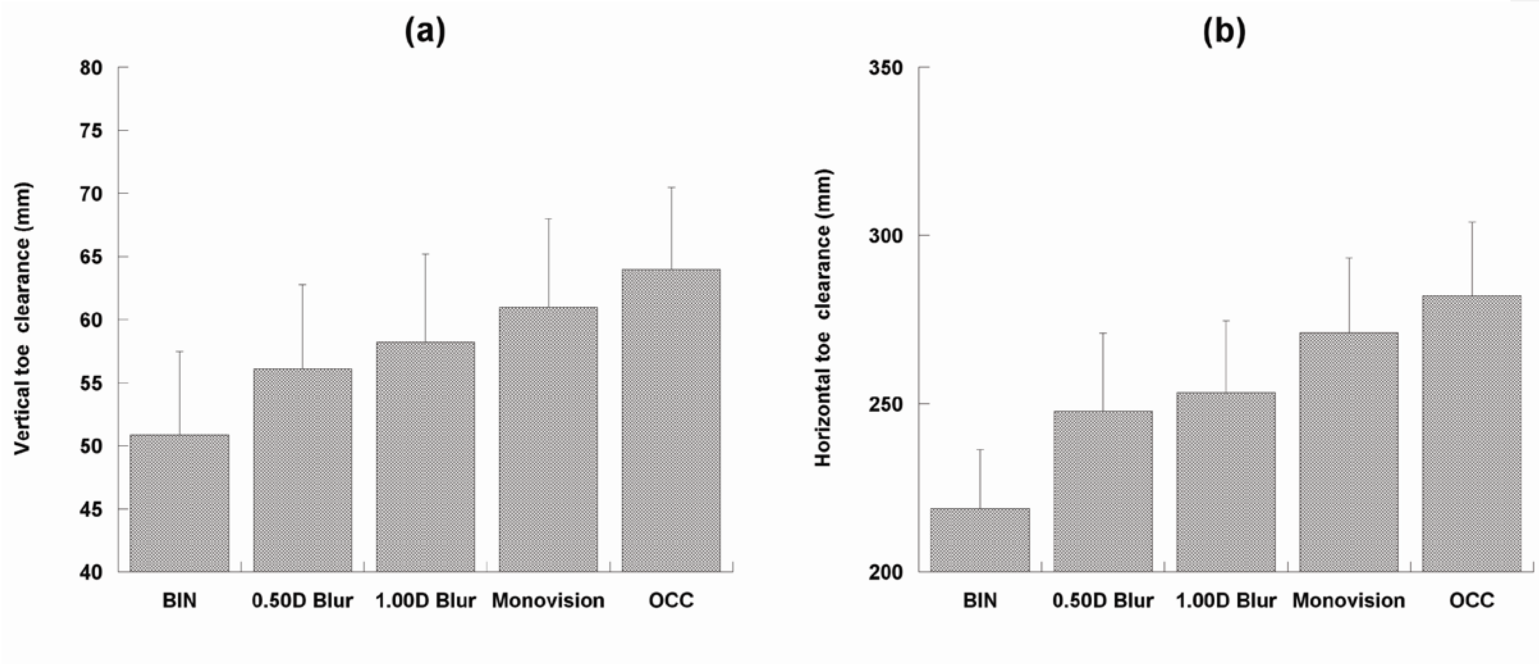



Figure 27. Mean ± 1 SE a) Vertical and b) Horizontal lead limb toe clearance across visual condition.

### 8.4 Discussion

Both horizontal and vertical lead-limb toe clearance increased as monocular blur increased, with the highest average toe clearance for trials when one eye was occluded. The results confirm our hypothesis that under conditions of monocular blur or occlusion elderly subjects would increase toe clearance of their lead limb as a safety strategy to avoid tripping on the front edge of the raised platform. This result corroborates our earlier work that found a similar response in young subjects when one eye was blurred (studies 1 and 2) and in elderly subjects who had unilateral cataract (Elliott et al., 2000). We also hypothesised the effect would be dependent on the level of blur, i.e. lower levels of blur would cause no or minimal increase in toe clearance values, than higher levels of blur. However, although greater blur led to larger toe clearance, even the lowest level of monocular blur (0.50DS) caused a significant increase in toe clearance.

Vertical toe clearance decreased with repetition, suggesting that subjects were able to learn the height of the raised surface through somatosensory feedback (joint angle and foot height/position sense) obtained from previous trials when the lead-limb foot landed on the raised surface. However such feedback would not provide any information regarding the horizontal position of the raised surface (unless contact with the front edge was made), so the decrease found in horizontal toe clearance with repetition suggests that horizontal toe clearance was not controlled completely independently from vertical toe clearance. Therefore the increase in horizontal clearance under conditions of monocular blur and occlusion may be due to the changed foot trajectory that was used to increase vertical clearance as well as subjects having difficultly judging the position of the raised surface. In Study 2 (Chapter 7) subjects increased the distance the trail foot was placed from the step, suggesting a more cautious approach to allow more time for flexion of the lead limb. We suggest the reason that no change in trail foot position was found in the present study was due to the variation in starting position (starting position was not varied in our previous study). This is supported by a study investigating the effect of monocular occlusion on negotiation of an obstacle (Patla et al., 2002). Again, the position of the obstacle within the travel path was varied, and no change in foot position was found prior to the obstacle in monocular compared to binocular conditions (Patla et al., 2002). This suggests that altering the position of the obstacle or raised surface in the travel path, relative to starting position, prevents subjects learning its location and thus adopting a strategy of placing the trail foot farther from the step to facilitate increasing lead limb toe clearance.

Increasing toe clearance when negotiating steps and stairs is likely to increase energy costs. Subjects, particularly elderly ones, appear to try to use the most energy efficient stepping strategy when possible. For example, Cavanagh and colleagues have shown that minimum foot clearance becomes progressively smaller as elderly subjects descend stairs (Simoneau et al., 1991, Hamel et al., 2005) and suggested that this was due to an energy saving strategy. Similarly, in other studies involving elderly subjects stepping up (Heasley et al., 2004, Buckley et al., 2005a, Heasley et al., 2005) trial repetition has led to a decreased toe clearance over the step edge. In all these cases, the reduced toe clearance with repetition effect has been the same either with or without visual blur, suggesting that safety driven adaptations remain, at least in the short term and take precedent over energy saving alterations. It should be noted that foot clearance in elderly subjects can reduce to very low levels in the mid-stair region of stairs (about 7%

of foot clearance are less than 5mm, Hamel et al., 2005), which highlights the small margin for error on stairs.

As well as the increase in toe clearance, subjects were slower when stepping up when one eye was blurred or occluded and spent longer in single limb support, suggesting increased caution when the height of the step could not be accurately judged. An increased time spent in trail limb single support has been previously found to be associated with increased medio-lateral (M-L) instability in elderly subjects performing a single step up to a new level under conditions of binocular blur, (Buckley et al., 2005a) and increased M-L instability has been linked with increased risk of falling (Chou et al., 2003). Although this result was not found in young subjects performing a single step up in conditions of monocular blur (Study 1, Chapter 6), it has been shown that elderly subjects do show greater M-L instability (defined as increased displacement of the CP) during single support when stepping up in conditions of binocular blur (Buckley et al., 2005a). However due to the study methodology this parameter could not be assessed in this study, as subjects would have had to place each foot within the force platforms during stepping up, and this would be unnaturally constrictive to stride lengths, especially for taller subjects.

All visual functions measured were significantly worse under conditions of monocular blur. The average difference between the binocular vision and monovision conditions was equal to approximately one line on the letter chart for both high and low contrast acuity. There was a scaling effect of blur on stereo thresholds, which agrees with previous findings (Ong and Burley, 1972, Westheimer and McKee, 1980). Monocular blur had a much greater effect on stereo threshold than on both high and low contrast log MAR acuity, which has also been shown in previous studies (Westheimer and McKee, 1980). Thus we suggest that the adaptations in gait seen under conditions of monocular blur were primarily driven by impairment of stereopsis for the following reasons. Firstly the decline in stereoacuity was much greater than the decline seen in high or low contrast acuity. Secondly the decline of stereo threshold, even seen with 0.50D monocular blur, fell to a level identified in epidemiology studies as being a risk factor for hip fracture (Ivers et al., 2000), whilst the declines in levels of visual acuity, even with the highest levels of monocular blur, have not previously been associated with any increased risk of falls or fall related injury.

The present study assessed gait changes to acute changes in monocular blur and reduced stereoacuity. This is a useful approach, particularly given that falls may be associated with changes in the level of visual impairment, as much as or even more than the visual impairment level itself (Coleman et al., 2004). The disadvantage of this approach is that the gait adaptations found may not be the same as those occurring over time. For example, subjects with acutely presented binocular blur showed increased toe clearance when performing a single step up to a new level (Heasley et al., 2004) but subjects with chronic binocular blur of the step edge (multifocal wearers) showed no increase in toe clearance during stepping up, but did show an increase in toe clearance variability (Johnson et al., 2007). Indeed, if the safety driven adaptations reported here were always used, it is unlikely that falls would occur. What these studies do show is subjects are very aware of the difficulties produced by acute monocular blur and adapt their gait appropriately, at least initially. In addition, it should be noted that even with acute monocular blur, 4 of 396 trials (~1%) led to a subject hitting the step and these were all under conditions of impaired stereoacuity.

In terms of gait adaptations with more chronic reduced stereoacuity, it has been reported that patients with binocular cataract show increased toe clearance of an obstacle compared to age-matched normals and this safety adaptation remains after first eye surgery (as does poor stereoacuity), but returns to normal after second eye surgery (Elliott et al., 2000). This suggests that adaptations in gait gained over several weeks does not appreciably change safety driven gait adaptations or that any adaptations gained are offset by possible changes in visual impairment due to progression of the cataract. Further work is required to investigate the effects of chronic monocular blur, and this will be addressed in the next chapter.

To summarise monocular blur caused a small decline in both high and low contrast visual acuity and caused a large decline in stereoacuity. Under conditions of monocular blur elderly subjects increased toe clearance when negotiating a raised surface, suggesting they were less able to accurately judge the height of the raised surface than with corrected binocular vision. This effect was found for monocular blur as small as 0.50DS and the increase in toe clearance was greater for higher levels of blur and monocular occlusion. Subjects were also slower in monocular blur conditions compared to binocular conditions, suggesting monocular refractive blur led to a safety led strategy for negotiating the raised surface. This study only looks at the effects of acute monocular blur and it does not provide any information regarding whether subjects can adapt to the presence of monocular blur and the associated decline in visual function. Therefore the effects of chronic monocular blur should also be investigated and this will be addressed in the following chapter.

# Chapter 9.

# Study 4: Gait and Toe Clearance Parameters When Stepping Up or Down Under Conditions of Chronic Monocular Blur

## 9.1 Introduction and Aim

In the previous three studies, subjects were asked to negotiate a raised surface under conditions of acute monocular blur. Under these conditions subjects demonstrated an adaptation of raising their lead limb higher in order to increase toe clearance over the step. This appears to be a safety strategy in response to loss of visual information regarding the position or height of the raised surface similar to findings in subjects under conditions of acute binocular blur (Heasley et al., 2004, Heasley et al., 2005, Buckley et al., 2008). However, it is unclear whether this safety strategy would also be used by patients with chronic monocular blur as prior studies investigating the effects of chronic blur (outlined below) on stepping strategy show different findings.

There are very few studies to date that have investigated how gait is affected by chronic blur. Elliott and colleagues showed that elderly subjects with unilateral or bilateral cataracts demonstrated increased toe clearance, compared to age match normals (Elliott et al., 2000). This study suggested that older adults with cataracts do not change their adaptive gait over time and continue to use a ‘safer’ stepping strategy in order to successfully avoid the obstacle. However, another study that investigated stepping strategy in multifocal wearers, who had worn them for several years so that subjects would be adapted to blur in their lower visual field, found that subjects did not increase average toe clearance when stepping onto a raised surface when wearing multifocals (Johnson et al., 2007). However there was increased variability in toe clearance when wearing multifocals compared to single vision distance spectacles and as a consequence subjects made more accidental contacts with the step edge (Johnson et al., 2007).

No studies have investigated the effects of chronic blur on stepping down. When stepping down under conditions of acute binocular blur, previous research has shown that subjects take longer to perform the step down (Buckley et al., 2005a, Buckley et al., 2005b) and have increased flexion of the knee and ankle at the instant of landing, increased vertical stiffness during initial landing (Buckley et al., 2005b), and have more body weight still being supported by the contralateral leg at the end of the initial landing period (Buckley et al., 2005b, Buckley et al., 2008). These changes suggested subjects were "feeling" the way to the floor, rather than dropping on to the floor (Buckley et al., 2005b). When subjects have one eye occluded during stepping down, scaling of lower limb kinematics (measured using kneedrop, how far the knee drops vertically at the instant the leg has stopped swinging outwards and starts to swing back towards the step) was impaired, demonstrating that subjects had uncertainty in judgement of the height of the step (Cowie et al., 2008).

The aim of the present study was to assess how subjects negotiate a raised surface, when stepping up or stepping down, under conditions of habitual, chronic, monocular blur, compared to corrected binocular vision. We hypothesised that under conditions of habitual monocular blur subjects would not show the same safety strategy as previously seen under acute monocular blurred conditions, and would instead show no change in toe clearance or stepping behaviour. However as their binocular vision would be impaired with monocular blur, subjects would demonstrate increased variability in these measures under habitual viewing conditions. In addition we hypothesised that under conditions of habitual, chronic, monocular blur subjects would show poor scaling of lower limb kinematics when stepping down as they would be less able to judge the step height. In order to investigate chronic monocular blur we recruited subjects who were habitual and well adapted monovision wearers, and thus habitually had monocular refractive blur in one eye and as a consequence impaired stereopsis (section 2.5.4).

## 9.2 Method

11 subjects (9 females and 2 males, mean age 52.5 ± 4.6 years, height 1.68 ± 0.06m, weight 69.8 ± 9.3kg) were recruited and screened as described in Chapter 5, section 5.1.3.

### 9.2.1 Vision Assessment

The dominant eye was determined using the Kay test (Section 5.2.4). Binocular visual acuity was determined with the ETDRS chart at 4 metres (Section 5.2.1a), binocular contrast sensitivity was measured using the Pelli Robson chart (Section 5.2.2) at 3 metres and stereoacuity was measured using the Frisby stereotest (Section 5.2.3b). All visual assessment was carried out under two visual conditions, the first was the subject’s habitual monovision condition with one eye corrected for distance and other corrected for close work and the second with the subjects wearing full distance refractive prescription binocularly. In both cases the type of contact lenses the patient would normally wear were worn, based on contact lens specifications supplied by the patient from their contact lens practitioner. The appropriate power of the distance contact lens, used for the binocular condition, was estimated from the patients' latest spectacle prescription and once inserted was checked with a spherical over-refraction. Following any change of the contact lens, a short period of approximately 5 minutes was allowed for the lens to settle and it was checked with the patient that the lens felt comfortable prior to any visual assessment being carried out. The order in which the visual conditions were assessed was randomised, based on the order in which the mobility trials were ordered (Section 9.2.2).

### 9.2.2 Protocol

Reflective markers were attached as per the Helen Hayes marker set (Section 5.3.3) and all trials were recorded using the Vicon MX system (Section 5.3.2). Trials were arranged in two visual condition blocks. Within each block there were 10 stepping up trials and 10 stepping down trials, the order of which were randomised giving 20 trials within each block for a total of 40 trials. The trials were blocked, due to the time needed to change the contact lenses and allow time for the lens to settle. By blocking the visual conditions, only one change of contact lens was required. The order of the visual condition blocks were counter-balanced so that six subjects undertook binocular trials first.

#### 9.2.2a Stepping Up Protocol

The protocol used was the same as that in Chapter 8 (section 8.2.2)

### 9.2.2b Stepping Down Protocol

Trials started with subjects standing stationary on top of the step with their feet side-by-side. The step was positioned on top of a single force platform (Section 5.3.4). When instructed to do so, subjects took a single step down so that they landed within the second force platform with their feet side-by-side and remained standing on the force platform for a few seconds, until instructed they could step off. As with the stepping up protocol subjects were asked to consistently use the same lead limb throughout all stepping down trials.

### 9.2.3 Data Analysis

Visual data were analysed using paired t-tests (SPSS 15.0) with the level of significance set at $p<0.05$.

### 9.2.3a Stepping Up Data Analysis

Analysis focussed on foot placement parameters during the approach and toe clearance parameters during the step up (Section 7.2.3) including horizontal toe clearance (Section 6.2.3a).

### 9.2.3b Stepping Down Data Analysis

The following parameters were examined for stepping down[1].

[1] Time spent in double support is not included in analysis. This is owing to the way the parameters were calculated did not allow double support to be calculated accurately

- Time in single support: the period when only the trailing limb was in contact with the step as the lead limb was swung forward towards the ground; calculated from lead limb toe off to instant of foot contact with the second force platform.
- Step distance: calculated as the displacement in the y- position of the lead limb toe marker prior to heel-off up to instant of foot contact with the second force platform.
- Weight Transfer time: the period from the instant of lead limb foot contact with the second force platform to toe-off of the trail limb.
- Knee drop: the distance that the knee descends from its maximum height whilst the shank swings outwards. i.e. the difference between the knee marker (lateral femoral condyles, section 5.3.4) maximum vertical position and vertical position at shank swing peak (Cowie et al., 2008).

Lead limb toe-off was defined as the instant when the toe marker moved from its stationary position by more than 2mm in the anterior-posterior plane for five consecutive frames. Foot contact was defined as the instant at which the vertical ground reaction force for the lead limb (measured from 2nd force platform) exceeded 20N.

Kinematic data for both stepping up and stepping down were analysed for two visual conditions (binocular distance vision, monovision), and repetition (1-10) using a repeated measures ANOVA (SPSS 15.0). Level of significance was set at $p < 0.05$. Post-Hoc analyses were performed using Bonferroni adjusted pair wise comparisons.

## 9.3 Results

### 9.3.1 Vision

Six subjects were dominant in their right eye and five were dominant in their left eye. Six subjects wore their distance correction in their dominant eye. The mean monocular addition worn was 1.43 ± 0.50DS. One subject had "natural monovision" so that she was myopic in one eye (-1.50DS) and was essentially emmetropic in the other eye (+0.25DS). She occasionally wore a contact lens in the myopic eye for driving but normally did not wear any correction. The average length of time subjects had worn monovision correction was 5.4 ± 2.6 years, with the minimum length of time being 2 years. Mean ± 1SE are presented for binocular visual acuity, binocular contrast sensitivity and log stereoacuity for the monovision and binocular conditions (Table 9)

Table 9. Group mean ± 1 SE binocular visual acuity (VA in logMAR), binocular contrast sensitivity (log CS) and log stereoacuity for 11 subjects with a habitual monovision correction.

| | **Binocular distance vision** | **Monovision** |
|---|---|---|
| **Binocular visual acuity** | -0.08 ± 0.02 | -0.04 ± 0.02* |
| **Binocular contrast sensitivity** | 1.81 ± 0.03 | 1.76 ± 0.03 |
| **Log Stereoacuity (secs of arc)** | 1.22 ± 0.09 (16.6") | 1.94 ± 0.14** (87.1") |

significantly different from binocular condition
*p < 0.05
**p < 0.001

There was a significant difference between binocular visual acuity scores for binocular distance and monovision conditions ($p = 0.03$) and between binocular distance and monovision stereoacuities ($p<0.001$). There was no significant difference in binocular contrast sensitivity ($p = 0.24$).

### 9.3.2 Stepping Up

Four subjects stepped up using their right foot and seven subjects used their left foot. The main outcome measure was vertical toe clearance, which showed significant repetition effects indicating a significant learning effect ($p = 0.018$). This was expected as it is a common finding in stepping studies and likely reflects an energy conservation strategy (Simoneau et al., 1991, Hamel et al., 2005). However, this learning effect was also evident in the large effect of visual condition testing order on some stepping up parameters. In order to fully understand the study findings it was felt that more complex analysis than ANOVA was required.

Stepping up data was therefore analysed by Mr Andy Scally (Institute of Health Research, University of Bradford), using Stata version 8.0 statistical program (Chapter 7, section 7.2.3). Factors of interest were incorporated sequentially and their statistical significance assessed. Level of significance was set at $p < 0.05$ and all factors reaching that level were retained in the final model. p values quoted are those associated with specific terms in the final regression model, which were (1) vision: a fixed factor with two levels, binocular distance vision and monovision; (2) visual condition order, so that order 1 for each visual condition meant that the particular visual condition was tested first and order 2 meant that the particular visual condition was tested second, and (3) repetition: a fixed factor with 10 levels, trials 1-10.

In addition to investigate variance we used a linear mixed model, the lme() function in R version 2.7.2 (The R Foundation for Statistical Computing ISBN 3-900051-07-0), which permitted the modelling of different residual variances for the four levels of the interaction between order and vision condition. All statistics reported for stepping up data are those supplied by Mr Scally.

There were no significant interaction effects for vision and order or vision and repetition for any of the investigated parameters. The distance the lead foot was placed before the raised surface was unaffected by visual condition ($p = 0.09$), or order ($p = 0.64$). For trail foot position before the raised surface there was no significant effect of visual condition ($p = 0.11$) or order ($p = 0.14$). There was an effect of repetition ($p = 0.027$) with the trail foot being placed closer to the surface for the 9$^{th}$ and 10$^{th}$ repetition.

Vertical toe clearance of the lead limb was not significantly affected by visual condition ($p = 0.90$, Figure 28). There was however a significant effect of order ($p < 0.001$, Figure 28) with vertical toe clearance reduced for the second block of trials, regardless of visual condition. Vertical toe clearance also decreased with repetition ($p = 0.019$), with significant reductions for the 9$^{th}$ and 10$^{th}$ trials.

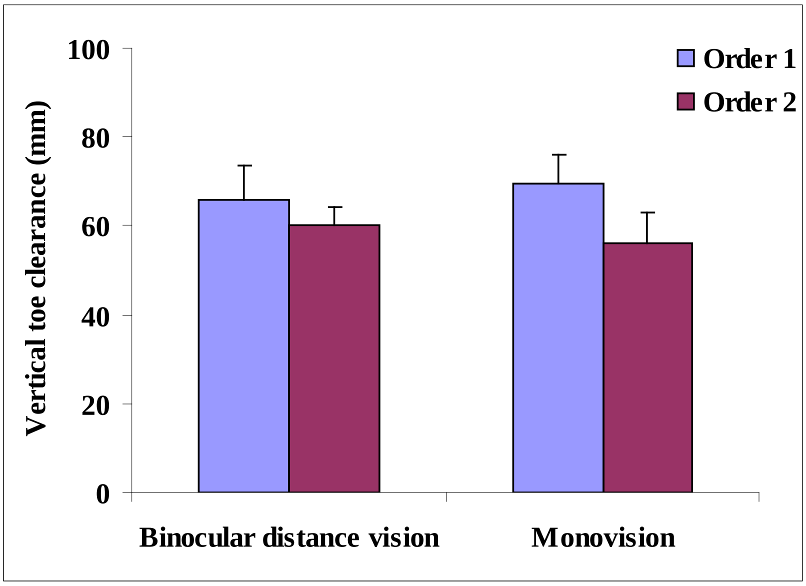



Figure 28. Mean vertical toe clearance (± 1SE) of the lead limb when stepping up for 11 subjects with habitual monovision correction

For vertical toe clearance, R found that the model that incorporated different residual variances for the order-vision interaction produced a significantly better fit to the data than the model incorporating a common variance for all levels of the interaction (likelihood test ratio = 9.74, p = 0.021). For order 1 the monovision condition was found to have 33% greater variance than binocular distance vision (Figure 29). However for order 2 both monovision and binocular distance visual conditions variances were reduced (by 13 and 10% respectively) compared to binocular distance vision variance in order 1 (Figure 29). For all other parameters investigated the fixed variance model was a better fit to the data.

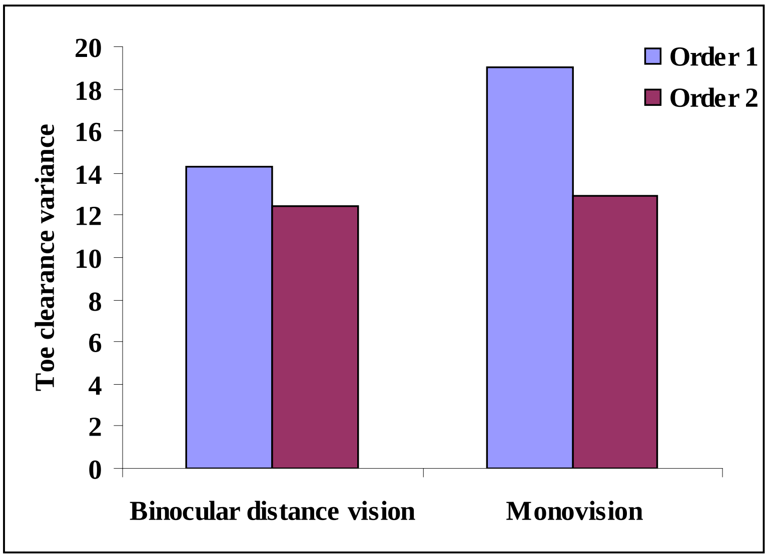



Figure 29. Vertical toe clearance variance for 11 subjects with habitual monovision correction.

There was a significant effect of visual condition (p = 0.035) on horizontal toe clearance with a reduction of approximately 20mm for the monovision condition compared to binocular distance vision. There was no effect of order (p = 0.30) or repetition (p= 0.77). There was a significantly main effect of repetition on lead foot position on the raised surface (p = 0.02), with subjects placing their lead foot significantly further onto the step (with respect to the edge of the raised surface) for trials 6 to 10 compared to the first trial. There was also a significant effect of order (p = 0.007) but no significant effect of visual condition on foot placement on the raised surface, indicating that subjects placed their foot farther on to the raised surface in later trials.

Average velocity when stepping up onto the raised surface increased with repetition, with subjects faster from the third trial (p = 0.013). There was also a significant effect of order on average velocity ($p < 0.001$) and, a significant effect of visual condition on average velocity ($p < 0.001$), with subjects travelling significantly slower under monovision condition ($0.960ms^{-1}$) than under binocular distance visual conditions ($0.982ms^{-1}$). These effects indicates that which ever visual condition is assessed first, subjects significantly increase their average velocity in the second visual condition but in addition subjects were slower when one eye was blurred.

There was no significant effect of repetition or visual condition ($p > 0.05$), for single support although there was a significant effect of order ($p = 0.04$) on time spent in single support. This finding shows that subjects spent less time in single support for the second block of trials and therefore the above findings for velocity that subjects were quicker for the later trials.

### 9.3.3 Stepping down

Five subjects stepped down leading with their right foot and five led with their left foot. There were no main effects of visual condition, visual condition order or repetition on any of the parameters investigated ($p > 0.05$, Table 10)

Table 10. Group mean ± 1 SE for stepping down parameters, collapsed across group and repetitions for 11 subjects wearing a monovision correction.

| | **Binocular distance vision** | **Monovision** |
|---|---|---|
| **Step Distance (mm)** | 469 ± 9 | 479 ± 9 |
| **Time in single support (s)** | 0.600 ± 0.015 | 0.605 ± 0.016 |
| **Weight Transfer time (s)** | 0.170 ± 0.011 | 0.176 ± 0.014 |
| **Knee drop (mm)** | 8.01 ± 0.52 | 8.05 ± 0.50 |

## 9.4 Discussion

There was a significant loss of binocular visual acuity and stereoacuity when subjects wore their monovision correction, but no loss of contrast sensitivity. This is similar to previous findings with monovision patients (Back et al., 1992, Collins et al., 1993, Back, 1995). Contrast sensitivity has been found to be impaired in monovision wear previously but only at high spatial frequencies (8 and 16 cycles per degree, Collins et al., 1989). Contrast sensitivity was measured with the Pelli-Robson chart at 3 metres and measures close to peak contrast sensitivity at intermediate spatial frequencies of 1.5-2 cycles per degree (Pelli et al., 1988). There was a greater effect of monovision on stereoacuity than with visual acuity and this finding agrees with our previous work (Chapters 5,6 and 7, Vale et al., 2008) and previous studies investigating the effect of monocular blur on visual function (Westheimer and McKee, 1980, Schmidt, 1994). We have not been able to look at the influence of eye dominance of monocular blur, because, the majority of subjects habitually had their non-dominant eye blurred for distance, with 4 subjects wearing their distance contact lens in their non-dominant eye and the amount of monocular blur varied between subjects, therefore the study does not have the power to examine the effect of dominant and non-dominant chronic monocular blur. As the majority of the literature reports that the dominant eye is normally corrected for distance vision (Jain et al., 1996) it might be expected that more subjects would have had their dominant eye corrected for distance vision. However we assessed ocular dominance using a sighting test, which may have been different to the test used by the subject's contact lens practitioner, for example a test of blur suppression, which has not been found to be related to sighting dominance (Schor et al., 1989).

There was no main effect of visual condition on lead foot position or trail foot position prior to the raised platform. This is an agreement with findings of acute monocular blur (Chapters 7 and 8) and monocular occlusion (Patla et al., 2002).

The mean amount of monocular blur worn by subjects in this study of 1.42DS provides similar levels of binocular visual acuity and stereopsis as the acutely presented monocular blur in previous chapters. In addition 0.50DS and 1.00DS of acutely presented monocular blur were sufficient to increase toe clearance (Chapter 8). However in subjects with habitual monovision correction the results demonstrate that, in stark contrast to findings under acute monocular blur, subjects did not change vertical lead limb toe clearance of the step, compared to corrected binocular vision. This appears to demonstrate an adaptation to chronic monocular blur. There was however increased variance found for the monovision condition provided the condition was tested first and subjects did not have sufficient previous trials to learn the step height, which suggests that subjects could still not accurately judge the position of the step height in monocular blur conditions.  An increase in variability of lead limb toe clearance in addition to no increase in magnitude of clearance represents a potentially less safe strategy for negotiating the platform as the subject is more likely to make contact with the step edge. In addition in the monovision condition subjects were found to reduce horizontal toe clearance compared to in binocular conditions, potentially increasing the risk of hitting the step edge further.

There was a decrease in vertical toe clearance with repetition. Subjects initially raised their foot higher, but reduced vertical toe clearance for later trials, similar to findings in previous studies (Chapters 6,7 and 8, Vale et al., 2008). This also supports findings indicating when negotiating a flight of stairs subjects reduce toe clearance over the later steps as they learn the height of the step through somatosensory feedback (Simoneau et al., 1991, Hamel et al., 2005).

Subjects were slower in the monovision conditions. This suggests that although they did not use the safety strategy of increasing lead limb toe clearance they were still more cautious in their approach to negotiating the raised surface. Subjects increased their velocity in later trials, as demonstrated by the increase in velocity for the second block and with repetition, which again is similar to previous findings (Chapters 7 and 8, Vale et al., 2008). It appears that subjects were happy to increase their velocity after undertaking several trials and when they had good binocular vision and as a consequence good stereopsis, but may have remained more cautious in monovision condition even after a number of trials.

**Comment [j3]:** Results indicate this was just a trend

The findings of no change in vertical toe clearance are in contrast to findings by Elliott et al (2000) who found that toe clearance of an obstacle increased in patients with monocular cataracts, compared to age match normals. However, this difference may be due to cataracts being progressive and so perhaps subjects did not show any adaptation to the loss of visual function due to cataract as the level of visual impairment was changing. In contrast, as the refractive strength of the near addition prescribed is likely to remain stable for long periods, monovision patients will have time to adapt to the loss of stereoacuity and visual acuity caused by the near addition. The increase in lead limb toe clearance variability in monovision conditions are in agreement with findings by Johnson et al (2007) which found an increase in toe clearance variability in conditions of chronic monocular blur in adapted multifocal wearers.

There was no effect of visual condition on stepping down with all parameters remaining unchanged. This therefore shows that subjects were able to judge the height of the step in both conditions equally well. As loss of binocular vision (through monocular occlusion, Cowie et al., 2008) and binocular blur (Simoneau et al., 1991, Buckley et al., 2005a, Buckley et al., 2005b) results in changes in how subjects step down, it was expected that monocular blur would also result in changes to the way the step was negotiated. This suggests that subjects were adapted to chronic monocular blur and were able to use monocular cues or the remaining stereopsis to accurately judge the height of the step, to safely control their descent. However the height of the step was not changed throughout the trials. Therefore subjects would be able to gain somatosensory information regarding the step height throughout the trails, although if this was the case we might expect to see a repetition effect on these data, as found with stepping up trials. In addition in order to step down subjects had to first step up to the raised surface, so that they had somatosensory information regarding the step height prior to any trials. Therefore perhaps our results do not show any effect of visual condition as subjects had sufficient knowledge of the step height prior to commencement of the trial. Clearly this area of research requires further study.

Limitations of this study include the small number of subjects, with difficulties in recruitment being due to the inclusion criteria of having worn monovision successfully for at least three months. The small number of subjects may have led to the study being underpowered and unable to detect small changes in response to change in visual condition. In addition the small numbers in the study did not allow a further investigation into whether there was a greater effect of monocular blur when worn in the dominant eye, as found in previous studies (Chapter 7, Erickson and McGill, 1992, Vale et al., 2008). Within this study there was a large learning effect, caused by both a large number of repetitions and due to the visual conditions being completed in blocks (counter balanced) rather than randomised.

In summary, monovision subjects did not change vertical lead limb toe clearance, decreased horizontal toe clearance and demonstrated increased vertical toe clearance variability in monovision conditions compared to binocular distance vision correction. Stereopsis was impaired in monovision conditions. These findings therefore indicate that subjects are not able to accurately judge the height of a step edge but demonstrate that subjects no longer use the safety strategy adopted in conditions of acute monocular blur. It therefore is suggested that monovision should not be used by older contact lens patients and should be avoided as a permanent method of vision correction.

# Chapter 10.

# Study 5: Measurement of Stereoacuity in an Elderly Population

## 10.1 Introduction and Aim

Epidemiology studies have not consistently found that stereopsis is a significant risk factor for falls (Section 4.4.8). There are many possible reasons for this including differences in collection of falls data, failure to correct for co-founders such as age and co-morbidity and variation in sample sizes. Another factor may be the different tests for stereopsis used. Tests for stereopsis often demonstrate poor correlation with each other and numerous reasons have been offered of why that is the case, including differences in the type of stereopsis measured i.e. local or global (Section 1.2), difference in target size, absence or presence of monocular cues and whether the test requires perception of depth or form discrimination (Hall, 1982). Tests used within epidemiological studies include the Randot (Nevitt et al., 1989, DargentMolina et al., 1996, Ivers et al., 2000, Friedman et al., 2002, Freeman et al., 2007) Frisby (Lord and Dayhew, 2001) and Howard Dolman apparatus (Cummings et al., 1995, Lord and Dayhew, 2001, Wainwright et al., 2005). Epidemiological fall studies that have not directly measured stereopsis have used differences in acuity between the eyes as a surrogate measure (Felson et al., 1989, Klein et al., 2003). However although this provides a reasonable indicator of stereopsis there can be large variation among subjects on how much differences in visual acuity affects stereopsis (Donzis et al., 1983). In addition it has been suggested that stereoacuity tests that utilise random dot stereograms may not be a suitable test in elderly subjects (Garnham and Sloper, 2006) with findings that some elderly subjects who score good stereoacuity on other tests only measure gross or absent stereopsis on the TNO. Although not used in the Garnham and Sloper (2006) study it has been suggested that this may apply not just to the TNO test but also to the Randot stereotest (Freeman et al., 2007) which has contoured targets on a random dot background. In addition a design flaw present in the TNO test is that there is a difference in target contrast viewed through the red and green filters. It has been shown that this can lead to large differences in the stereoacuity scores in amblyopic subjects, depending on which way round the filters are worn; i.e. green in front of the right eye and red in front of the left eye or vice-versa (Simons and Elhatton, 1994). This result has not been found in visually normal young subjects (Jenkins and Curran, 1978), but as elderly subjects are more likely to have differences in contrast sensitivity between their eyes, for example due to media opacities, this may be an additional source of error with the TNO test in elderly subjects.

The HD apparatus used in a number of studies is not a clinically available test, and although a straightforward design there is no standardisation for the test and its measurements. For example the gap between the rods has an influence on the stereothreshold measured (Simons, 1981). To date epidemiological studies have used mean alignment error (Lord and Dayhew, 2001) or standard deviation of alignment error (Cummings et al., 1995, Wainwright et al., 2005) to determine stereothreshold (Chapter 3, section 3.3.2). However it is reported that neither method represents a true measurement of stereopsis (Larson, 1985). An alternative method is that used by Graham (1965) in which subjects are presented with misaligned rods and subjects have to correctly identify which rod is displaced towards them, stereothreshold is determined using a staircase technique. This technique is time consuming and may not be appropriate if part of a large battery of tests. Due to these problems and lack of standardisation between apparatus we have not investigated the HD apparatus as part of this study. For this particular study we have taken the Frisby test to be the gold standard. This is because is has been found to have excellent test-retest reliability in young subjects (Situ and Elliott, 2000), and if used correctly it contains no monocular cues (Hinchcliffe, 1978). The design of the test has allowed modifications so that perceptually equal step sizes are presented and there are multiple presentations at each level. The main drawback to the Frisby stereotest is that in order to achieve a large range of stereoacuity the working distance needs to be adjusted and therefore in presbyopic subjects appropriate working lenses must be used.

The aim of this study was to investigate the reliability of the most commonly used stereotests to find out which tests are most appropriate to measure stereoacuity in an elderly population with speed and accuracy. In addition it was investigated whether tests which utilise random dot stereograms (TNO and Randot) underestimate stereoacuity in elderly subjects as suggested by Garnham and Sloper (2006) and if the TNO is subject to error in elderly subjects due to differences in contrast between the red/green stimuli as suggested by Simons and Elhatton (1994). We also investigated whether poor monocular or binocular VA was an accurate predictor for the level of stereoacuity. Finally based on the results, we hoped to recommend a test for use in future epidemiology studies in order to determine whether poor stereoacuity is indeed a significant risk factor in falls.

## 10.2 Method

### 10.2.1 Data Collection

24 Elderly subjects (Section 5.1.2, 12 males, 12 females, age 73.1 ± 6.3 years) attended for two testing sessions, approximately 1 week apart (7.3 ± 0.3 days) At each session monocular and binocular visual acuities were assessed (Section 5.2.1b) followed by five stereotests. The order of stereotests was randomised between subjects and testing session. For each stereotest, patients wore their habitual distance prescription in a trial frame with appropriate working distance lenses added for testing. Spectacles provided with the stereotests were placed over the trial frame. Lighting levels were measured prior to testing and were kept consistent between testing session (approximately 700 lux). All subjects provided written informed consent prior to the any collection of data and the tenets of the declaration of Helsinki were followed.

The following tests were used

- TNO stereotest (Section 5.2.3a)
- TNO reversed – the red and green lenses were reversed so that the green lens was placed over the subject's right eye. In order to maintain crossed disparity the test plates were held upside down. Otherwise the test administration was unchanged.
- Frisby stereotest (Section 5.2.3b)
- Titmus circles test (Titmus Optical Co, Inc., Chicago, USA) – a polarised vectograph consisting of 9 groups of four contoured circles which are viewed with polarised spectacles (Figure 30) and is sometimes called the Wirt Test. The patient had to identify which of the four circles within each block appeared in depth, giving a four alternative forced choice. The range of stereoacuity tested at

40cm ranged from 800 to 40 sec of arc (2.90 to 1.60 log units of secs of arc) with the range extended to 20 secs of arc (1.30 log units of secs of arc) when the test was presented at 80cm.

Figure 30. The Titmus Circles Stereotest (left upper hand corner of test booklet).

- Randot stereotest (Stereo Optical Co, Inc., Chicago, USA) – Similar to the Titmus circles test. Ten groups of three circles of which the circle with disparity had to be identified, giving three alternate forced choice method (Figure 31).The circles are presented on a random dot background. The range was from 400 to 20 secs or arc (2.60 to 1.30 log units of secs of arc) which was decreased to 10 secs or arc (1 log unit of secs of arc) when held at 80cm.

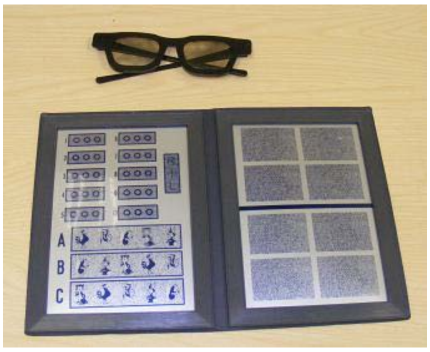


Figure 31. Randot Circles Stereotest (left upper corner of test booklet).

### 10.2.2 Data Analysis

Correlations between test and retest data were calculated using Spearman Rank correlation coefficients for all the stereotests as the majority of tests (with the exception of the Frisby test) do not have regular interval step sizes and some of the test data were not normally distributed. The 95% confidence limits for change was also calculated (Elliott et al., 1991). The 95% range identifies the level of difference needed to detect a clinically significant change and is calculated by direct viewing of the test-retest difference data and considers the average step size for each test (Figure 32).

TNO data were collated into two groups; stereoacuity with the red lens over the subject’s eye with the poorest visual acuity score (TNO-worst) and stereoacuity with the red lens over the eye with the best visual acuity score (TNO-best). If the two eyes had equal acuity then the stereoacuity scores were not reordered for that subject. As correlations reflect only the strength of a relation between two variables and not the agreement between them (Bland and Altman, 1986) and are influenced by the extent of the range of values (Bland and Altman, 1986, Haegerstrom-Portnoy et al., 2000), in addition to correlations, Bland-Altman plots, where the mean of the two test scores are plotted against the difference in scores for each test, were calculated to allow for comparison between tests.

In order to assess if visual acuity was a predictor for poor stereoacuity, linear regression was undertaken comparing results on the Frisby stereotest with binocular visual acuity, worst monocular acuity and finally the difference in monocular acuity scores.

## 10.3 Results

Mean binocular habitual visual acuity was -0.07 ± 0.09 logMAR (Snellen equivalent 6/5). All subjects were able to achieve a score on all stereotests, except for one measurement taken on the TNO test where the subject failed to see the screening plates, although was able to achieve a score on repeat testing. For the purposes of analysis for this one measurement the score was given as 3.30 log units, the maximum score possible on the TNO. Table 11 summarises the stereotests used in the study, including step size and range of stereoacuity scores. For the Randot and Titmus tests the range was extended by holding the test at 80cm, if the subjects successfully identified all the targets at 40cm.

Table 11. Summary of the stereotests used in Study 5.

| | **Frisby** | **Titmus** | **Randot** | **TNO** |
|---|---|---|---|---|
| **Log Range (secs of arc)** | 0.95-3.03 (9-1070”) | 1.30-2.90 (20-800”) | 1.00-2.60 (10-400”) | 1.18-3.30 (15-1980”) |
| **Working Distance (cm)** | 20-120 | 40-80 | 40-80 | 40 |
| **Near Addition (DS)** | +0.75 to +5.00 | +1.25 or +2.50 | +1.25 or +2.50 | +2.50 |
| **Number of Steps** | 14 | 9 | 10 | 7 |
| **Presentations per level** | 4 | 1 | 1 | 1 |
| **Mean step size (Log Units)** | 0.16 | 0.18 | 0.16 | 0.35 |
| **Effective step size** | 0.04 | 0.18 | 0.16 | 0.35 |
| **Alternate forced choice** | 4 | 4 | 3 | 8 |
| **Type of stereopsis** | Global | Local | Local | Global |
| **Additional spectacles** | No | Yes (Polaroid) | Yes (Polaroid) | Yes (Red-green) |

Table 12 provides the mean ± 1 SD test and retest score for each stereotest and median and range for the TNO test, along with test-retest Spearman-Rank correlation coefficient and 95% limits for change. Table 13 shows the Spearman-Rank correlations between the stereotests.

Figure 32 a to e are frequency distribution plots of the discrepancy between test and retest stereoacuity for each stereotest. Figure 33a to j show the Bland-Altman  plots for difference in stereoacuity against the mean stereoacuity (Bland and Altman, 1986).

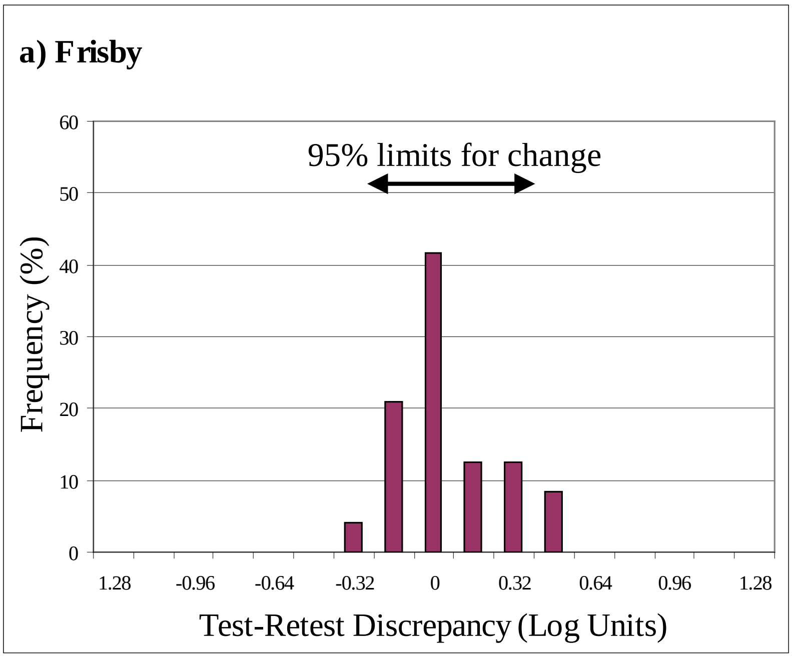
Table 12. Mean ± 1 SD (secs of arc) and median (range, secs of arc) test and retest scores where appropriate, with Spearman rank test –retest correlation and 95% confidence limits for change for the five stereotests for 24 elderly subjects.

| **Test** | **Test score** | **Retest score** | **r** | **p Value** | **95% limits for change** |
|---|---|---|---|---|---|
| **Frisby** | 1.69 ± 0.52 (49”) | 1.68 ± 0.43 (48”) | 0.92 | < 0.001 | ± 0.36 |
| **Titmus** | 1.85 ± 0.34 (71”) | 2.00 ± 0.26 (100”) | 0.41 | 0.048 | ± 0.54 |
| **Randot** | 1.62 ± 0.27 (42”) | 1.64 ± 0.68 (44”) | 0.62 | 0.001 | ± 0.48 |
| **TNO-worse** | 1.92 (1.78-3.30, 83”) | 2.07 (1.48-2.68, 117”) | 0.75 | <0.001 | ± 0.70 |
| **TNO-best** | 1.78 (1.18-3.30, 60”) | 1.78 (1.18-3.30, 60”) | 0.56 | 0.006 | ± 0.70 |

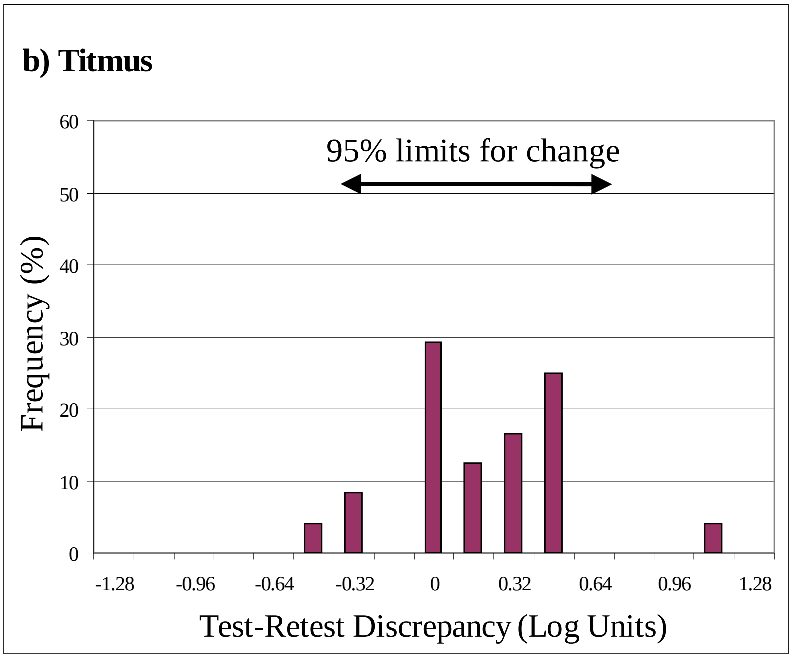
Table 13. Spearman-Rank correlation coefficients between the five stereotests.

| **Test** | Titmus | Randot | TNO-worse | TNO-best |
|---|---|---|---|---|
| Frisby | 0.57* (p = 0.004) | 0.35 (p = 0.089) | 0.43* (p = 0.045) | 0.46* (p = 0.032) |
| Titmus | | 0.42* (p = 0.041) | 0.52* (p = 0.013) | 0.48* (p = 0.025) |
| Randot | | | 0.34 (p = 0.121) | 0.38 (p = 0.081) |
| TNO-worse | | | | 0.56* (p = 0.007) |

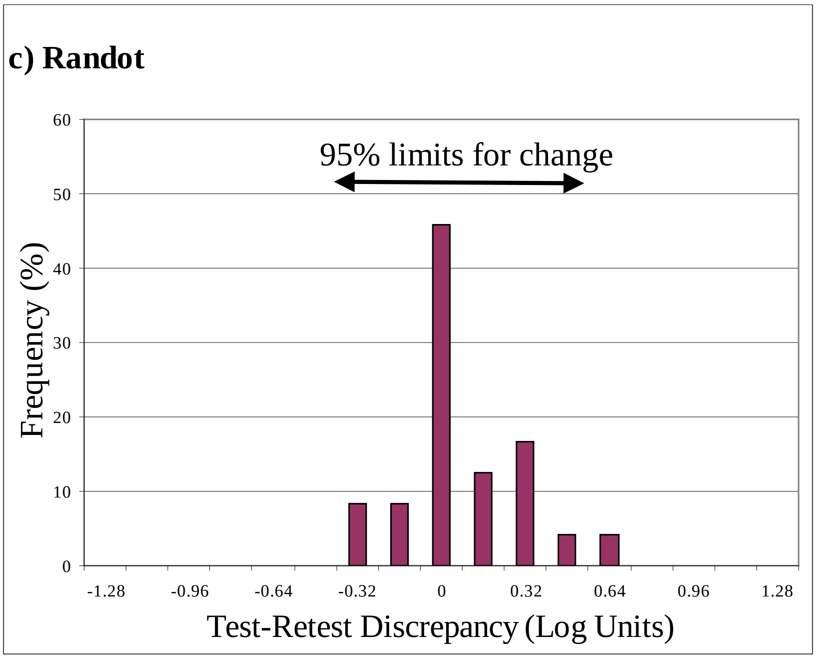
*significant correlation between tests

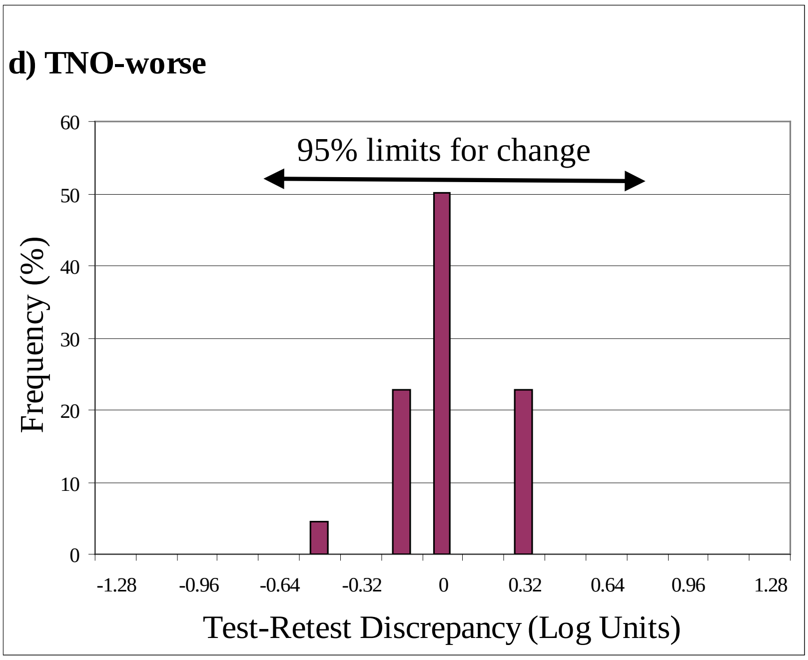


a) Frisby
95% limits for change
Frequency (%)
60
50
40
30
20
10
0
1.28
-0.96
-0.64
-0.32
0
0.32
0.64
0.96
1.28
Test-Retest Discrepancy (Log Units)

b) Titmus
95% limits for change
Frequency (%)
60
50
40
30
20
10
0
-1.28
-0.96
-0.64
-0.32
0
0.32
0.64
0.96
1.28
Test-Retest Discrepancy (Log Units)


c) Randot
95% limits for change
Frequency (%)
60
50
40
30
20
10
0
-1.28
-0.96
-0.64
-0.32
0
0.32
0.64
0.96
1.28
Test-Retest Discrepancy (Log Units)


d) TNO-worse
95% limits for change
Frequency (%)
60
50
40
30
20
10
0
-1.28
-0.96
-0.64
-0.32
0
0.32
0.64
0.96
1.28
Test-Retest Discrepancy (Log Units)

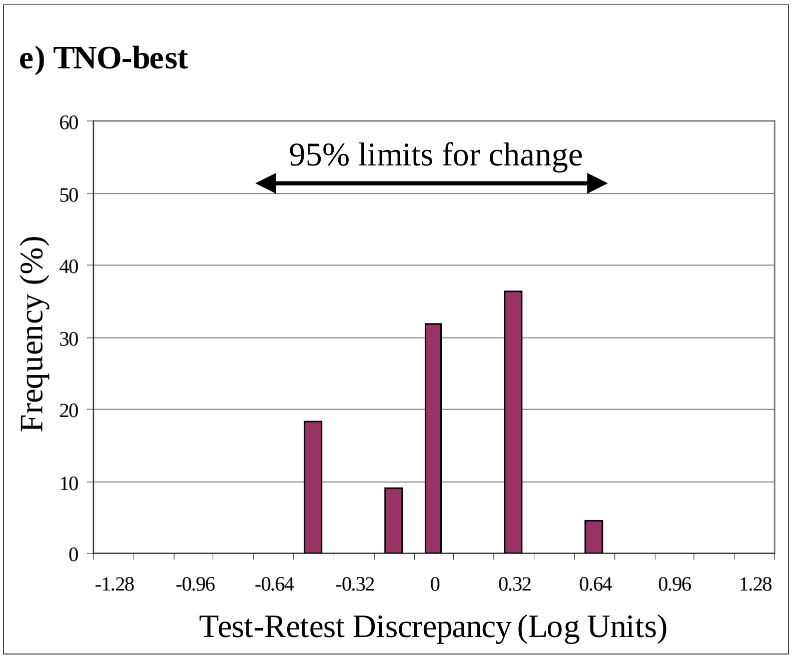
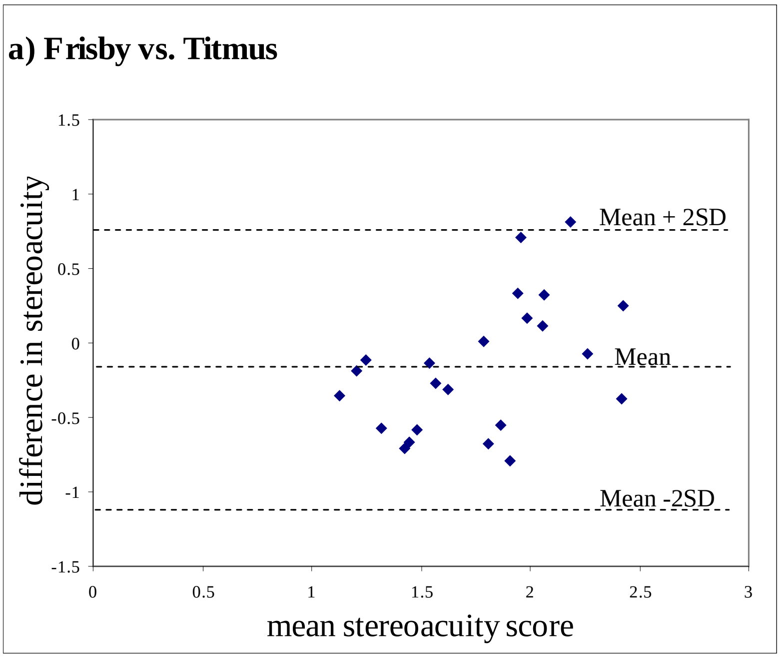
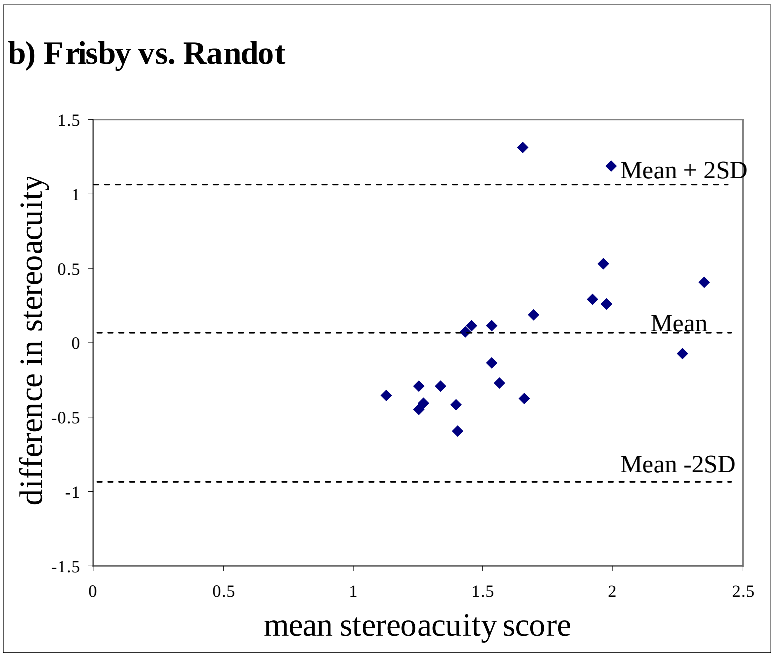
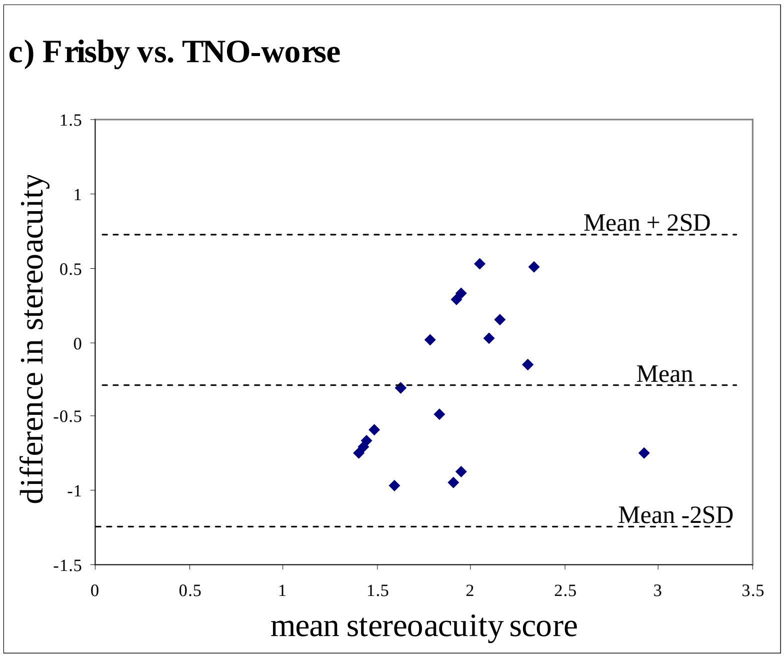
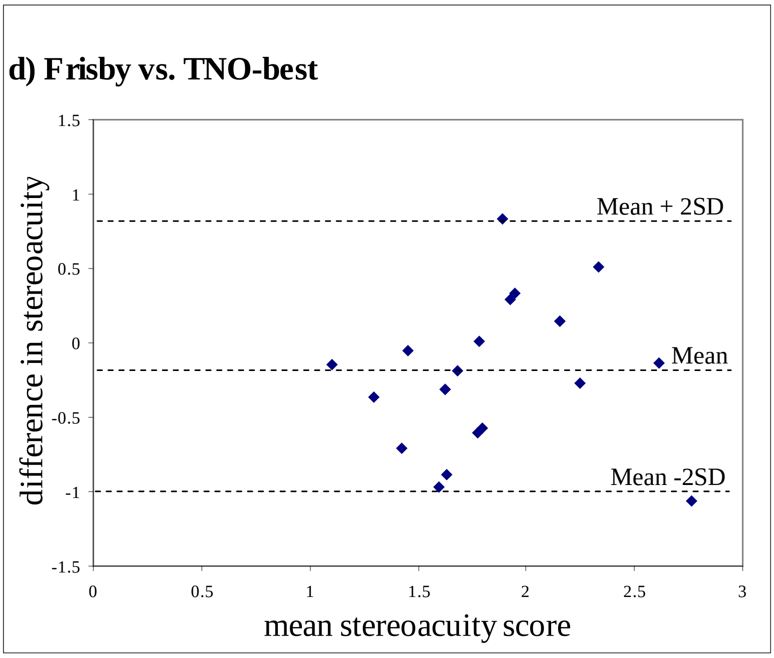


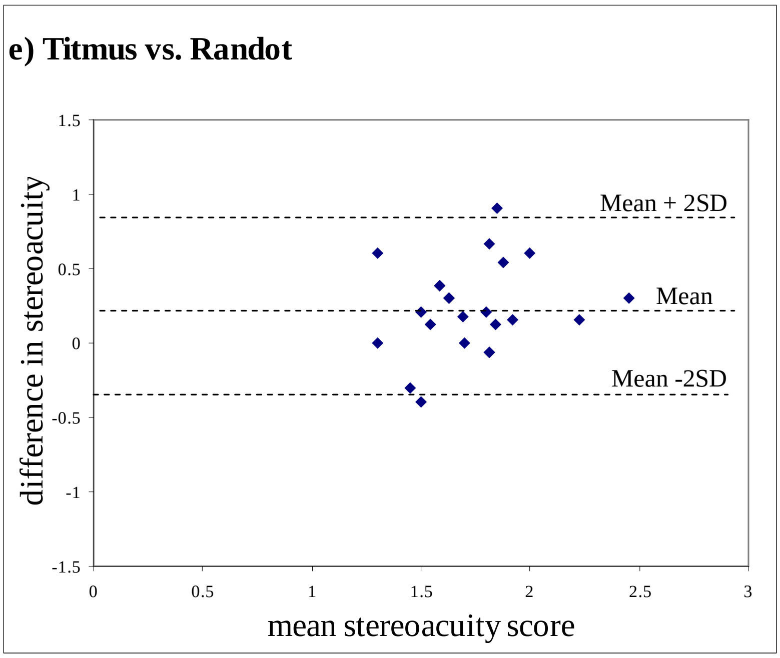

Figure 32. Frequency distribution plots of the discrepancy in Test-Retest data for a) Frisby, b) Titmus, c)Randot, d)TNO-worst and e) TNO-best.



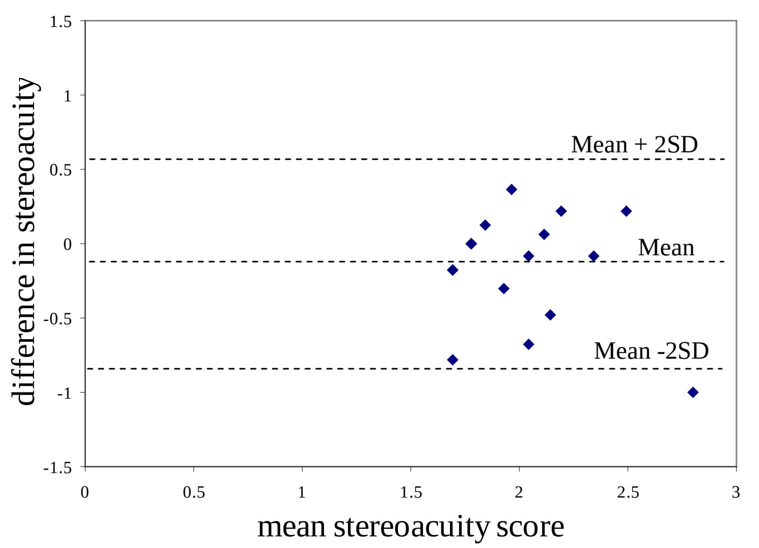

b) Frisby vs. Randot
difference in stereoacuity
mean stereoacuity score
Mean + 2SD
Mean
Mean -2SD
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.5
1
1.5
2
2.5


c) Frisby vs. TNO-worse
difference in stereoacuity
mean stereoacuity score
Mean + 2SD
Mean
Mean -2SD
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.5
1
1.5
2
2.5
3
3.5

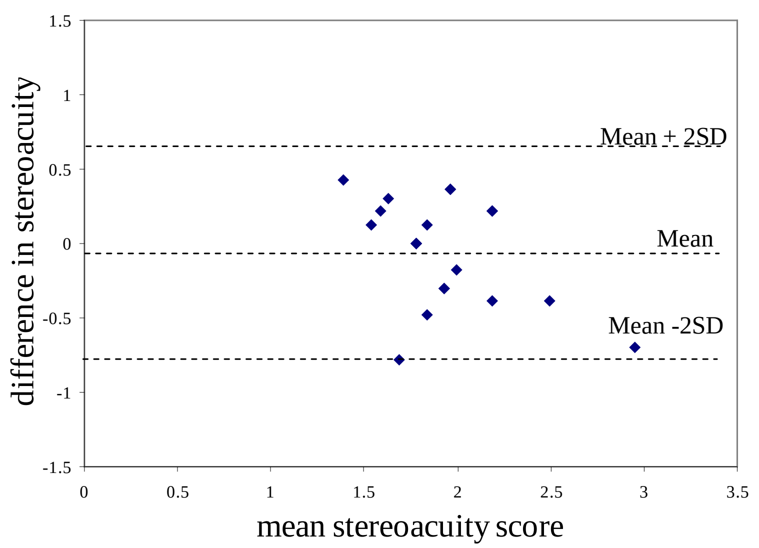

d) Frisby vs. TNO-best
Mean + 2SD
Mean
Mean -2SD
difference in stereoacuity
mean stereoacuity score
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.5
1
1.5
2
2.5
3

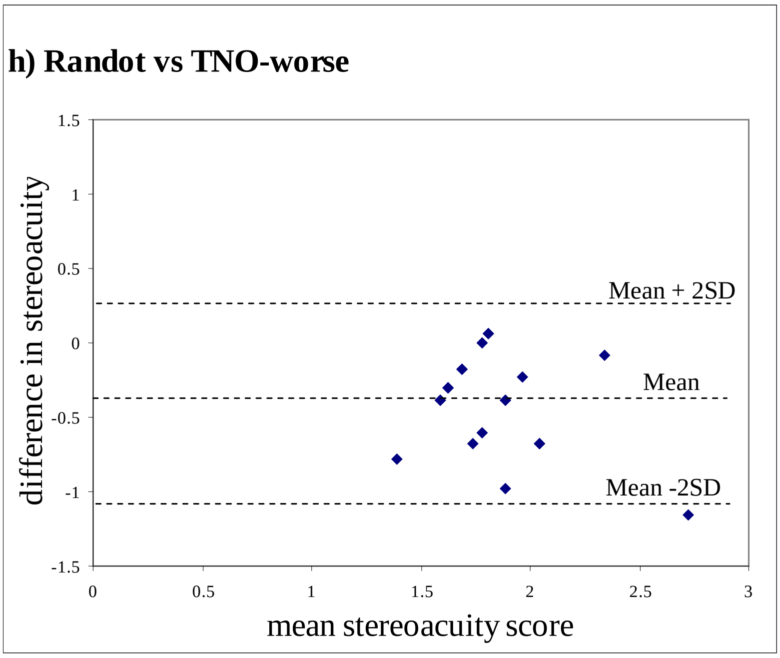

e) Titmus vs. Randot
Mean + 2SD
Mean
Mean -2SD
difference in stereoacuity
mean stereoacuity score
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.5
1
1.5
2
2.5
3

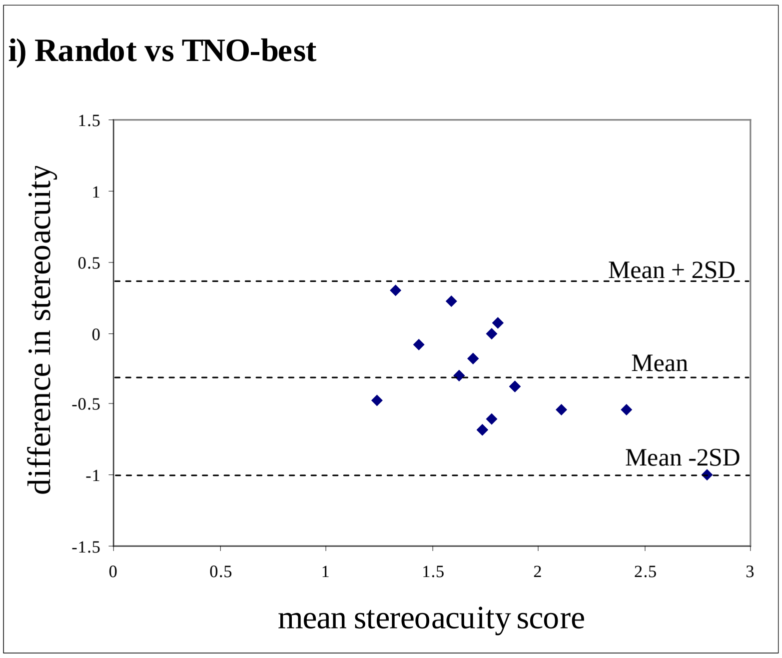
**f) Titmus vs. TNO-worse**




**g) Titmus vs. TNO-best**




h) Randot vs TNO-worse
difference in stereoacuity
mean stereoacuity score
Mean + 2SD
Mean
Mean -2SD
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.5
1
1.5
2
2.5
3


i) Randot vs TNO-best
difference in stereoacuity
mean stereoacuity score
Mean + 2SD
Mean
Mean -2SD
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.5
1
1.5
2
2.5
3

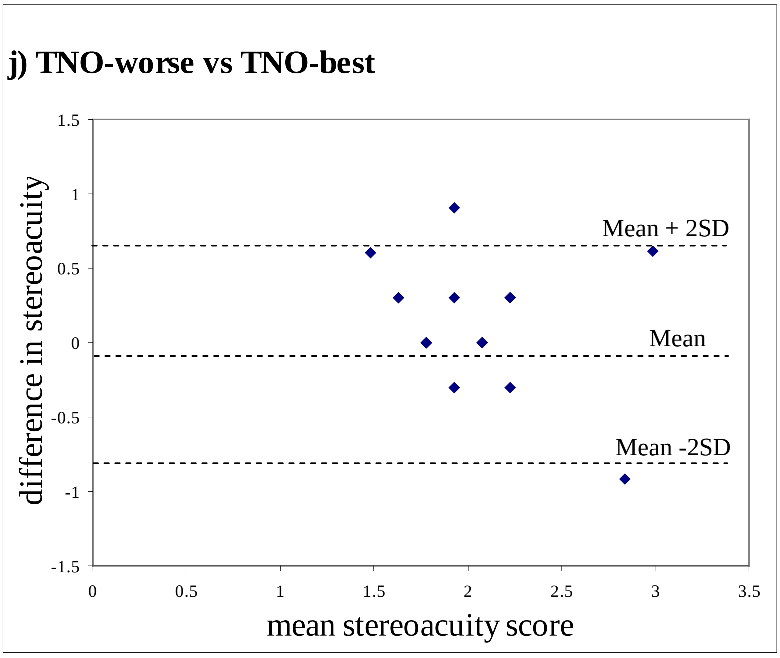



Figure 33. Bland Altman plots of the difference in stereoacuity against the mean stereoacuity (Log Units) for a) Frisby vs. Titmus, b) Frisby vs. Randot, c) Frisby vs. TNO-worse, d) Frisby vs. TNO-best, e) Titmus vs. Randot, f) Titmus vs. TNO-worse, g) Titmus vs. TNO-best, h) Randot vs. TNO-worse, i) Randot vs. TNO-best and j) TNO-worse vs. TNO-best.

The plots (Figures 33a to j) show that the differences between tests do not vary in any systematic way over the range of measurement. Therefore in order to measure the agreement between tests, the mean and standard deviation of the differences were calculated. The differences between tests were normally distributed (Shapiro-Wilk $p>0.05$). The mean difference, which indicates bias and the 95% confidence interval limit can then be calculated from 2 standard deviations of the mean. Table 14 shows the Mean and 95% confidence interval of the differences between the tests.

Table 14. Mean difference and 95% confidence interval between tests (log stereoacuity).

| **Test** | Titmus | Randot | TNO-worse | TNO-best |
|---|---|---|---|---|
| Frisby | -0.16 ± 0.90 | 0.07 ± 0.99 | -0.29 ± 0.96 | -0.20 ± 0.99 |
| Titmus | | 0.23 ± 0.61 | -0.14 ± 0.68 | -0.05 ± 0.70 |
| Randot | | | -0.41 ± 0.66 | -0.32 ± 0.69 |
| TNO-worse | | | | -0.09 ± 0.77 |

There was no significant difference between results for the TNO test over the worse eye compared to the TNO-test over the best eye (Wilcoxon signed Rank, $p = 0.20$).

Binocular visual acuity predicted the score on the Frisby test ($R^2 = 0.18$, $p = 0.039$) as did worse monocular acuity score, ($R^2 = 0.23$, $p = 0.018$) although the difference in monocular acuities ($R^2 = 0.01$, $p = 0.64$) did not.

## 10.4 Discussion

Overall the tests for stereopsis found elderly subjects to have an average stereoacuity of approximately 1.7 log units (50 seconds of arc). This is better than elderly subjects have achieved in other studies (Greene and Madden, 1987, Wright and Wormald, 1992, Haegerstrom-Portnoy et al., 1999, Schneck et al., 2000, Garnham and Sloper, 2006) although comparison is difficult due to differences in age range, exclusion criteria and methodology used for testing (for example some studies have only shown the Frisby plates at one test distance and used a pass fail criterion rather than a measure of absolute threshold, Wright and Wormald, 1992, Haegerstrom-Portnoy et al., 1999). In addition within this study we ensured subjects were corrected for the appropriate test distance and used a high level of task lighting (700 lux).

In contrast to Garnham and Sloper (2006), although the level of stereoacuity was slightly poorer using the TNO stereotests for measurement, there was not the marked discrepancy found in their study in elderly subjects. Garnham and Sloper (2006) found that 5 out of 30 older subjects (aged 50 or above) with normal stereoacuity and good visual acuity in both eyes were only able to see the screening or no plates on the TNO test. This was not the case within this particular study where only 1 of 24 subjects failed to see the screening plates on one presentation of the TNO test.

Decline of stereoacuity with age is a consistent finding in the literature (Jani, 1966, Greene and Madden, 1987, Wright and Wormald, 1992, Brown et al., 1993, Yap et al., 1994, Rubin et al., 1997, Haegerstrom-Portnoy et al., 1999, Schneck et al., 2000, Zaroff et al., 2003, Lee and Koo, 2005, Garnham and Sloper, 2006). However all the above studies have used the patients' habitual spectacle correction, which may underestimate the true value of stereopsis due to high levels of uncorrected ametropia in elderly populations (Wormald et al., 1992, Foran et al., 2002, Evans and Rowlands, 2004) and inappropriate working distance lenses as near addition increases and working distance decreases with age (Millodot and Millodot, 1989) and so may be unsuitable for 40cm testing distance used by most clinical stereotests, especially in women where the working distance is shorter than for men (33cm compared to 37cm in adults aged 43 to 80 years old, Millodot and Millodot, 1989). Uncorrected refractive error or inappropriate working distance may have a greater effect on the TNO stereotest than on other stereotests as it is composed of high spatial frequency targets and refractive blur acts as a low pass filter, selectively attenuating high spatial frequency patterns (Westheimer and McKee, 1980, Wood, 1983). This may explain Garnham and Slopers' results of particularly poor stereoacuity on the TNO test. Within this study we would not expect to repeat this result as appropriate working distance lenses were used and, although subjects did not undergo a subjective refraction for this study and therefore were wearing a habitual prescription all subjects were regular attendees of the University of Bradford Eye Clinic and hence and had a full eye examination, including subjective refraction in the past year. Thus it would be expected that there was a far lower rate of undercorrected refractive error compared to the general elderly population. This is supported by the high level of binocular distance visual acuity (-0.07 logMAR, approximately 6/5 Snellen in the study group) which compares to optimally corrected monocular visual acuity in elderly adults over the age of 75 years (-0.02 LogMAR, Elliott et al., 1995b).

In terms of test-retest reliability the Frisby demonstrated good reliability and 95% limits for change values whilst the other tests performed less well. The TNO has been found to have better test-retest correlation previously (correlation coefficient = 0.91, Jenkins and Curran, 1978), although that was in a young population. The higher values found for 95% limits for change reflect the average step size of the tests, with therefore the TNO scoring poorest. The Titmus and Randot scored similar limits for change, due to similarity of design although the Titmus test had marginally worse limits due to the lower number of steps and consequently slightly higher mean step increment (see Table 12).

In addition to showing the best repeatability, the Frisby does not have to be used with an additional pair of spectacles, making testing easier when subjects are wearing their own spectacles or a trial frame. The main disadvantage of the modified Frisby test is that it is used at a range of distances, and hence in a presbyopic population the working distance needs to be changed for each new working distance. This is also a disadvantage of the Randot and Titmus tests if the range is increased to include stereoacuity of 1 log unit or 1.3 log units respectively. It is of note that when using the Frisby test in a presbyopic population Garnham and Sloper (2006) used the subjects' habitual spectacles and did not use additional working distance lenses. Their argument was that only a few older presbyopic subjects (whose spectacles typically would include lenses suitable for approximately 30- 40cm) had stereoacuity checked at the longer working distance, and that the induced blur at this distance had a minor effect due to the large size of the pattern detail featured on the Frisby stereotest. Appropriate working distance lenses were used throughout in this particular study so it is unclear how only using the patients habitual near correction will affect the repeatability of the test.

It appears that there was no significant effect of whether the red or green filter was worn over the best or worse eye for the TNO, although a difference in median score (20 secs of arc) was found. This differs from young subjects who had amblyopia, where a discrepancy of at least 2:1 in the TNO score was found in over 90% of subjects wearing the red lens over their worst eye, compared to the red lens over their non-amblyopic eye (Simons and Elhatton, 1994). This suggests that the TNO is suitable for use in subjects with no history of strabismus or amblyopia. However this assumes that discrepancy in monocular measurement of visual acuity identified the otherwise visually normal subjects who may be vulnerable to be affected by the artefact in the TNO test, as visual acuity was used to define the worse eye in Simons and Elhatton (1994). However if subjects had good acuity but poor contrast sensitivity then this may influence the results, as it is a difference in contrast that is caused by the differing transmission of the filters.

The stereotests show only moderate correlation or no significant correlation between themselves and much lower correlation than tests of other visual function such as visual acuity measurements (McGraw et al., 2000) and tests of contrast sensitivity (Haymes and Chen, 2004). In addition the Bland-Altman charts demonstrate poor agreement between all tests of stereopsis. Poor correlation between clinical stereotests has been demonstrated previously in adults (Heron et al., 1985) and it has been shown previously that young subjects achieve poorer scores on the Titmus compared to the Randot (Simons, 1981) and therefore, despite the similarities in target and test design it is not surprising to find poor agreement. The reason previously given for the difference in score is due to the contiguous background texture on the Randot, compared to the blank gap surrounding the Titmus target circles. In addition the random elements within the Frisby test are widely spaced which explains why the stereoacuity threshold is found to be slightly higher in the Frisby test, compared to the Randot. The presence of monocular cues, as in those found in Titmus and Randot tests has also been found to improve stereoacuity scores in patients with impaired stereopsis (Frisby et al., 1975) and normal stereoacuity (Simons, 1981), and patients with poor or absent stereoacuity have been found to be able to guess which test circle has disparity from the monocular cues at higher stereoacuity (worse than 2.2 log units of secs of arc, Fawcett and Birch, 2003). The TNO test achieved lower scores of stereoacuity which is likely due to absence of any monocular cues, and difference in tasks to the other tests, where rather than identify the target presented in depth, subjects have to be able to accurately identify the form of the target (Hall, 1982). In addition in order to achieve a score at each level subjects have to correctly identify the shape of both targets. This gives a 16 forced choice alternative task, rather than 4, making subjects less likely to achieve a good score through guesswork. Although poor agreement exists between all tests, the Frisby test shows poorest agreement with the other stereotests (Table 14), which may reflect differences in test design or the use of the modified scoring system.

Both binocular and worst monocular scores were predictors of stereoacuity, although only a weak correlation was found. Although discrepancy in acuity may be expected to be a better predictor of poor stereoacuity, this was not found to be the case, although due to the fact that subjects who could not achieve 0.2 log MAR in either eye were excluded from the study this may be due to the very limited range of visual acuity (Haegerstrom-Portnoy et al., 2000) and VA may be found to be a much better predictor if such stringent exclusion criteria were not applied. In addition other measures of visual function have been found to be a better predictor of stereoacuity score including contrast sensitivity (Greene and Madden, 1987) and other factors such as glare recovery or disability glare may be more important (Schneck et al., 2000).

In conclusion among the five stereotests investigated the Frisby showed the best repeatability whilst the Randot and Titmus were moderately good and TNO tests showed the worst repeatability. Although criticisms aimed at the TNO, including its unsuitability for an elderly population and the presence of an artefact due to the coloured filters were found not to be the case within this study, it is not recommended as a suitable test for quantifying stereoacuity due to poor repeatability and large step sizes. The most appropriate test remains the modified Frisby test. It presents perceptually equal step sizes throughout the range and contains no monocular cues. The Randot stereotest, which has been more frequently used in epidemiological studies (Nevitt et al., 1989, DargentMolina et al., 1996, Ivers et al., 2000, Friedman et al., 2002, Freeman et al., 2007) has been found to have reasonable repeatability compared to other tests, in an elderly population but still may overestimate stereopsis, due to the presence of monocular cues in the test design. In addition is has uneven step sizes, with larger step sizes when measuring poor levels of stereoacuity.

The tests for stereoacuity show poor agreement, making comparison between epidemiological studies that have used different tests difficult. In addition the poor agreement between tests may suggest a difference in what the tests are measuring. As well as differences in test design, some tests measure global (Frisby and TNO) and other tests measure local (Titmus and Randot) stereopsis. It is unclear whether local or global stereopsis is more important as a predictor for falls. For example detecting a step edge may use local stereopsis, if the step edge is well defined with high contrast edges. However identifying the step edge within a pattern (stairs covered in a patterned carpet for example) may use global stereopsis. However studies report that there is no difference in mechanisms that subserve local and global stereopsis (Richards and Kaye, 1974, Blake and Wilson, 1991, Rose and Price, 1995). It has been found previously that both poor global stereopsis (measured using the Frisby test) and poor local stereopsis (measured using Howard-Dolman apparatus) both were found to predict falls in an elderly population (Lord and Dayhew, 2001). The difference between tests may therefore merely be a reflection in the different test design particularly as the tests measuring global stereopsis do not show any closer agreement than when compared to the tests for local stereopsis. Therefore it only appears necessary to use one type of stereotest within a study and based on the findings in this study the modified Frisby remains the gold standard.

# Chapter 11

## Study 6: Does My Step Look Big In This?

A version of this chapter has been accepted for publication as Elliott D. B., Vale A., Buckley J. G. and Whitaker D. Does my step look big in this? A visual illusion leads to safer stepping behaviour. In Press. PLoS ONE

### 11.1 Introduction and Aim

In this study we investigated whether a perceptual illusion, superimposed on to a step, could make the step appear taller and whether any perceptual change would lead to a change in stepping strategy in terms of an increased toe elevation and subsequently increased toe clearance when stepping up onto a stair. A modification to a step that leads to an increase in toe clearance could be a safety strategy against tripping for elderly people. In the previous chapters (chapters 6, 7 and 8) we demonstrated the role of binocular vision in control of adaptive gait when stepping up. In this study we aim to investigate this further by comparing monocular and binocular conditions when a perceptual illusion is used: whether the absence of stereoscopic cues causes more weight to be placed on monocular cues and as a consequence leads to the perceptual causing a greater effect  to perception and control of adaptive gait in monocular conditions. Previous studies investigating the effect of perceptual illusions on reaching and grasping in binocular and monocular conditions are discussed further in section 11.1.5.

### 11.1.1 The Horizontal- Vertical Illusion

The visual pattern chosen to be superimposed on the step was a version of the horizontal-vertical illusion (Avery and Day, 1969) where a vertical line that is bisected by a horizontal line of the same length appears longer by about 10-20% (Avery and Day, 1969, Vishton et al., 1999). This illusion is widely used in fashion and design in that outfits with vertical stripes tend to be promoted as they are thought to enhance perceived height and slenderness.

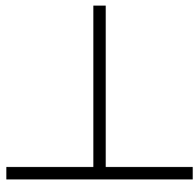


Figure 34. The Horizontal-Vertical Illusion. The vertical line appears longer than the horizontal, but they are the same length.

### 11.1.2 Perception and Action

It is not clear that a change in visual perception of a step should lead to a change in stepping strategy. For example, Aglioti et al (1995) reported that the grasping or prehension action towards a disc placed within the Titchener circles illusion was not scaled to their perceived size, but rather their actual size. They proposed that this dissociation of perception and action supported the proposal of Goodale and Milner (1992) that the mediation of visual “perception” and visuomotor “action” are separated in the visual system in the ventral and dorsal streams respectively. Following this proposal, a large body of literature has arisen that has investigated the link between perceptual illusions and visuomotor actions, typically prehension and pointing. Some studies have replicated Aglioti's original findings and show a dissociation between perception and action (Carey, 2001, Milner and Dyde, 2003, Westwood and Goodale, 2003, McCarville and Westwood, 2006, Ganel et al., 2008, Goodale et al., 2008), whilst others have not found a dissociation (Franz et al., 2000, Glover and Dixon, 2001, Dassonville and Bala, 2004, Li and Matin, 2005). In addition reviews of the studies have interpreted the studies to draw differing conclusion. For example Franz (2001) concludes that the majority of studies find no dissociation and that studies where dissociation between perception and action have been found is due to inappropriate matching of perceptual and motor tasks, such as in the seminal study by Aglioti et al (1995), where the perceptual task was based on relative judgements of the central discs in the Titchener array, whilst the motor task was based on subjects attending to the absolute judgement of size to a single disc within the array (Aglioti et al., 1995). This criticism is also applied to other studies which have followed Aglioti et al's methodology (Marotta et al., 1998, Haffenden and Goodale, 2000, Haffenden et al., 2001). In addition other studies have not used standard perceptual measures, such as adjusting the size of a comparison figure to match the target, but have measured perceptual judgements using non standard measures, for example estimating the target size by opening the index finger and thumb (Daprati and Gentilucci, 1997, Otto-de Haart et al., 1999, Haffenden and Goodale, 2000, Franz, 2001, Haffenden et al., 2001) which could be argued to be a mimed motor task (Franz, 2001). However Carey (2001) argued that findings can be reconciled with Goodale and Milner's separate pathways theory, and that dissociation is found as long as the motor response is exclusively controlled by the dorsal stream. He argued that the dissociation between perception and action will be found if the visual control of the task occurs in real time, and not following a delay where actions are guided from memory, if the task uses egocentric rather than judgements relative to other targets and if the targets are real three dimensional targets and the actions represent an actual rather than mimed task and finally when the task provides some cues to peripheral vision (Carey, 2001).

In the following sections the studies that have investigated the following key effects are explored in more detail.

### 11.1.3 Egocentric vs. Allocentric

Egocentric frame of reference refers to when judgements are based on the target relative to the viewer, allocentric frame of reference refers to when the components of the target are judged relative to each other (Bruno, 2001). Carey (2001) indicated the importance of using an egocentric frame of reference in order to demonstrate dissociation between perception and action, and Bruno (2001) explored this further in a review of the literature, suggesting that rather than the dissociation occurring between perception and motor tasks it could be dependent on the viewer's frame of reference. For example Vishton et al (1999) reported a dissociation between perception of the horizontal-vertical illusion and grip scaling when subjects were asked to grasp a line in an array, if subjects were asked to perceive a single element of the display, the perceived illusion (that the vertical line was overestimated and the horizontal line underestimated in length) was reduced but matched the grip scaling. Finally grip scaling was affected by the illusion when subjects were asked to reach with three fingers to the points of a triangular figure (Vishton et al., 1999). The dissociation was only present when the frame of reference between the perceptual and motor task did not match i.e. if the perceptual judgement was based on components of the display relative to each and the motor response was based on one part of the array relative to the observer. This interpretation can also explain Franz et al (2000) findings that disputed Aglioti's experiment. If the perceptual judgement in based on one Titchener circle (egocentric) rather than comparison of two Titchener circles (allocentric) then although the perceived effect of the illusion is smaller it matched the motor response to the illusion (Franz et al., 2000).

### 11.1.4 Open Loop vs. Closed Loop

Most studies have used closed loop conditions for the motor task, where the hand could be seen by the subjects as it reached towards the target (Aglioti et al., 1995, Daprati and Gentilucci, 1997, Marotta et al., 1998, Otto-de Haart et al., 1999, Haffenden and Goodale, 2000, Haffenden et al., 2001). In open loop conditions the view of target array is occluded and in these conditions the motor response is influenced by the visual illusion (Gentilucci et al., 1996, Westwood and Goodale, 2003, Meegan et al., 2004). This is consistent across different task and illusion, whether it is the grip aperture when picking up the target in a size contrast illusion (Westwood and Goodale, 2003) or pointing towards the vertex of the Muller Lyer illusion (Gentilucci et al., 1996, Meegan et al., 2004). Reasons given for this loss of dissociation is the real time control of the dorsal stream, where the dorsal stream doesn't have its own memory and as a consequence memory guided actions are controlled from perceptual mechanisms in the ventral stream (Carey, 2001, Westwood and Goodale, 2003). However, closed loop conditions provides online visual feedback to continuously fine tune grip size or finger position, so that the visual illusion tends to have reduced or no influence on the final outcome.

### 11.1.5 Monocular vs. Binocular

It has been suggested that subjects may be more reliant on scene based monocular cues in the absence of binocular cues, and as a consequence be more influenced by a visual illusion for both perceptual and motor responses (Marotta et al., 1998). In addition it has been suggested that the dorsal stream relies on binocular input, so that the loss of binocular cues would cause a loss of dissociation between perception and motor response (Otto-de Haart et al., 1999). In fact the findings of both studies are not in agreement. Marotta et al (1998) found that in the absence of monocular cues the motor system did indeed become more influenced by the visual illusion, whilst the later study found no effect of loss of binocular cues (Otto-de Haart et al., 1999). The main reason given for the discrepancy in findings is that there was no variation in depth of target across trials, in that Marotta et al (1998) varied the height of the targets relative to the subjects and they were unable to scale their grip to the actual size of the target in monocular conditions.

### 11.1.6 Lower Limb Tasks

To date studies that have investigated the effects of visual illusions on motor control of lower limbs have concentrated on tasks where subjects control foot placement on to the illusion and have used the Muller-Lyer illusion (Wraga et al., 2000, Glover and Dixon, 2004, McCarville and Westwood, 2006). Wraga et al (2000) demonstrated dissociation between verbal estimates of a line in the Muller-Lyer configuration and a blind walk of the extent of the line, but only if subjects stood at one end point of the Muller-Lyer configuration for the judgement of the line length and the walking task. If the tasks were repeated offset from the configuration i.e. subjects stood away from the target during the verbal estimate task and walked the estimated length of the target at 90º to the actual target, then no dissociation was found. The importance of egocentric encoding, as shown previously in reaching and grasping tasks (section 11.1.3) was therefore proposed as important for producing the perception-action dissociation in visual control of the lower limbs (Wraga et al., 2000).

Both Glover and Dixon (2004) and McCarville and Westwood (2006) demonstrated that there was a small but significant effect of the Muller-Lyer illusion when subjects were asked to step forward on to the end of the line in either Muller-Lyer configuration in closed loop conditions. The effect of the illusion increased in open loop conditions where vision was occluded just as subjects stepped forward and increased further if there was a time delay of 3 seconds, following occlusion, prior to subjects stepping forward. Of note neither study asked subjects to make perceptual judgement of the lines prior to stepping so it is unclear if there was a large dissociation of perceptual compared to motor judgments of the line length. However, as all subjects positioned themselves at one end of the configuration then this would produce egocentric encoding and hence a dissociation between perceptual and motor judgements would be expected (Wraga et al., 2000). The key finding of all studies is that the importance of experimental conditions replicate previous findings in reaching and grasping studies. This suggests that both upper and lower limb movements depend on a common visuomotor control (Wraga et al., 2000, Glover and Dixon, 2004, McCarville and Westwood, 2006) and the finding is consistent across different lower limb motor tasks, such as a step or a hop (Glover and Dixon, 2004).

The main aim of the study was to determine whether a visual illusion could lead to a safer stepping strategy on a step or stair. Despite this aim, the literature described above suggested that the experimental design hugely favoured finding a dissociation between visual perception and visuomotor action, in that that the perceptual size judgements were egocentric rather than allocentric, the targets were real objects, the action was 'actual' and performed in real time and in closed-loop conditions, with no occlusion of vision during the motor task and the target provided some cues to the peripheral visual system. In addition the actions were highly practised and undertaken with the subject's chosen limb, which can make a finding of dissociation between perception and action more likely (Goodale et al., 2008) and finally the likely locus of the horizontal vertical illusion is deep within the ventral stream and not located in the primary visual cortex V1 whilst it has been suggested that dissociation of perception and action does not occur if the visual illusion used results from early in the visual processing pathway (Milner and Dyde, 2003).

As a result of the experimental setup we therefore hypothesised that the horizontal-vertical illusion would affect the subjects' perception of the step height but there might not be any difference in lead toe elevation or toe clearance of the step leading to a dissociation of perception and action.

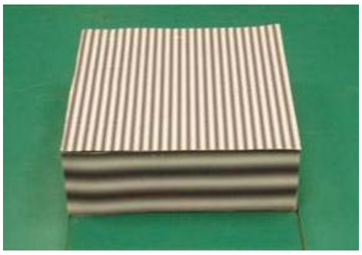
## 11.2 Method

Twenty one young subjects (10 males and 11 females, mean age 28.2 ± 8 years; height 169 ± 12cm; mass, 65.3 ± 12.2kg) as outlined in Section 5.1.1 were recruited for the study.

### 11.2.1 Target

The horizontal-vertical illusion was placed on the step (Section 5.2.1) in one of two configurations. A vertical sine wave (black and white) grating with relatively high spatial frequency (54 cycles per metre) was placed on the front surface (the riser) of the step with a horizontal grating of relatively low spatial frequency (20 cycles per metre) on the top surface of the step (V, figure 35a). The second configuration had the horizontal grating on the riser (H, figure 35b)

a)



b)

Figure 35 a) V configuration and b) H configuration of visual target placed on the step.

### 11.2.2 Protocol

Prior to any data collection subjects were asked to take two steps (one stride length) and then step up on to the step. This determined their starting position and a line was drawn along the laboratory floor so that subject could start at the same point consistently throughout data collection. Starting with their toes behind the starting line, subjects were asked to estimate the height of the step using a sliding scale (0-300mm) held at eye height in the same plane as the step and controlled by the experimenter. A Bekesy staircase method was used in which the scale was increased and decreased until the subjects indicated that it matched the height of the step riser. Subjects were then asked to turn away whilst the target on the step was changed to the opposite configuration. Subjects were asked to repeat the estimation of height in different vision and target conditions. The estimation of each target array was undertaken with subjects' monocular (non dominant eye occluded) and binocular, giving 4 estimations of height in total. The order of the height estimates was randomised for each subject.

Kinematic data were collected using the Vicon MX system (Section 5.3.3) as each subject took two steps (one stride length) and then stepped up onto to the step, remaining stationary on top of the step for a few seconds. Subjects wore their own flat (low heeled) shoes. Markers were worn from the Helen Hayes marker set (Section 5.3.4) but were confined to leg markers only.

To ensure subjects used visual information to determine step height rather than somatosensory feedback from previous trials the height of the step was randomly adjusted by small amounts (-10mm or +5mm) every third trial. No data were collected during the trials using the change of height, but were used to prevent subjects learning the height of the step.  Subjects were advised that the height of the step would be varied throughout the study. Subjects were asked to be consistent with their lead limb throughout the trials and the choice of lead limb was self selected. Subjects completed each trial wearing their habitual correction, either in monocular or binocular conditions and using both target arrays (H or V). An eye patch was worn during the monocular trials. All trials were repeated 5 times giving 20 trials and 6 "dummy trials" where the height of the step was changed. Between each trial subjects were asked to turn away from the step so they could not view how the step was being altered. A member of the research team was positioned near the front edge of the step to ensure that if subjects should trip or stumble they didn't fall.

### 11.2.3 Data Analysis

The analysis focussed on maximum elevation of the lead limb above the step and vertical lead toe clearance over the step edge (Section 7.2.3). Data were analysed using a repeated measures ANOVA (SPSS 15.0) with the level of significance set at $p < 0.05$. Post-Hoc analyses were performed using Bonferroni adjusted pair wise comparisons.

## 11.3 Results

Subjects perceived the step to be higher in the V configuration compared to the H configuration ($p=0.01$), increasing on average by 5.3mm (~4.5% of average perceived height, Figure 36).

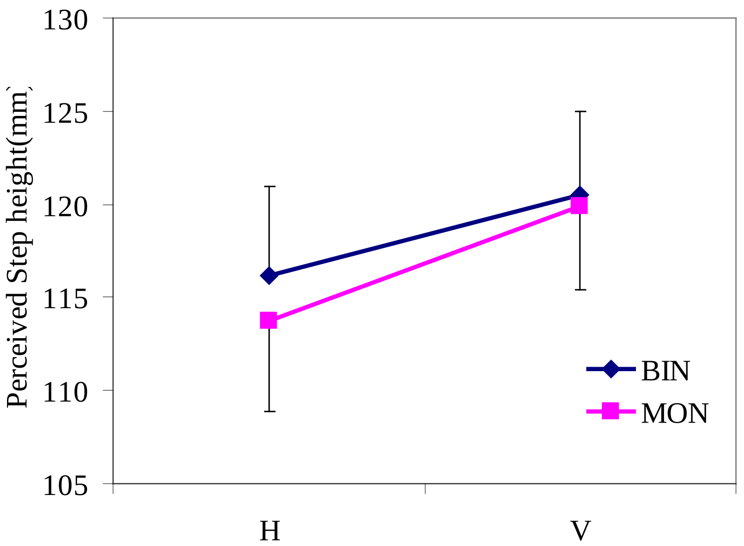



Figure 36. Mean ± 1 SE perceived step height (mm) for H and V target configurations and monocular and binocular vision conditions for 21 young subjects.

There was no difference in the estimation of the height of the step between binocular and monocular vision conditions ($p = 0.35$, Figure 36).

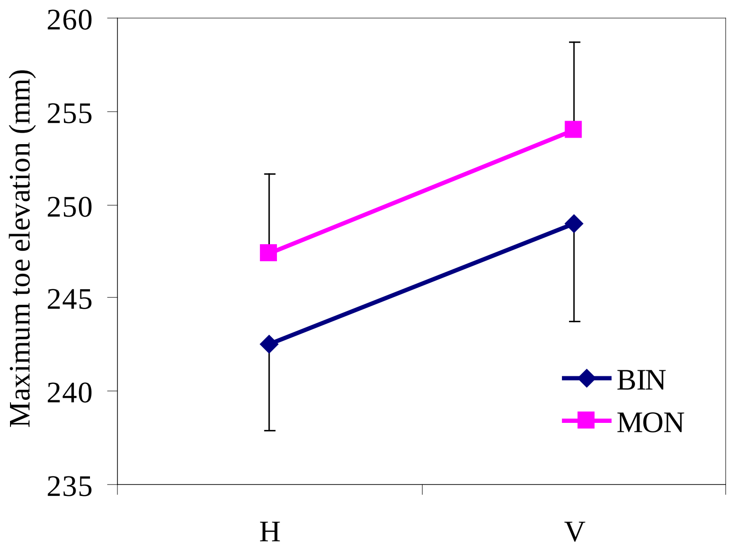



Figure 37. Mean ± 1SE maximum lead toe elevation (mm) for H and V target configurations and monocular and binocular vision conditions for 21 young subjects.

Subjects increased maximum toe elevation in the V configuration compared to the H configuration (Figure 37, $p<0.001$) and toe elevation was greater for both configurations when one eye was occluded ($p=0.003$), but there was no significant interaction ($p=0.49$) Toe elevation decreased with trial repetition ($p = 0.001$), but there were no significant interactions between repetition and vision ($p=0.17$) or repetition and target ($p=0.37$).

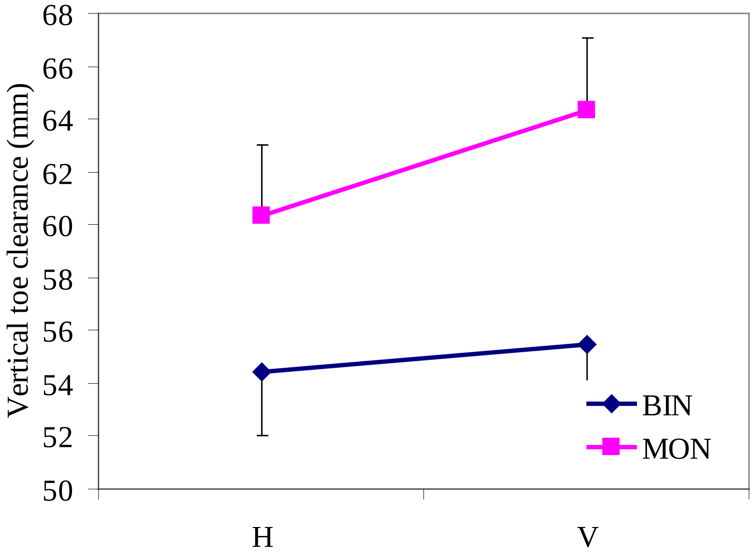



Figure 38. Mean ± 1 SE vertical toe clearance (mm) for H and V target configurations and monocular and binocular vision conditions for 21 young subjects.

Subjects increased vertical lead limb toe clearance in the V configuration compared to the H configuration (Figure 38, p=0.01) and toe clearance was greater for both configurations when one eye was occluded (Figure 38, p<0.001), but there was no significant interaction (p=0.06) Toe clearance decreased with trial repetition (p = 0.001), but there were no significant interactions between target and repetition (p=0.66) and vision and repetition (p=0.37).

As the central nervous system controls maximum toe elevation rather than toe clearance (Maclellan and Patla, 2006) the association between perceived step height and maximum toe elevation was determined to see if there was a link between perception and visuomotor action. The difference between the perceived height of the step in the V and H configurations (Monocular 6.1± 2.2, binocular 4.3 ± 2.2) were similar to the difference between the toe elevation with the V and H configurations (monocular 5.4 ± 1.7, binocular 6.9 ± 1.9) in both binocular (two-tailed paired t-test t= 0.82, p = 0.42) and monocular viewing (t-test t=-0.26, p = 0.79). In addition, linear regression analyses showed highly significant associations between perceived step height and maximum toe elevation in all conditions (V- Binocular $R^2 = 0.31$, $p < 0.01$ Figure 39; V- Monocular $R^2 = 0.30$, $p = 0.01$; H- Binocular $R^2 = 0.36$, $p < 0.01$; H- Monocular $R^2 = 0.26$, $p = 0.02$)

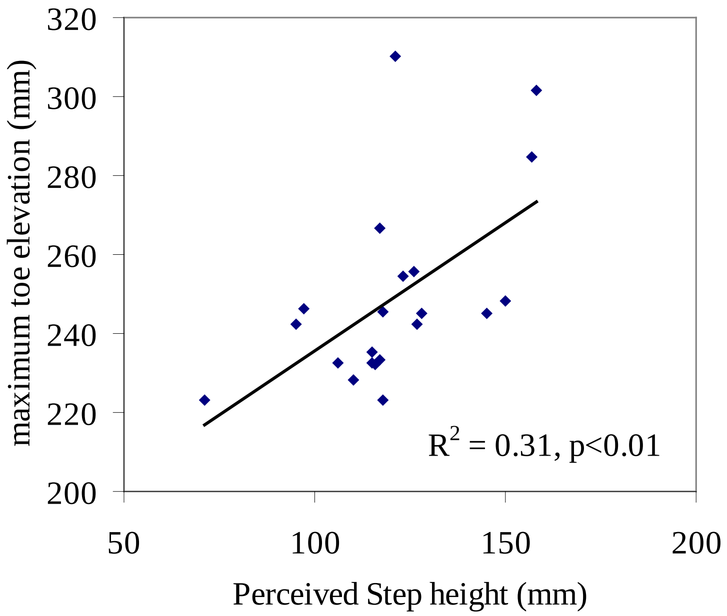



Figure 39. Scatter plot of perceived step height (mm) and maximum lead toe elevation (mm) in the V configuration and binocular vision condition for 21 young subjects.

## 11.4 Discussion

Perception of the height of a step was significantly affected by the vertical-horizontal illusion with the perceived step height being larger when the vertical sine wave grating was placed on the step riser. The average perceived step height of approximately 115mm is similar to the effective height of the step viewed from eye level of 110mm (step height of 152mm viewed from mean two step distance of 1.4m and mean subject height of 1.69m). The mean 4.5% magnitude of the increased perceptual illusion was smaller than that previously reported for the horizontal-vertical illusion (10-20%, Avery and Day, 1969, Vishton et al., 1999). This is most likely a result of the multifactorial nature of the illusory effect, with some factors accentuating the overall magnitude of the illusion, yet others negating it. For example it is likely that the Helmholtz square illusion (Robinson, 1972), where the objects appear to expand in a direction orthogonal to the stripe texture is also present in the illusion used on the step and will work in opposition of the Horizontal-Vertical illusion. In addition within the study step height was based on absolute judgement, rather than relative, in which typically the size of the effects have been found to be smaller (Vishton et al., 1999, Franz et al., 2000).

When subjects stepped up on to the step they lifted their lead foot higher in the V configuration condition compared to the H configuration condition as indicated by an increase in the maximum toe elevation and this led to a greater lead limb vertical toe clearance as the foot passed over the front surface of the step. The amount of increase in the maximum toe elevation in the V configuration compared to the H configuration was similar to the perceived difference in height of the step riser in the two target configurations. These results suggest that the changed perception of step height produced by the horizontal-vertical illusions led to a similar change in action by the lead foot to ensure that the step wasn't hit to avoid tripping and falling. Despite "dummy trials" using different step heights to limit the usefulness of somatosensory feedback from previous trials regarding step height, maximum toe elevation and subsequent toe clearance reduced with repetition. This learning effect of reduced toe clearance is commonly found with repeated stepping trials (Heasley et al., 2004, Heasley et al., 2005, Vale et al., 2008) and also when subjects climb a flight of stairs (Simoneau et al., 1991). There were no interaction effects between step configuration and repetition, suggesting that this learning effect had no bearing on the main outcome measures.

Under monocular conditions there was an increase in toe elevation and vertical toe clearance of the lead limb, irrespective of step configuration. This finding agrees with previous studies investigating negotiation of a raised surface or obstacle within the travel path, which found that binocular vision loss caused subjects to increase lead limb margins of safety due to loss of visual information regarding the height of the step (Chapters 6, 7 and 8, Vale et al., 2008) or obstacle (Patla et al., 2002). However, the results do not demonstrate any difference between binocular and monocular vision in the effect of the horizontal-vertical illusion on perceived step height or toe elevation This agrees with the findings of one study (Otto-de Haart et al., 1999) but disagrees with another that reported grasping actions under monocular conditions were more affected by a visual illusion than under binocular conditions (Marotta et al., 1997).

The strong link between visual perception and visuomotor actions found in this study is contradictory to those that have reported a clear dissociation between perception and action. This is despite the experimental design of the study being significantly in favour of finding dissociation between perception and action as highlighted in the introduction. One explanation may be that stepping tasks are processed in a very different way to other visuomotor tasks such as prehension, although other studies have suggested that a common visuomotor system likely subserves both upper and lower limb movements (Wraga et al., 2000, Glover and Dixon, 2004, McCarville and Westwood, 2006). In addition within this study there was a close match between perceptual and motor tasks, with both based on absolute rather than relative judgements of step height, which agrees with previous findings where no dissociation between perception and action were found (Bruno, 2001, Franz, 2001).

In this study, the gait task was performed in real time in closed-loop conditions and allowed on-line control, in that subjects could use visual feedback throughout the trial. It would therefore be expected that as subjects approached the step they would be able to "fine tune" the appropriate toe elevation and no effect of the target on the motor response would be found. However this is contrast to our findings. Although on-line visual feedback may be used when intended foot placement changes during a step (Reynolds and Day, 2005, Patla and Greig, 2006), as reported in section 3.2.4 in adaptive gait conditions vision is thought to control negotiation of a step or obstacle in the travel path in a feed-forward manner, with subjects typically fixating two steps ahead (Patla and Vickers, 1997). Thus in the present study it is unlikely that on-line visual feedback would have been used as toe elevation would have been planned using feed-forward control. This likely explains why we found both perception and action to be affected by the illusion. It seems reasonable that the original proposal by Goodale and Milner (1992) of two separate and distinct visual streams for visual perception and visuomotor action requires updating as there are clearly links beyond the primary visual cortex between these two streams for some tasks. For example, recent fMRI studies indicate links between the ventral and dorsolateral stream for certain types of prehension movements (Grol et al., 2007, Verhagen et al., 2008).

To summarise, our results indicate that the vertical–horizontal illusion affected perception of step riser height with step height looking relatively taller with vertical gratings on the riser compared to horizontal gratings. During subsequent negotiation of the step, the foot was lifted higher above the step by a corresponding amount, and thus toe clearance was also greater with vertical configuration condition. This could have functional value in making the most dangerous steps, the first and last ones that most people trip over (Templer, 1992) appear taller and generate a higher clearance and this deserves further study.

# Chapter 12

# Discussion of Findings across Thesis and General Conclusions

## 12.1 Summary and Conclusions

The first three studies investigated the effects of acute refractive monocular blur on the negotiation of a raised surface during a single stepping task or during ongoing gait. A consistent finding across all three studies (and therefore in both young and elderly subjects), was that when one eye was blurred or occluded, subjects increased their lead limb toe elevation leading to an increase in vertical toe clearance over the step edge. In addition it was found that blurring of the dominant eye caused a greater reduction in stereoacuity and consequently a greater increase in vertical toe clearance than blurring of the non-dominant eye; although this was only the case in Study 2. The null finding for eye dominance in Studies 1 and 3 may have been due to having a smaller number of participants in these studies, reducing the power of the studies, or, in Study 3, due to fewer subjects demonstrating a clear preference for one eye in the sighting task, which may have negated finding differences between dominant and non-dominant blur conditions. The findings of a significant difference between sighting dominant and non-dominant eyes for Study 2, supports using a sighting test to define the dominant eye.

The increase in vertical toe clearance when one eye (either) was blurred or occluded appears to be a safety based adaptation made by subjects to avoid accidentally striking the edge of the step when visual information regarding the height of the step was uncertain. Horizontal lead limb toe clearance was also consistently found to increase when one eye was blurred or occluded, which suggests that judgment of the horizontal position of the step edge, and not just the height was impaired. Studies 1 and 2 investigated the effect of only one level of blur (+2.00DS) but Study 3 which investigated the effects of different levels of blur (from 0.50 up to 3.00DS) demonstrated that even minimal levels of blur (+0.50DS) caused a significant increase in toe clearance. In addition, there was no difference between toe clearance for the higher levels of blur used and having one eye occluded, suggesting that over a certain level (over 200 seconds of arc) stereoacuity is no longer fine enough to accurately judge the height of a step within the travel path.

Vertical toe clearance decreased with repetition in all studies, which demonstrated that subjects learnt the height of the step, presumably through somatosensory feedback from the lower limbs, despite varying step height across repetitions (Studies 1 and 2) or varying subjects' starting position across repetitions (Study 3). Interestingly, horizontal toe clearance was unaffected by repetition in Study 1 but did decrease with repetition in Study 3. This may be due to the different task employed; in Study 1 subjects stepped up from a stationary position, whilst in Study 3 the step was negotiated during ongoing gait. During ongoing gait horizontal and vertical toe clearance of the raised surface appear to be linked, however, when stepping up from a stationary position it appears subjects independently modified both vertical and horizontal toe clearance in response to blur suggesting, as stated above, that judgement of the horizontal position of the step edge is impaired by monocular blur.

Other consistent changes to adaptive gait caused by acute monocular blur were a decrease in average walking velocity and more time spent in single support. Both these findings are consistent with a more cautious approach, with subjects becoming slower when they were unsure of the position and/or height of the raised surface, and consequently increasing lead limb toe elevation which meant they had a longer lead-limb swing time (i.e. spent more time in single support).

Monocular blur caused a small decline in contrast sensitivity (measured on the Pelli-Robson chart at 2 metres) and was found in Study 3 to cause a decline in both high and low contrast acuity, compared to optimal binocular correction. In all studies, and irrespective of stereotest, monocular refractive blur led to a significant impairment of stereoacuity. Although correlations were not found between the level of stereoacuity and the increase in toe clearance, we propose that it is impairment of stereoacuity that drives the change in adaptive gait for the following reasons: (a) the impairment of visual acuity and contrast sensitivity are significant but small and fall far below the level of impairment found to cause difficulties with mobility (Rubin et al., 1994); and (b) a correlation has previously been found between stereoacuity and toe clearance in cataract patients (Elliott et al., 2000) where the range of stereoacuity within the cataract patients was much greater than the range in our studies for which only one level of blur was used in normal patients, and therefore much less likely to give rise to a significant correlation (Haegerstrom-Portnoy et al., 2000).

Due to differences in methodology, used within the studies, it is difficult to directly compare elderly and young adults' response to monocular blur. For example visual acuity in binocular conditions appeared to show that the elderly had better binocular visual acuity (-0.04 logMAR, Study 3) than young subjects (-0.02 logMAR, Study 2). However this is due to the truncation effect (Chapter 6) of the letter chart at the shorter test distance used in Studies 1 and 2, as elderly subjects have previously been found to have visual acuity similar to this study's findings (-0.02 logMAR) whilst younger subjects were found to have much better acuity (-0.13 logMAR, Elliott et al., 1995b). Stereoacuity measurements again appeared to show that elderly subjects had better stereoacuity (49 secs of arc, Study 3) than young subjects (60 secs of arc, Study 2), in optimally corrected conditions but the difference is due to the tests used (TNO stereotest for young and the Frisby stereotest for elderly subjects) with, as outlined earlier the measurements from different stereotests showing poor agreement (Chapter 10), and the Frisby test typically measuring lower thresholds than the TNO.

The adaptive gait tasks show that elderly subjects were slower than younger subjects (1.0 $ms^{-1}$ compared to 1.13 $ms^{-1}$ average velocity for binocular conditions), which support previous findings indicating elderly individuals are generally found to have slower gait than younger individuals (Chen et al., 1991). In addition, although elderly subjects showed similar vertical toe clearance in binocular conditions compared to young subjects (51 compared to 49mm) they showed a greater increase in toe clearance following the loss of binocular vision (increasing to 64mm in occluded conditions, compared to 57mm for young subjects). Elderly subjects irrespective of visual condition placed their trail foot farther away from the raised surface compared to young subjects (201mm compared to 186mm) which agrees with previous work (Begg and Sparrow, 2000), although the differences in the present thesis between young and elderly adults may have also been due to the variations in starting position used in Study 3 (Chapter 8). Begg and Sparrow (2000) suggested that placing the trail foot farther from the edge combined with a shorter stride length in elderly subjects may result in less latitude regarding where the foot can be safely placed on top of a raised surface, and may therefore be less safe than the strategy used by young subjects, who place their foot closer to the step edge. Trail foot horizontal positioning during obstacle crossing has also been found to increase in elderly subjects compared to young subjects (Chen et al., 1991). However Chen et al (1991) suggested that the increase in trail foot position enabled elderly subjects to increase toe clearance over the obstacle, and meant that if the obstacle was hit by the foot it occurred later in the swing phase, where a trip would be less likely to lead to a fall due to the relative position of the body's CoM.

The differences in toe clearance and foot positioning found in the present thesis between young and elderly adults therefore appear to reflect that older adults increase safety margins to a greater extent than young subjects when visual information in disrupted. This may be because older adults are more concerned about the consequences of a fall than young adults (Chen et al., 1991, McKenzie and Brown, 2004, Heasley et al., 2005). However, this is speculation as no direct comparison between young and elderly subjects was carried out, and thus further work would be needed to confirm this.

Findings for the effect of chronic monocular blur (Study 4), where subjects who were adapted to habitual monovision contact lens correction, for on average 5.4 ± 2.6 years, were asked to undertake the same adaptive gait task as used in Studies 2 and 3, show very different findings from the effects of acute monocular blur. Despite monocular blur due to the monovision contact lens correction still causing an impairment of stereoacuity, compared to binocular distance correction, subjects appeared to show adaptation to monocular blur, as there was no increase in toe clearance in monovision conditions compared to binocular distance correction and subjects demonstrated increased variability of toe clearance when wearing monovision. Although the subjects were slower in their average walking velocity in monovision conditions, suggesting they were still using a somewhat more cautious approach. Overall though the stepping strategy used by patients with chronic monocular blur can be viewed as a riskier strategy that subjects under conditions of acute blur as subjects had impaired stereoacuity and therefore difficultly accurately judging the step height, but did not increase toe clearance to compensate and were more variable, making foot contact with the step edge more likely.

Based on the findings of this thesis, it appears clear that monocular refractive blur, either from acute or chronic monocular blur, causes impairment to stereoacuity and consequently affects adaptive gait. However a review of the epidemiology fall studies shows that there is no consistency on whether poor stereoacuity is a risk factor for falls or hip fracture (Nevitt et al., 1989, Cummings et al., 1995, DargentMolina et al., 1996, Ivers et al., 2000, Lord and Dayhew, 2001, Friedman et al., 2002, Wainwright et al., 2005, Freeman et al., 2007). Although a number of differences in methodology have been identified that may account for this lack of agreement, it may be in part due to the different stereotests used in the different epidemiological studies. The findings from Study 5 in the present thesis show very poor agreement between clinical stereotests. In addition stereotests with larger step sizes (for example the TNO) show very large 95% limits for change, so it is difficult to measure meaningful differences between subjects. The results of Study 5 suggest that the Frisby test should be used in future epidemiology studies, utilising the modified scoring system outlined in Section 5.2.3b, which gives smaller and perceptually equal step sizes and excellent test-retest reliability. This will allow better comparisons between studies and may help establish whether impaired stereoacuity is a consistent risk factor for falls.

The final study in the present thesis (Study 6) investigated if negotiation of a step could be made safer by using a visual illusion (the horizontal-vertical illusion) to cause the step to appear taller and hence result in subjects increasing their toe elevation and toe clearance over the step. In addition it was hypothesised that manipulating the appearance of the step would have a greater effect when one eye was occluded and there was a loss of stereoscopic cues. Due to Goodale and Milner's proposed separation of perception and visual control of action (Goodale and Milner, 1992), and following on from Aglioti et al's (1995) seminal study which found a dissociation between perception and action in response to a visual illusion, it would be expected that the illusion would have no effect on subsequent toe clearance. However, findings revealed that the perceived increase in step height induced by the vertical configuration of the horizontal-vertical illusion led to a comparable increase in toe elevation and toe clearance. In addition, there was no difference between monocular and binocular conditions for the perceived height of the step, although in monocular conditions subjects increased toe clearance of the step, in line with previous findings (studies 1, 2 and 3), but the effect of the illusion on toe elevation was the same for both binocular and monocular conditions. These findings suggest that Goodale and Milner's original proposal of two separate pathways for visual perception and visual control of action may need to be revised. Indeed a review of the literature, along with Study 6 findings, suggests that how visuomotor action was controlled may be a factor. For example when on-line vision is available then the visuomotor action can be "fine tuned" as the hand or foot nears the target, reducing any effect of the visual illusion. In the case of visuomotor control of foot trajectory during adaptive gait, it has been shown that feedforward control is customarily used (Patla and Vickers, 1997, Mohagheghi et al., 2004) which may explain the findings of the study of an effect of the horizontal-vertical illusion on both the perceived height of the step and toe elevation during negotiation of the step.

To conclude, the studies undertaken in this thesis demonstrate that acute monocular blur, caused both young and elderly subjects to adopt a safety strategy of increasing toe clearance and reducing average walking velocity when negotiating a raised surface from either a stationary starting position or during ongoing gait. These findings demonstrate that good binocular vision is important for the control of adaptive gait, and in addition that the magnitude of the effect of monocular blur on adaptive gait is dependent on whether the blur is over the dominant or non-dominant eye (Study 2) and also on the degree of blur (Study 3). This suggests that it is not just the presence or absence of stereopsis that is important in control of foot trajectory during adaptive gait, as found by Patla et al (2000) but that the level of stereoacuity is important in how accurately the position and height of a step is judged and hence how the foot trajectory is controlled by vision. However it appears that the reported changes in adaptive gait under conditions of acute monocular blur do not occur when the monocular blur is chronic, possibly increasing the risk of accidentally hitting the step edge in subjects with chronic monocular blur as their judgement of the step edge may still be impaired but no attempt is made to increase safety margins. Findings suggest that as even low levels of monocular blur can significantly affect adaptive gait, it is important to correct even small changes in refractive error in elderly patients. In addition, findings suggest that greater levels of anisometropia, as might be found in monovision correction lead to changes in adaptive gait equivalent to if one eye is occluded. Therefore caution must be advised in giving elderly patients, particularly those with other risk factors for falling, monovision correction, especially as a permanent outcome following cataract or refractive surgery.

## 12.2 Future Work

Within Study 4 (chapter 9) limitations of the study protocol were outlined. Future work could include a repeat study using an improved study protocol. Firstly the new protocol should have a reduced number of repetitions at the same height and ideally use a platform where the height could be varied randomly by small increments between every trial. If this is not practically possible, the protocol could be adapted to be similar to the protocol used in Study 6, where every few trials, there would be a “dummy” trial where the height of the platform is raised or lowered in order to ensure somatosensory feedback of the step height cannot be relied on, which could cause subjects to be more dependent on vision. In addition when stepping down in Study 4, subjects had the opportunity to learn the step height just by stepping up onto the top of the step prior to the trial commencing. In order to prevent this, a protocol where subjects had to negotiate a series of “stepping stones” of varying heights in order to reach the step could be used, again to disrupt somatosensory learning of the step height. In order to increase the number of study participants, recruitment could expand to include monovision patients from local optometry practices, or to contact patients from laser vision centres who have been given monovision as a refractive surgery outcome. This would be particularly interesting as these patients would be adapted to a constant monovision correction, so may show different findings to those in the contact lens monovision group.

The findings from Study 6 show that young subjects increased toe clearance of the step in the presence of an illusion that caused the step to appear taller. As the rationale for this study was to see if the illusion would act to improve safety by causing increased toe clearance of a step it appears pertinent to assess if elderly subjects respond in the same way as young subjects. The design of the targets used in Study 6 was of relatively high frequency sine wave gratings. It would be interesting to investigate if a similar or even larger perceived response of a taller step could be achieved with a simpler single line target, possible placed at the edges of the step.

Finally, it has been shown that stereopsis declines with age (Jani, 1966, Greene and Madden, 1987, Wright and Wormald, 1992, Brown et al., 1993, Yap et al., 1994, Rubin et al., 1997, Haegerstrom-Portnoy et al., 1999, Schneck et al., 2000, Zaroff et al., 2003, Lee and Koo, 2005, Garnham and Sloper, 2006), but the reasons for this decline are unclear. Measurements of stereoacuity have usually been undertaken with subjects wearing their habitual refraction. However epidemiological studies have shown that many elderly people do not wear an up-to-date refractive correction (Wormald et al., 1992, Foran et al., 2002) and refractive error change is common in elderly patients due to the presence of lens opacities (Brown and Hill, 1987, Pesudovs and Elliott, 2003). Hence the decline in stereoacuity with age may be partially due to uncorrected refractive error. A future study should therefore measure improvements in levels of stereoacuity when elderly subjects are given an optimal refractive correction. The measurements could be carried out within optometry practices, when patients attend for an eye exam using the modified Frisby test as outlined in section 5.2.3b. The study could contribute to findings on why stereoacuity is reduced in elderly patients and, in addition it could provide evidence based advice for optometrists on what level of refractive change is appropriate to prescribe (O'Leary and Evans, 2003).

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# Appendices

## Appendix 1: Studies 1 and 2

**Assessment Sheet** **Subject Number**

**DOB**

**GH** **Meds**

**Eye Height**

**Test Distance**

**Distance PD (mm)**

| **Refraction** | | | |
|---|---|---|---|
| R | VA | L | VA |
| +1.00 Blur | | +1.00 Blur | |

**Cover Test** **With RX** **Without RX**
Distance
Near

**Ocular Motility**

**Dominant Eye** R L No pref

| **Visual Conditions** | **VA (logMar)** | | **CS (PR)** | | **TNO** |
|---|---|---|---|---|---|
| | monoc | binoc | monoc | binoc | |
| Binocular | | | | | |
| Dominant occluded | | | | | |
| +2.00D dominant | | | | | |
| +2.00D non-dominant | | | | | |

Subject Number

| Measurements in cms | Left | Right |
|---|---|---|
| toe marker to tip(V) | | |
| Toe marker to tip (H) | | |
| Ankle | | |
| Knee | | |
| Hand thickness | | |
| Wrist | | |
| Elbow | | |
| Shoulder offset | | |
| Leg length | | |
| foot length | | |
| ASIS | | |
| Height | | |
| Weight | | |

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PROFESSOR DAVID ELLIOTT

# Patient Information Sheet

**Study title:** Effects of impaired depth perception on stepping strategy when stepping up to a new level.

You are invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with friends and relatives if you wish.

**What is the purpose of the study?**
To see what effects impaired depth perception has on stepping strategy when stepping up to new level.

**Why is the study important?**
Because falls due to visual problems are common and have serious consequences including injury and loss of confidence in walking outside the home.

**Why have I been chosen?**
You have been chosen because you are healthy and have normal vision in both eyes

**Do I have to take part?**
It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason. This will not affect the standard of care you receive.

**What will happen to me if I take part?**
You will be asked to visit to make two visits to the Biomechanics Laboratory at the Department of Optometry, University of Bradford (this is within the University campus, off Richmond Road, and NOT within the eye clinic). During your first visit your vision will be tested using various letter charts and depth perception tests. For your second visit you will be asked to wear flat soft-soled shoes, comfortable loose-fitting trousers or shorts and a T-shirt or short sleeved blouse. There will be space available to change in private. You should maintain your usual diet and activity level before your visit.

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You will then be asked to walk along and step up on to a platform and continue walking along a walkway, and to do a step up from a stationary start adjacent to the step. This will be repeated wearing lenses in a trial frame that will blur or occlude one eye. During these tests you will have a number of small shiny markers placed on your clothing and skin and cameras will track your body movements. The visit will take approximately 2.5 hours to complete (including rest periods). You will be given a small amount of money to cover travel expenses.

**Is there any risk of harm to myself?**

There is a very small risk of you losing your balance when performing the physical tests, but we have never had anybody do so after many of these studies. In addition, a research assistant will stand next to you when you perform the tests and will help you (if required) to regain your balance. The eye tests are regularly used by optometrists (opticians) in general practice.

**What should I do if I would like to help with the study?**

Contact, by telephone, any of the researchers listed at the end of this form. Or fill out and return (using the attached SAE) the contact slip given at the end of this form. Alternatively hand the slip in to reception at the Eye Clinic.

The results of this study will be used for research purposes. If published, you will not be mentioned by name.

**Further information**: if you would like more information about the study and what is being asked of you please contact **Dr John Buckley,** or **Mrs Anna Vale,** at the University (tel. 01274 234641 or 236261).

Thank you for reading this information sheet.

**Research Team:**

Dr John Buckley, Research Fellow
Professor David B Elliott, Head of Department and Professor of Clinical Vision Science
Mrs Anna Vale Research Assistant
Dept of Optometry, University of Bradford, Richmond Road, Bradford. BD7 1DP. Telephone: 01274 236587 / 234641.

## CONSENT FORM

**Study title: Effects of impaired depth perception on stepping strategy when stepping up to a new level**

I have read the Patient Information Sheet and have kept a copy **Yes/No**

I have had the opportunity to ask questions and discuss this Study with one of the investigators **Yes/No**

All my questions have received satisfactory answers. **Yes/No**

I have understood the purpose of the Study and know what my involvement will be. **Yes/No**

I do not need any more information now but am free to request it at any time. **Yes/No**

I can refuse to take part in this Study or withdraw at any time without giving a reason and without affecting my medical care.

I agree to take part in the Study. **Yes/No**

SIGNED ……………………… DATE …………………………..

**NAME IN CAPITALS………………………………………………**

**Contact details ………………………………………………………**
**…………………………………………………………………………**

WITNESSED ………………………………. DATE ………………

**Research Team:**
Dr John Buckley, Research Fellow
Professor David B Elliott, Head of Department and Professor of Clinical Vision Science
Mrs Anna Vale Research Assistant
Dept of Optometry, University of Bradford, Richmond Road, Bradford. BD7 1DP. Telephone: 01274 236587 / 234641.

**Appendix 2: Study 3**

## Assessment Sheet

**Subject** **DOB** **M/F**

**GH**

**Meds**

**Dominant eye** **R** **L** **No pref** **PD**

**Spectacle Rx (date / / )**

**R** **L** **Add**

**Visual Assessment**

| | HCVA | | LCVA | | Stereopsis |
|---|---|---|---|---|---|
| NDom occ | | NV NDom | | 0.5 NDom | |
| 1 Dom | | 1 Dom | | 1 NDom | |
| NV NDom | | 0.5 NDom | | Occ Dom | |
| 0.5 Dom | | 1 NDom | | NV NDom | |
| Binoc | | 0.5 Dom | | NV Dom | |
| 0.5 NDom | | NV Dom | | 0.5 Dom | |
| 1 NDom | | Occ Ndom | | 1 Dom | |
| NV Dom | | Binoc | | Binoc | |
| Dom occ | | Occ Dom | | Occ NDom | |

**Mobility Measurements**

Timed up and Go 1 2 Mean

Functional reach 1 2 3 Mean

Plantar sensation R L

Height (cm) Mass (kg)

Eye height (cm)

| | Left | Right |
|---|---|---|
| Leg length (cm) | | |
| Knee width (cm) | | |
| Ankle width (cm) | | |
| 2nd to tip (H) | | |
| 2nd to tip (V) | | |
| Interasis | | |

DEPARTMENT OF OPTOMETRY
HEAD OF DEPARTMENT
PROFESSOR DAVID ELLIOTT

**Patient Information Sheet**

**Study title:** Effects of monocular blur on stepping strategy when negotiating a raised surface.

You are invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with friends and relatives if you wish.

**<u>What is the purpose of the study?</u>**
To see what effects monocular refractive blur, of different levels, has on stepping strategy when negotiating a raised surface.

**<u>Why is the study important?</u>**
Because falls due to visual problems are common and have serious consequences including injury and loss of confidence in walking outside the home.

**<u>Why have I been chosen?</u>**
You have been chosen because you are healthy and have normal vision in both eyes, with no history of a squint or a lazy eye.

**<u>Do I have to take part?</u>**
It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason. This will not affect the standard of care you receive.

**<u>What will happen to me if I take part?</u>**
You will be asked to visit to attend the Biomechanics Laboratory at the Department of Optometry, University of Bradford (this is within the University campus, off Richmond Road, and NOT within the eye clinic). During your visit your vision will be tested using various letter charts and depth perception tests. You will be asked to wear flat soft-soled shoes, comfortable loose-fitting trousers or shorts and a T-shirt or short sleeved blouse. There will be space available to change in private. You should maintain your usual diet and activity level before your visit.

You will then be asked to walk along and step up on to a platform and continue walking along a walkway. This will be repeated wearing lenses in a trial frame that will blur or occlude one eye. During these tests you will have a number of small shiny markers placed on your clothing and skin and cameras will track your body movements. The visit will take approximately 2 hours to complete (including rest periods). You will be given a small amount of money to cover travel expenses.

**Is there any risk of harm to myself?**

There is a very small risk of you losing your balance when performing the physical tests, but we have never had anybody do so after many of these studies. In addition, a research assistant will stand next to you when you perform the tests and will help you (if required) to regain your balance. The eye tests are regularly used by optometrists (opticians) in general practice.

**What should I do if I would like to help with the study?**

Contact, by telephone, any of the researchers listed at the end of this form.

The results of this study will be used for research purposes. If published, you will not be mentioned by name.

**Further information**: if you would like more information about the study and what is being asked of you please contact **Dr John Buckley,** or **Mrs Anna Vale,** at the University (tel. 01274 234641 or 236261 or email Mrs Vale on a.vale@bradford.ac.uk).

Thank you for reading this information sheet.

**Research Team:**
Dr John Buckley, Research Fellow
Dept of Engineering
Professor David B Elliott, Head of Department and Professor of Clinical Vision Science
Mrs Anna Vale Research Assistant
Dept of Optometry, University of Bradford, Richmond Road, Bradford, BD7 1DP.

## CONSENT FORM

**Study title:** Effects of monocular blur on stepping strategy when negotiating a raised surface.

I have read the Patient Information Sheet and have kept a copy **Yes/No**

I have had the opportunity to ask questions and discuss this Study with one of the investigators **Yes/No**

All my questions have received satisfactory answers. **Yes/No**

I have understood the purpose of the Study and know what my involvement will be. **Yes/No**

I do not need any more information now but am free to request it at any time. **Yes/No**

I can refuse to take part in this Study or withdraw at any time without giving a reason and without affecting my medical care.

I agree to take part in the Study. **Yes/No**

SIGNED ……………………… DATE …………………………..

**NAME IN CAPITALS………………………………………………**

**Contact details …………………………………………………………**
**……………………………………………………………………………**

WITNESSED ………………………………. DATE ………………

**Research Team:**
Dr John Buckley, Research Fellow
Dept of Engineering
Professor David B Elliott, Head of Department and Professor of Clinical Vision Science
Mrs Anna Vale Research Assistant
Dept of Optometry, University of Bradford, Richmond Road, Bradford. BD7 1DP. Telephone: 01274 236587 / 234641.

**Appendix 3: Study 4**

**Assessment Sheet**

**Subject** **DOB**

**GH** **Meds** **OH**

**Gender**

**Dominant eye**

**Binocular RX**
R VA L VA
CS CS
Binoc VA
Binoc CS
CT
Stereoacuity (secs of arc)

**Monovision RX**
R VA L VA
CS CS
Binoc VA
Binoc CS
CT
Stereoacuity (secs of arc)

**Mobility Measurements**
Height (cm) Mass (kg)

| | Left | Right |
|---|---|---|
| Leg length (cm) | | |
| Knee width (cm) | | |
| Ankle width (cm) | | |
| 2nd to tip (H) | | |
| 2nd to tip (V) | | |
| Interasis | | |

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PROFESSOR DAVID ELLIOTT

**Patient Information Sheet**

**Study title:** Effects of adapting to monovision on stepping strategy when negotiating a raised surface.

You are invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully.

**What is the purpose of the study?**
To see what effects monovision has on depth perception and stepping strategy when negotiating a raised surface, when stepping up and down.

**Why is the study important?**
Because falls due to visual problems, including loss of depth perception, are common and have serious consequences including injury and loss of confidence in walking outside the home.

**Why have I been chosen?**
You have been chosen because you have worn monovision correction for an extended period (i.e. over 3 months) and are healthy with no significant mobility problems.

**Do I have to take part?**
It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

**What will happen to me if I take part?**
You will be asked to make one visit to the Vision and Mobility Laboratory at the Department of Optometry, University of Bradford (this is within the University campus, off Richmond Road, and NOT within the university eye clinic). During your visit your vision will be tested using various letter charts and depth perception tests. For your mobility trials you will be asked to wear flat soft-soled shoes, shorts or a short skirt and a T-shirt or short sleeved blouse. There will be space available to change in private. You should maintain your usual diet and activity level before your visit.

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For each trial you will then be asked to walk along and step up on to and down from a platform. During these trials you will have a number of small shiny markers placed on your clothing and skin and cameras will track your body movements. The visit should not last more than 2 hours (including rest periods).

**Is there any risk of harm to myself?**

There is a theoretical risk of you losing your balance when performing the physical tests, but we have never had anybody do so after hundreds of trials in previous studies. In addition, a research assistant will stand next to you when you perform the tests and will help you (if required) to regain your balance. The eye tests are regularly used by optometrists (opticians) in general practice and do not require any eye drops.

**What should I do if I would like to help with the study?**

Contact, by telephone or email, either of the researchers listed at the end of this form.

The results of this study will be used for research purposes. If published, you will not be mentioned by name.

**Further information**: if you would like more information about the study and what is being asked of you please contact **Dr John Buckley** or **Mrs Anna Vale** at the University (tel. 01274 234641 or 236261) or email Mrs Vale on a.vale@bradford.ac.uk

Thank you for reading this information sheet.

**Research Team:**
Dr John Buckley, Research Fellow
Professor David B Elliott, Head of Department and Professor of Clinical Vision Science
Mrs Anna Vale Research Assistant
Dept of Optometry, University of Bradford, Richmond Road, Bradford, BD7 1DP.

## CONSENT FORM

**Study title: Effects of adapting to monovision on stepping strategy when stepping up to a new level**

I have read the Patient Information Sheet and have kept a copy **Yes/No**

I have had the opportunity to ask questions and discuss this Study with one of the investigators **Yes/No**

All my questions have received satisfactory answers. **Yes/No**

I have understood the purpose of the Study and know what my involvement will be. **Yes/No**

I do not need any more information now but am free to request it at any time. **Yes/No**

I can refuse to take part in this Study or withdraw at any time without giving a reason and without affecting my medical care.

I agree to take part in the Study. **Yes/No**

SIGNED ……………………… DATE …………………………..

**NAME IN CAPITALS………………………………………………**

**Contact details ………………………………………………………**
**…………………………………………………………………………**

WITNESSED ……………………… DATE ………………………

**Research Team:**
Dr John Buckley, Research Fellow
Professor David B Elliott, Head of Department and Professor of Clinical Vision Science
Mrs Anna Vale Research Assistant
Dept of Optometry, University of Bradford, Richmond Road, Bradford. BD7 1DP. Telephone: 01274 236587 / 234641.

**Appendix 4: Study 5**

## <u>Assessment Sheet</u>

No.

Date

DOB M / F

R VA L VA
BINOC VA

CT with RX Dist Near

| Stereotest | Results |
|---|---|
| TNO | |
| RANDOT | |
| FRISBY | |
| TITMUS | |
| TNO REV | |

---

**Retest**

Date

RVA LVA
Binoc VA

| Stereotest | Results |
|---|---|
| TNO REV | |
| TNO | |
| RANDOT | |
| FRISBY | |
| TITMUS | |

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PROFESSOR DAVID ELLIOTT

## Patient Information Sheet

**Study title:** Stereopsis in the elderly

You are invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully.

**What is the purpose of the study?**
To measure stereopsis (ability to see depth) using different tests in an older population

**Why is the study important?**
Depth perception helps us perform many everyday tasks so it is important to know which clinical tests are most accurate and appropriate to measure depth perception.

**Why have I been chosen?**
You have been chosen because you are of a suitable age and do not have a squint or lazy eye.

**Do I have to take part?**
It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

**What will happen to me if I take part?**
You will be asked to do a series of different tests which measure your depth perception. These tests are routinely used in by optometrists (opticians) in practice. The tests will be repeated when you next attend the eye clinic so we can measure how reliable the different tests are.

**Is there any risk of harm to myself?**
No harm will come to you from taking part in this study. Your name will not appear on the form used by the research team. If published, all data will remain anonymous. However, if you wish to be notified when and where

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the research is published please note it down on the consent form. This will be kept separate from the collected data so it can remain anonymous. You can withdraw from the study at any time.

**Why should I be involved**

You are under no obligation to take part in the study. However your participation will be greatly valued and will contribute to identifying how we can measure depth perception in an older population.

**Further information**: if you would like more information about the study and what is being asked of you please contact **Mrs Anna Vale,** at the University (tel. 01274 234641 or 236261) or email a.vale@bradford.ac.uk

Thank you for reading this information sheet.

**Research Team:**

Dr John Buckley, Research Fellow
Professor David B Elliott, Head of Department and Professor of Clinical Vision Science
Mrs Anna Vale Research Assistant
Dept of Optometry, University of Bradford, Richmond Road, Bradford, BD7 1DP.

## CONSENT FORM

**Study title:** Stereopsis in the elderly

I have read the Patient Information Sheet and have kept a copy **Yes/No**

I have had the opportunity to ask questions and discuss this Study with my optometrist or one of the investigators **Yes/No**

All my questions have received satisfactory answers. **Yes/No**

I have understood the purpose of the Study and know what my involvement will be. **Yes/No**

I do not need any more information now but am free to request it at any time. **Yes/No**

I can refuse to take part in this Study or withdraw at any time without giving a reason and without affecting my medical care.

I agree to take part in the Study. **Yes/No**

I would like to be informed when and where results of the study are published **Yes/No**

SIGNED ……………………… DATE …………………………..

**NAME IN CAPITALS………………………………………………**

**Contact details …………………………………………………………**
**…………………………………………………………………………**

WITNESSED ………………………………. DATE ………………

**Research Team:**
Mrs Anna Vale Research Assistant
Professor David B Elliott, Head of Department and Professor of Clinical Vision Science
Dr John Buckley, Research Fellow
Dept of Optometry, University of Bradford, Richmond Road, Bradford. BD7 1DP. Telephone: 01274 236587 / 234641.

**Appendix 5: Study 6**

## Assessment Sheet

**Subject** **DOB**

**GH** **Meds**

**Distance PD (mm)**

**Current RX (specs/contact lenses)** **Date (if known)**
**R** **L**

**LogMAR VA** **R** **L** **Bin**

**Pelli Robson CS** **R** **L** **Bin**

**TNO (secs of arc)**

**Cover Test (habitual)**
Distance Near

**Ocular Motility**

**Dominant Eye** R L No pref

**Height (cm)** **Eye Height (cm)**

**Mass (kg)**

**2nd toe to floor (mm)** **R** **H** **V**
**L** **H** **V**

| Condition | Estimate of height (mm) |
|---|---|
| VHM | |
| HVB | |
| VHB | |
| CONM | |
| CONB | |
| HVM | |

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HEAD OF DEPARTMENT
PROFESSOR DAVID ELLIOTT

## Patient Information Sheet

**Study title:** Effects of different visual targets on stepping strategy when stepping up to a new level.

You are invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully.

### What is the purpose of the study?

To see what effects visual targets has on stepping strategy when stepping up to new level.

### Why is the study important?

Because falls due to visual problems are common and have serious consequences including injury and loss of confidence in walking outside the home.

### Why have I been chosen?

You have been chosen because you are healthy, with no history of epilepsy or migraine and have normal vision in both eyes

### Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

### What will happen to me if I take part?

You will be asked to visit the Biomechanics Laboratory at the Department of Optometry, University of Bradford (this is within the University campus, off Richmond Road, and NOT within the eye clinic). During your visit your vision will be tested using various letter charts and depth perception tests. You will be asked to wear flat soft-soled shoes. If you wear spectacles or contact lenses the most recent pair should be brought with you. You should maintain your usual diet and activity level before your visit.

You will then be asked to walk along and step up on to a platform. During these tests you will have a number of small shiny markers placed on your shoes and skin and cameras will track your body movements. The visit will take approximately 90 minutes to complete (including rest periods).

**Is there any risk of harm to myself?**

There is a very small risk of you losing your balance when performing the physical tests, but we have never had anybody do so after many of these studies. In addition, a research assistant will stand next to you when you perform the tests and will help you (if required) to regain your balance. The eye tests are regularly used by optometrists (opticians) in general practice.

**What should I do if I would like to help with the study?**

Contact, by telephone or email, any of the researchers listed at the end of this form.

The results of this study will be used for research purposes. If published, you will not be mentioned by name.

**Further information**: if you would like more information about the study and what is being asked of you please contact **Dr John Buckley,** or **Mrs Anna Vale,** at the University (tel. 01274 234641 or 236261) or email a.vale@bradford.ac.uk

Thank you for reading this information sheet.

**Research Team:**

Dr John Buckley, Research Fellow
Professor David B Elliott, Head of Department and Professor of Clinical Vision Science
Mrs Anna Vale Research Assistant
Dept of Optometry, University of Bradford, Richmond Road, Bradford, BD7 1DP.

**CONSENT FORM**

**Study title: Effects of different visual targets on stepping strategy when stepping up to a new level**

I have read the Patient Information Sheet and have kept a copy **Yes/No**

I have had the opportunity to ask questions and discuss this Study with one of the investigators **Yes/No**

All my questions have received satisfactory answers. **Yes/No**

I have understood the purpose of the Study and know what my involvement will be. **Yes/No**

I do not need any more information now but am free to request it at any time. **Yes/No**

I can refuse to take part in this Study or withdraw at any time without giving a reason and without affecting my medical care.

I agree to take part in the Study. **Yes/No**

SIGNED ……………………… DATE …………………………..

**NAME IN CAPITALS………………………………………………**

**Contact details ………………………………………………………**
**…………………………………………………………………………**

WITNESSED ………………………………. DATE ………………

**Research Team:**
Dr John Buckley, Research Fellow
Professor David B Elliott, Head of Department and Professor of Clinical Vision Science
Mrs Anna Vale Research Assistant
Dept of Optometry, University of Bradford, Richmond Road, Bradford. BD7 1DP. Telephone: 01274 236587 / 234641.

THE COLLEGE OF OPTOMETRISTS

Mrs Anna Vale
University of Bradford
Department of Optometry
Richmond Road
Bradford BD7 1DP

29 May 2008

Dear Mrs Vale

**Travel Bursary**

Your application for a Travel Bursary to attend the European Conference on Vision Perception August 2008 was considered by the Research Committee at its recent meeting.

I am pleased to inform you that the Research Committee approved the award of a grant of £400.00.

I trust that you have an enjoyable and profitable visit.

However, before payment can be made I require documentary evidence that your paper had been accepted for presentation. Please send this to Theresa Murtagh at the College.

Please note also that it is a requirement that the College is acknowledged on publication of the research paper.

Yours sincerely

F. Nixon

**Fiona Nixon**
**Director**
**Professional Services**

Appendix 8 Abbrevaitions for Figure 21 (Helen Hayes Marker set)

Abbreviations refer to the location of the body marker

| | |
|---|---|
| RFHD | right forehead |
| LFHD | left forehead |
| RBHD | right backhead |
| LBHD | left backhead |
| CLAV | clavical |
| C7 | cervical spine, $7^{th}$ vertebrae |
| RSHO | right shoulder |
| LSHO | left shoulder |
| STRN | sternum |
| RELB | right elbow |
| LELB | left elbow |
| T10 | thoracic spine, $10^{th}$ vertebrae |
| RASI | right anterior superior iliac spine |
| LASI | left anterior superior iliac spine |
| RPSI | right posterior superior iliac spine |
| LPSI | left posterior superior iliac spine |
| RWRA | right wrist, adjacent to thumb |
| LWRA | left wrist, adjacent to thumb |
| RWRB | right wrist, opposite to thumb |
| LWRB | left wrist, opposite to thumb |
| RTHI | right thigh |
| LTHI | left thigh |
| RKNE | right knee |
| LKNE | left knee |
| RTIB | right tibular |
| LTIB | left tibular |
| RANK | right ankle |
| LANK | left ankle |
| RHEE | right heel |
| LHEE | left heel |
| RTOE | right toe |
| LTOE | left toe |