Vision and Driving After Stroke

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The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Much of the work in Chapter 6 of the thesis will appear in publication as follows: Smith, M., Mole, C.D., Kountouriotis, G.K., Chisholm, C., Bhakta, B. & Wilkie, R.M. (2015) Driving with Homonymous Visual Field Loss: Does Visual Search Performance Predict Hazard Detection? British Journal of Occupational Therapy, special issue on Driving and Community mobility.

This paper reports a subset of the data presented in Chapter 6. I was responsible for carrying out the experimental design, data collection, analyses and write up. The contribution of the other authors was the review and modification of this written work to make good for publication. Callum Mole edited a number of the figures to ensure they were of publishable quality.

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Abstract

Driving a car is often an essential part of maintaining mobility and quality of life, but after a stroke many are forced to cease driving. Homonymous visual field defects (HVFDs) and unilateral spatial neglect (USN) are common sequelae of stroke. For people with HVFDs a legal threshold for extent of field loss exists beyond which a person is not allowed to drive, and most people with clinically detectable USN are also censured from driving. However, some people with HVFDs have been deemed safe to drive, and some with USN have shown normal performance on other skilled visuo-motor tasks. It seems that there is great variation in abilities across individuals with HVFDs and USN, and driving performance cannot be predicted from simple measures such as extent of visual field loss. Several studies have suggested that compensatory eye-movement strategies (particularly saccades into the affected visual field) may be linked with functional improvements post-stroke.

This thesis investigates whether eye-movement behaviours are important for stroke patients performing skilled actions such as driving. To test this theory 18 people with HVFDs and/or USN following a stroke and 18 older adult controls were recruited. A series of behavioural measures were taken using a battery of tests: Cognitive and visuospatial measures from classic pen and paper tasks and visual field mapping, saccadic and smooth pursuit accuracy, visual search, simulated steering and simulated hazard perception measures. Across these measures there was a consistent theme that impairments to perception-action functions varied considerably across participants with stroke, but that some individuals were able to function remarkably well. Compensatory eye movement patterns were observed in many, and driving performance was predicted to some extent by saccadic accuracy and visual search performance. The implications are discussed with respect to using eye-movements as a potential target for rehabilitation treatment.

List of Abbreviations

AC – Adequately Compensated (subgroup of the HVFD group)

IC – Inadequately Compensated (subgroup of the HVFD group)

HH – Homonymous Hemianopia

HVFD – Homonymous Visual Field Defect

LHH – Left Homonymous Hemianopia

LHVFD – Left Homonymous Visual Field Defect

LLQ – Left Lower Quadrant or Left Lower Quadrantanopia

LUQ – Left Upper Quadrant or Left Upper Quadrantanopia

LUSN – Left Unilateral Spatial Neglect

RHH – Right Homonymous Hemianopia

RHVFD – Right Homonymous Visual Field Defect

RLQ – Right Lower Quadrant or Left Lower Quadrantanopia

RT – Reaction Time

RUQ – Right Upper Quadrant or Left Upper Quadrantanopia

RUSN – Right Unilateral Spatial Neglect

UFOV – Useful Field of View (A computer based test of visual attention which has some predictive value for on road driving assessment)

USN – Unilateral Spatial Neglect

VFD – Visual Field Defect

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Chapter 1: Introduction to Homonymous Visual Field Defects and Unilateral Spatial Neglect after Stroke

Each year in the UK, around 110,000 people in England, 4000 in Northern Ireland and 11,000 in Wales will have a stroke (*Facts and Figures about Stroke*, 2012; Scarborough P, 2009). Around 300,000 people in the UK are living with significant disability because of a stroke (Adamson et al., 2004). Whilst this is not the most common cause of disability in the UK, it could be said to be the most common cause of complex disability.

The two most common visual impairments caused by stroke are homonymous visual field defects (HVFDs) and unilateral spatial neglect (USN) (commonly manifesting as unilateral visual inattention). In its purest form, a visual field defect could be seen as a problem with bottom up processing – some of the input data to the visual system is no longer available, but all of the higher processing systems are intact. If this is the case then one could reasonably theorise that the extent of visual disability experienced would depend solely on the extent of visual field loss and its exact location – perhaps in relation to the central part of the visual field. In some tasks such as reading, performance is strongly related to extent of visual field loss (Zihl, 1995a), but in other tasks such as visual search, the extent of visual field loss is less predictive of performance (Poppelreuter, 1917 (Translation Zihl, J 1990); Zihl, 1995b; Gassel and Williams, 1963a). In simulated hemianopia (an example of a pure sensory deficit), people adapt their eye movements to optimise their search strategy and after a small number of iterations, performance is close to that of controls (Simpson et al., 2011). However a proportion of people with HVFDs are unable to make an accurate saccade to a target, even when it's location is already known or can be predicted (and often even when the target is in the unaffected visual hemifield) (Meienberg, 1983; Gassel and Williams, 1963a; Zihl, 1995b). Problems with executing accurate saccades for some people with HVFDs may explain why some such individuals show a disorganised visual scanning pattern and demonstrate poorer performance in visual search, whilst others seem to have efficient compensatory eye movement patterns and superior performance (Zihl, 2000; Poppelreuter, 1917 (Translation Zihl, J 1990)). Some evidence suggests that individuals who fail to compensate may have damage to the pathways that communicate visual information from the striate cortex to other areas of the brain, and these people have problems with visual perception, spatial memory and other 'higher' visual functions that renders them unable to adequately compensate for their visual field loss (Zihl, 1995b; Zihl, 1999). In these circumstances it may be that for visual search tasks, the size and location of the infarct within the brain is the key factor affecting performance, rather than the extent of field loss.

In contrast to homonymous visual field defects, unilateral spatial neglect (USN) could be described as a problem with higher visual processing. In its purest form, spatial neglect is not associated with problems sampling the visual information from the scene (the visual fields are left intact), rather these individuals experience difficulties attending to visual stimuli, or processing information from particular regions of space, and it is this that leads to errors in task performance (Heilman et al., 1984). For problems caused by USN, it is not simple to identify behavioural changes that would effectively compensate for the underlying processing deficits. It is therefore unsurprising that persisting spatial neglect often leads to severe functional disability and rehabilitation is extremely problematic (Buxbaum et al., 2004).

This first Chapter will examine what is currently known about homonymous visual field defects and unilateral spatial neglect – in terms of exactly what components of the visual system are affected, how the brain then adapts and recovers from the insult, how performance in particular tasks is affected and how individuals may compensate for or be rehabilitated from the impairment. Ultimately this thesis is going to examine visual deficits caused by stroke in relation to driving, which is a complex perceptual motor task that is of particular importance to this patient population. The end of this chapter will outline the hypotheses and explain how these will be tested in a series of experimental studies.

1.1 Homonymous Visual Field Defects

1.1.1 Introduction

The cardinal feature of homonymous visual field loss after stroke is an inability to see things in part of the visual field. The visual field loss will be the same for both eyes (Figure 1.1). The deficit can be caused by damage to any part of the postchiasmic optic tract, optic radiation or visual cortex. A single stroke affecting the central optic pathway of the brain will cause homonymous visual field loss within the contralesional visual field. Homonymous visual field deficits are commonly found after stroke with various studies reporting an incidence of between 20% and 67% (Rowe, Dec 2008), although in some instances this may be due to previous stroke or ocular pathology (Rowe et al., 2009).

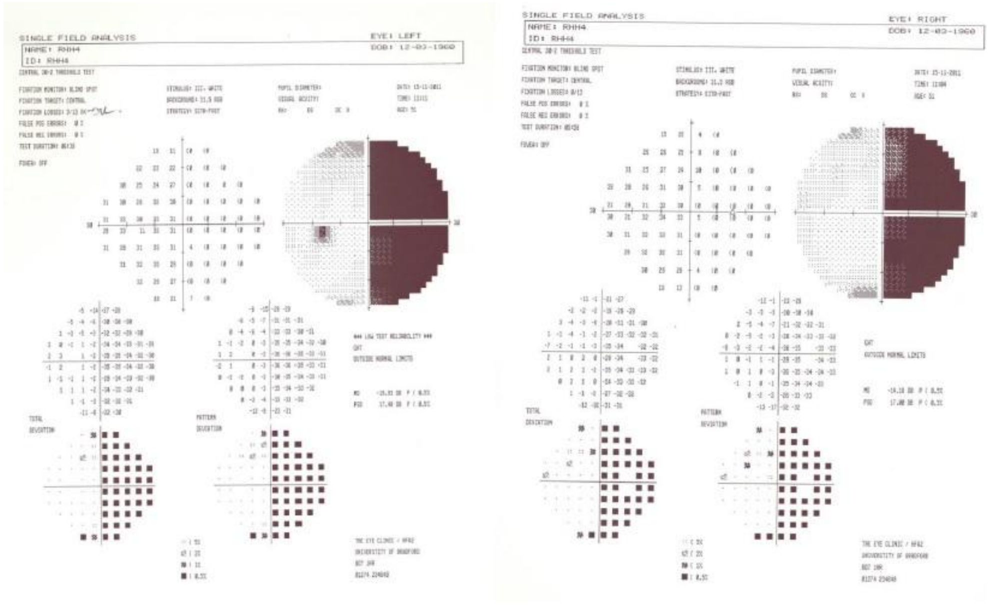

Figure 1.1: Example visual field map for participant RHH4 illustrating that visual field loss is the same in both eyes. Left panel = left eye, right panel = right eye

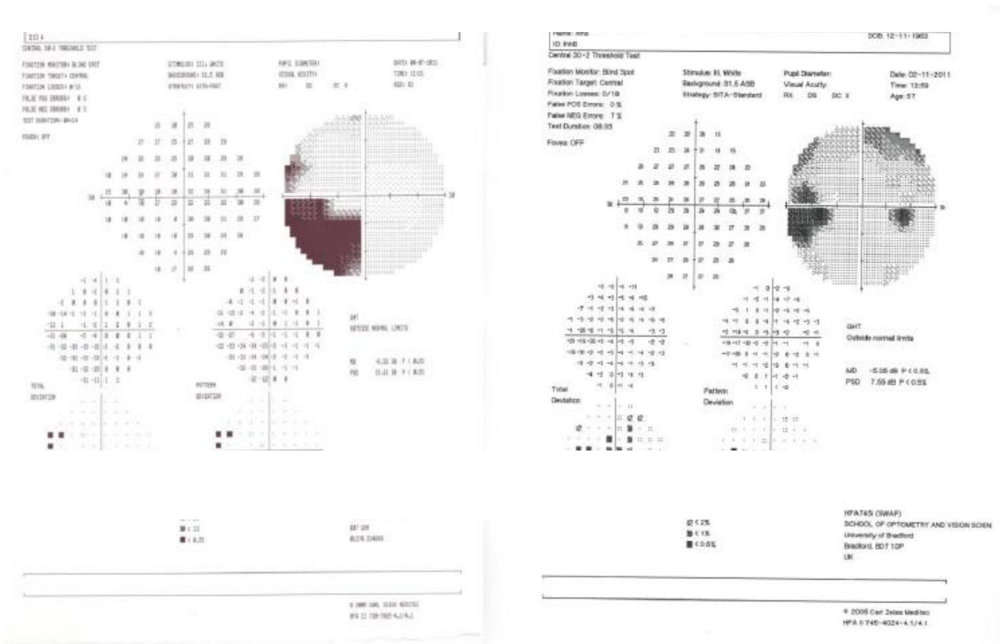

Figure 1.2: Examples of homonymous visual field loss. Left panel = LHH2 with a partial left inferior quadrantanopia. Right panel = LHH6 with a left paracentral scotoma

A wide variety of patterns of visual field loss are seen after stroke (Zihl, 2000). These range from a total hemianopia extending outwards from the vertical midline (Figure 1.1), to an area of field loss in a single quadrant (Figure 1.2, left panel) or a paracentral scotoma (Figure 1.2 right panel). It is also possible for some qualities of vision to be relatively more spared than others – for instance one may have homonymous colour blindness, whilst another may have impaired vision for brightness, but sparing of vision for colour or form.

1.1.2 Foveal Sparing of the Visual Field

It is common for foveal vision to be relatively spared in homonymous visual field loss. Sparing of 5 degrees or more is commonly reported. A comprehensive case series of 413 people with homonymous hemianopia showed that only 34.1% had visual field loss extending to within 2 degrees of the midline (Zihl, 2000).

The anatomy of the primary visual cortex was first mapped out by Tatsuji Inouye working with gunshot survivors in the Russo-Japanese war of 1904-1905. He demonstrated that the occipital pole was the site of foveal vision. Peripheral vision was then represented progressively anteriorly along the cortex. He also showed that foveal vision is represented on a greater volume of cortex than more peripheral areas. His work was translated into English in 2000 (Inouye, 2000). Inouye – like many others before and since him – attributed the presence of sparing of foveal vision to bilateral representation of central vision in the primary visual cortex.

Despite the idea of bilateral representation of foveal vision having been widely discussed through the years, there is very little experimental evidence to support the existence of an ipsilateral visual area in primary visual cortex. Using electrophysiological recordings with anaesthetised squirrel monkeys, Cowey found that visual stimuli in the foveal region did produce a response in some cells ipsilaterally, but that these cells did not form a discrete visual area and the response was small compared with the contralateral side (Cowey, 1967). MRI evidence also suggests that there is no bilateral representation of foveal vision at the occipital poles (Gray et al., 1997). It has also been postulated that there may be bilateral representation of foveal vision on the retina itself. This has been studied by sectioning the optic tract in monkeys and then later staining the eye to look for anterograde degeneration of retinal ganglion cells (Stone et al., 1973). This did show some spared retinal cells on the affected side of the retina but only to within 1 degree of the midline. This phenomenon would not explain therefore the common finding of central sparing of 5 or more degrees. In any case, if foveal vision was bilaterally represented in humans, the common phenomenon of macular splitting hemianopia would be difficult to explain.

It has also been postulated that experimental difficulties in mapping visual fields may explain the apparent presence of macular sparing in homonymous hemianopia. It is certainly true that with standard perimetry, people with homonymous field loss do make small saccades to targets in the ‘blind’ part of the visual field (Sugishita et al., 1993) which could theoretically cause the appearance of macular sparing. Careful testing with tangent point perimetry (where 3 targets lined up vertically move together from the hemianopic visual field towards the intact visual field) has shown that people with homonymous hemianopia detect the target on the horizontal meridian first (Coyle and Milam, 1977) – a finding that is consistent with true macular sparing rather than artefactual macular sparing.

The explanation that best fits the observations of macular vision that is spared from visual field defects seems to be incomplete damage to the primary visual cortex or its connections by the index event. The amount of space taken up by foveal vision on the visual cortex may be approximately 15 times larger than for peripheral vision (Daniel and Whitteridge, 1961). The anatomical pattern of blood supply to the visual cortex is highly variable and a number of variations have been demonstrated whereby blood supply to foveal vision areas at the occipital pole have been separate from, or in addition to, blood supply to the rest of the striate cortex (Walsh and Hoyt, 1969; Smith and Richards.Fg, 1966). A stroke causing a thromboembolus in the main artery supplying striate cortex may therefore spare the foveal visual areas supplied with blood from another source.

1.1.3 Hemianopic Alexia and the Central Visual Field

The central visual field is clearly of particular importance to humans. Any stimulus that we wish to gain more information about we immediately bring into central vision using saccadic eye movements (see Chapter 3). Large areas of the visual cortex are given over to processing central vision (Inouye, 2000). One would therefore expect that someone with a visual field defect extending close to the centre will have greater difficulties with many tasks than someone with a greater degree of central sparing. Tasks such as reading require the fine spatial resolution of the fovea in order to distinguish letter characters, and so are particularly affected by deficits in central vision. Those who struggle with reading because of visual field loss are said to have hemianopic alexia. In 1907, Wilbrand described that people with homonymous visual field defects extending into the central areas of vision show characteristic difficulties with reading. People with left sided field loss typically find it difficult to get back to the start of a line and may omit parts of words at the start of a line. People with right sided field loss may get stuck on a word and find it difficult to move on, often omitting the end of words (Wllbrand, 1907). Ten years later Poppelreuter also observed that during reading, the usual eye movement pattern of stepwise fixations and rightward saccades were disrupted and eye movements were disorganised (Poppelreuter, 1917 (Translation Zihl, J 1990)). A comprehensive study by Zihl using infra red oculography demonstrated clearly that people with left sided field loss predominantly have problems getting back to the start of a line whereas those with right hemianopia had difficulty getting across each line with many saccades back to the left and refixations. Right sided visual field loss was associated with higher numbers of fixations, lower saccadic amplitudes, reduced reading speed and reduced reading accuracy in comparison to left sided visual loss. The amount of central sparing was also strongly associated with improved reading performance (Zihl, 1995a). People with left hemianopia needed around 4 degrees of central sparing for reading performance to be near normal. For people with right sided field loss, reading performance was near normal with 6 degrees of central sparing (Zihl, 1995a). Other studies have found that people with right hemianopia exhibit a larger number of smaller saccades whilst reading along a line compared to those with left hemianopia or controls, with gaze often landing within the same word (McDonald et al., 2006; Trauzettel-Klosinski and Brendler, 1998).

An interesting question is whether the eye movement problems demonstrated by people with hemianopia whilst reading are visually elicited (i.e. occur as a direct consequence of the visual field loss) or whether they occur because of damage to other systems in the brain. In the Zihl study of reading there was a small group of hemianopic participants who showed near normal reading performance with very little central sparing. These participants also appeared to have fairly normal eye movement patterns whilst reading (Zihl, 1995a). MRI evidence has suggested that people with strokes that damage the optic radiation or visual cortex but spare the white matter pathways feeding forward visual information into perceptual and attentional processing structures show a much greater ability to adapt to their field loss with reading and visual search tasks (Zihl, 1995b; Zihl, 1995a). The idea that a reading disability persists because the index cerebral injury has damaged other systems within the brain is given further weight by the fact that people with simulated hemianopia initially show the same abnormal eye movement patterns of someone with homonymous visual field loss, but subsequently adapt quickly and eye movements and reading speed and accuracy return to near normal (Schuett et al., 2009).

1.1.4 Improvement in Homonymous Visual Field Defects

The visual deficits discussed so far have been treated as if they are constant in terms of extent and severity. It is the case, however, that acquired homonymous visual field loss can improve over time. One study of 41 people reported resolution of hemianopia to confrontation in 30% of cases within 8 months (Hier et al., 1983). More detailed studies using perimetry have shown improvements in 16% and 12% of people (Zihl and von Cramon, 1986; Zihl, 1994). Patients with less macular sparing showed much poorer spontaneous improvement over time – perhaps because of more extensive damage from the index event. The amount of recovery was poor even for those who started with more than 10 degrees of central sparing for whom the mean improvement was only 7 degrees (Zihl and von Cramon, 1986; Zihl, 1994).

This finding of poor spontaneous improvement of visual fields (as compared to motor recovery after stroke for instance) suggests that the primary visual cortex has relatively poor plasticity. Certainly during development the visual cortex is quite plastic, but only over a relatively short period. This has been demonstrated by removing visual stimulus to one eye in juvenile mammals (by suturing the eye shut) and then subsequently staining the primary visual cortex with cytochrome oxidase. The visual cortex demonstrates light and dark bands (termed ocular dominance columns as they extend through layers of cortex) corresponding to areas of cortex receiving information from the seeing and blinded eyes respectively. In these studies the light bands are wider than the dark bands indicating that more cortex is given over to processing information from the seeing eye (Hubel and Wiesel, 1963; Hubel and Wiesel, 1977; Wiesel and Hubel, 1963). However in adult humans who lost an eye in adulthood, the ocular dominance columns are of the same width – indicating that visual cortex did not switch to receiving input from the remaining working eye (Adams et al., 2007).

A number of studies have investigated what happens to electrical activity in the corresponding part of the visual cortex if part of the retina of an animal is blinded, for instance by a laser pulse. Kaas et al. (Kaas et al., 1990) reported no change in primary visual cortex spiking activity at all following such a lesion. However when the opposite eye was enucleated to further deprive the visual cortex of input, neurons on the border of the retinal lesion zone began to respond to retinal stimuli adjacent to the lesion. This was the first time that pathological evidence for visual cortex plasticity had been shown. Dendritic sprouting of neurons in the part of the visual cortex deprived of visual stimulus has been witnessed (Dariansmith and Gilbert, 1994) which theoretically could provide a pathway by which information could reach the affected part of the visual cortex. Subsequent studies using monkeys (Heinen and Skavenski, 1991) repeated the findings of electrical activity in de-afferented visual cortex in response to ectopic retinal stimulation binocular lesioning. However the responses to ectopic stimuli were weak, the latency of response was considerably slowed and a diffuse area of retina appeared to produce the responses, casting doubts as to whether the plasticity was likely to be functionally useful in any way. An fMRI study showed no difference at all in activity of de-afferented visual cortex over time again suggesting that any plasticity of the visual cortex is unlikely to be functionally useful (Smirnakis et al., 2005). It is important to say that these findings are not necessarily reproducible since other studies show no change at all in visual cortex electrical activity following damage to the corresponding part of the retina (Chino et al., 1992; Chino et al., 1995; Murakami et al., 1997). Surgically rotating an eye (to cause double vision) also does not appear to cause any reorganisation of the visual cortex (Blakemore et al., 1975; Gordon et al., 1979).

In summary, the evidence indicates that, in mammals, the visual cortex may well be capable of some changes when deprived of sensory input from the retina, but it remains highly doubtful as to whether any functionally useful plasticity occurs. It may be true that de-afferentated visual cortex can, over time, begin to respond to visual stimuli from other parts of the retina. This certainly does not mean that one can see anything from the area of retina that has been lesioned (although the brain may be able to ‘fill in’ missing information through top down processes (Murakami et al., 1997)). Whether any plastic changes occur when areas of the visual cortex (rather than the retina) have been damaged is unknown, although evidence from the effect of visual restitution training provides an important insight into this. The concept of visual restitution training is simple – a person systematically practices perimetry testing using stimuli at the border zone. Several studies initially showed enlargement of the visual field through this practice (Cowey, 1967; Kasten et al., 1998; Zihl and Voncramon, 1985), strongly suggesting that some plasticity of the visual cortex exists. However, when visual fields are mapped more carefully by independent observers using techniques that control for eccentric fixation and saccades away from the fixation point, no improvement in the visual field has ever been demonstrated through visual restitution training (Balliet et al., 1985; Reinhard et al., 2005). Even one of the original studies of visual restitution therapy that reported enlargement of visual fields, did not find improvement in visual field using standard automated perimetry testing (Kasten et al., 1998).

The lack of evidence for plasticity of visual cortex and failure of visual restitution training has led many researchers to investigate whether it is possible to compensate for a HVFD through particular eye movement strategies. Why two people with HVFDs of similar extent can experience very different levels of visual disability is a closely related research question and answering this could potentially open the door to effective visual rehabilitation for those with homonymous visual field loss.

1.1.5 Anosognosia and Homonymous Visual Field Loss

Various studies have shown that it is uncommon for someone with homonymous visual field loss to be able to identify the nature of their deficit accurately (termed anosognosia), with only 12-37% accurately doing so (Bisiach et al., 1986; Celesia et al., 1997; Gassel and Williams, 1963b). It is more common for individuals to describe the deficits as ‘poor’ or ‘slow’ vision or problems with bumping into things rather than as a reduction in the size of the visual field (Critchley, 1949). Levine (Levine, 1990) proposed that the reason for this is that someone with injury to the visual pathway gains no direct sensory experience to allow them to identify the deficit – rather they must work this out from the visual information that they are not receiving and should be. Gassel (Gassel and Williams, 1963b) stated that the area of absence of vision had to be judged from a failure of performance rather than through direct observation. Complicating matters is the simple fact that an object positioned in the direction of the visual field loss relative to a person can easily be observed by moving the eyes to focus on it, which makes the discovery of the hemianopic deficit more difficult. So difficult that many otherwise cognitively intact people, cannot determine the nature of the problem. This can be compared with the response to total blindness where unawareness of the deficit only occurs in people with severe cognitive impairment.

Another source of evidence that can help to better understand anosognosia, is the degree to which people with hemianopia observe object ‘completion’ when only the half of the object lying in the intact visual field is actually displayed (Gassel and Williams, 1963b; Poppelreuter, 1917 (Translation Zihl, J 1990)). Gassel and Williams reported that hemianopic object completion only occurred in people with anosognosia for their deficit (Gassel and Williams, 1963b). Levine theorised that this phenomenon occurs because the person with hemianopia receives no information that the missing part of an object is there or that it is missing. They will therefore report seeing the object that is most likely to have produced that particular pattern of stimulus to his retinas. Object completion can be reduced by showing an incomplete object entirely within the working part of the visual field first – so that the possibility of only half an object is suggested first, reducing the persons expectation that a complete object should be being perceived. People without anosognosia report object completion far less – they are more resistant to suggestion of what should be in their hemianopic visual field as they are well aware that they cannot see into it.

1.1.6 Adaptation to Homonymous Visual Field Defects

Since plasticity of the visual cortex is poor and recovery from homonymous visual field defect is infrequent, the question arises as to whether people can compensate in other ways for their visual field loss. The most obvious way in which this may happen is by the use of frequent saccades into the hemianopic field to gather information about the visual scene there. (Head movements are unlikely to be as effective a compensation strategy. Head movements are usually guided by preceding visual saccades (Uemura et al., 1980) and attempting to reverse the order has an adverse effect on eye head co-ordination (Zangemeister et al., 1982) and visual exploration (Kerkhoff et al., 1992)).

The first documented incidence of spontaneous adaptation to hemianopia through adapting eye movements came from Poppelreuter (Poppelreuter, 1917 (Translation Zihl, J 1990)). In a visual search task, he documented that 7 out of 28 patients with hemianopia were able to complete the visual search task in a comparable time to control patients by using an effective gaze strategy. The other 75% had impaired visual search times and were documented to search the visual scene with 'characteristic clumsiness' and an unsystematically wandering gaze. Furthermore he reported that their eye movements were 'fragmented' with low amplitude saccades and a high number of fixations leading to a laborious search process and slow search times. Most importantly he was unable to find a clear relationship between the visual search time and the severity of hemianopia. Other authors (Zihl, 1995b; Gassel and Williams, 1963a) have found exactly the same pattern of visual search, with a proportion of individuals demonstrating normal search paths and scan times and a seemingly qualitatively separate population with highly abnormal eye movements, search paths and scan times. Hardiess et al (Hardiess et al., 2010) termed these populations as having 'adequately compensated' hemianopia or 'inadequately compensated' hemianopia according to performance on a simple dot counting task. Using a more complex visual search, 'spot the difference' task displayed on a very large screen measuring 120 degrees of visual field, they demonstrated that the adequately compensated population were slightly slower than controls, but were using a series of small saccades to take in a proportion of visual scene, moving the eye to the opposite side and using spatial memory to perform the comparisons. Whilst the inadequately compensated hemianopia group appeared to attempt to perform the task in a similar manner, the inaccurate eye movements and problems with spatial processing and memory meant that compensation attempts broke down and failed.

Evidence from a visual search task (Simpson et al., 2011) using simulated hemianopia with healthy subjects has demonstrated that task performance in this group rapidly improves. Within 5-7 trials, the subject learns to greatly increase the number of fixations into the heminaopic field. Following the initial rapid improvement further steady improvements in search times occur as more efficient search strategies are developed. This gives strong weight to the assertion that homonymous visual field loss, if it exists as a pure sensory phenomenon, should be highly amenable to compensation via eye movement strategies. For those that continue to show poor performance at visual search, it suggests that there is a problem with either the eye movements themselves, or with higher visual processing which prevents adequate compensation.

In hemianopic populations, problems with accurately making a saccade to a target (i.e. saccadic dysmetria) have been reported by several authors (Meienberg et al., 1981; Williams and Gassel, 1962). Zihl performed a simple saccade experiment wherein 125 patients with unilateral homonymous visual field loss performed oscillating horizontal saccades between 2 targets, each situated 10 degrees from the midline: 71% of patients showed saccadic dysmetria (i.e. made errors in accurately hitting the target). Saccadic dysmetria was more common in heminaopia than quadrantanopia or hemiamblyopia. There was no difference in accuracy between left or right sided field loss. Saccades were less accurate travelling into the side with field loss and around 75% of patients showed hypometria (i.e. the saccades fell short of the target). However around one quarter showed saccades that were hypermetric (i.e. fell past the target), and hypermetric saccades were relatively more common when landing in the 'good' hemifield (Zihl, 1995b). Patients with dysmetric saccades showed the characteristic difficulties with visual search (wandering search paths, increased time and decreased accuracy) and also self reported greater disability on a day to day basis (Zihl, 2000). Zihl also suggested that the failure of compensation mechanisms was due to additional damage to other anatomical areas concerned with higher visual processing, including the posterior thalamus or occipitopatietal cortex and their reciprocal white matter connections (Zihl, 1995b; Zihl, 1999).

The possibility that some difficulties in task performance commonly attributed to the sensory failure of HVFDs, actually occur because the stroke caused damage to areas other than primary visual cortex, is supported by the evidence from line bisection tasks. A proportion of people with homonymous hemianopia bisect lines in much the same place as control subjects. However, a distinct proportion of people with hemianopia display a contralesional line bisection bias and it has been suggested by MRI scans that the abnormal line bisecting population have additional damage to occipital or occipitoparietal white matter structures in the brain (Zihl et al., 2009). This line bisection error correlates with a distortion of 'subjective straight ahead' towards the side of the visual field loss which has been reported consistently by several authors (Kerkhoff and Bucher, 2008; Ferber and Karnath, 1999) in many people with homonymous visual field loss.

Several authors have attempted to overcome the problem of inaccurate saccades and inefficient scan paths in visual search, by training people with HVFDs to make systematic, high amplitude saccades into the affected hemifield. The intention was to improve the efficiency of visual search with the hope that the newly learned strategies would generalise to day to day activities. Such oculomotor training has been asserted to reduce response times in visual search (Kerkhoff et al., 1992; Bolognini et al., 2005; Pambakian et al., 2004; Kerkhoff et al., 1994) and to improve subjective and objective measures of activities of daily living as well (Zihl, 1995b; Nelles et al., 2001; Bolognini et al., 2005; Pambakian et al., 2004). However no trial has been controlled and compensatory eye movement strategies have been observed to evolve over time without specific training (Pambakian et al., 2000) so the effectiveness of visual compensation training remains empirically unproven.

1.7 Effect of Homonymous Visual Field Loss on Activities of Daily Living.

It is certainly the experience of clinicians and therapists that HVFDs can have a profound impact on return to independence following a stroke, but data are surprisingly sparse to support this. A study of 95 consecutive stroke rehabilitation admissions compared patients with motor and sensory deficits with or without homonymous visual field loss to determine the probability of regaining functional independence by the point of discharge. The probability of independently walking 50 yards dropped from around 30% for those without a HVFD to around 3% for those with a HVFD. Overall the probability of achieving full independence (modified Barthel >95) was reduced for those with a HVFD (from around 50% to around 10%) and the probability of achieving at least reasonable independence (modified Barthel>60) dropped from around 70% to around 50% (Reding and Potes, 1988). This finding was supported by a later study that indicated hemianopia has a profound effect on functional outcome as demonstrated by Barthel score, Function Independence Measure and the achievement of independence in at least 3 defined activities of daily living (Patel et al., 2000).

There is surprisingly little information available about the kinds of day to day problems that people with HVFDs experience. Self-report measures from one of the HVFD cohorts studied by Zihl indicates problems such as bumping into things and getting lost particularly in unfamiliar environments (Zihl, 2000). These problems seemed to be more common in those with impaired visual search times. Warren examined a convenience sample of 46 people that were referred to an optometry low vision clinic with homonymous visual field loss and no significant inattention or motor deficit. Of these, 41% reported problems with independence in personal hygiene tasks and 13% with self feeding. In terms of instrumental activities of daily living, 94% reported problems with shopping, 89% with managing finances and 50% with meal preparation. Specific problems, such as difficulty reading and disorientation in space seem to be the root of many of the problems reported (Warren, 2009). Specific vision related quality of life scores have been developed and homonymous visual field loss after stroke is strongly associated with a reduction in these scores (Chen et al., 2009; Gall et al., 2009; Papageorgiou et al., 2007). One of the activities of daily living that is particularly relevant for this thesis is driving, for which 98% reported problems with this task. Not only does this highlight that the majority of those with a HVFD feel they have problems driving, but that we need a better understanding of the underlying deficits that impact upon this important activity.

1.1.8 Driving with Homonymous Visual Field Loss after Stroke

In the UK, as in most countries, people with homonymous visual field loss exceeding more than a small portion of the visual field, are censured from driving (Colenbrander and De Laey, 2006). It is possible in the UK to make an ‘exceptional circumstances’ application with a doctors letter to say that one has a ‘fully compensated’ visual field defect and be granted an on-road driving assessment, (although the vast majority of people do not return to driving). It is unknown whether driving with visual field loss after stroke increases crash risk – crashes are rare events and one would need a large sample size and accurate data to assess this. Various attempts have been made to associate crash risk with peripheral visual field loss of any cause (presumably most of the subject group would have had purely ocular conditions). Currently only one study has shown an increase in crash risk associated with reduced visual fields (Johnson and Keltner, 1983), with a number of others showing no clear relationship (Ball et al., 1993; Danielson, 1957; Decina and Staplin, 1993; Owsley et al., 1998).

Whilst it is difficult to gather reliable data about the driving risk for those with HVFDs, it is somewhat easier to determine the impact of visual field loss on driving performance (which can be measured at one point in time either on-road or in a driving simulator). Wood has assessed the simulation of bilateral visual field restriction in otherwise healthy drivers (i.e. to simulate glaucoma) using an in-car assessment on a real closed road. Simulating an extremely narrow field of 20 degrees or 40 degrees produced significant difficulties with peripheral object detection, obstacle avoidance, accuracy whilst reversing and lane position especially whilst cornering – although speed judgement and stopping distance in response to an emerging hazard were unaffected (Wood and Troutbeck, 1992). A more modest restriction of 90 degree fields (which is still substantially less than normal vision) produced surprisingly few problems for drivers (even older participants) –with peripheral awareness of objects being the main domain affected (Wood et al., 1993; Wood and Troutbeck, 1994; Wood and Troutbeck, 1995).

Visual field restriction due to an ocular pathology such as glaucoma is relatively common and a number of studies have looked at both real and simulated driving in these circumstances. It is assumed that ocular pathology will produce only a sensory deficit and any deterioration in performance would be due to the field restrictions alone, rather than because of functional changes to neural circuitry. Lovsund et al. (Lovsund et al., 1991) noted a reduced ability and speed to detect hazards in the affected part of the visual field. A detailed study by Coeckelbergh (Coeckelbergh et al., 2002a) with 87 patients using simulated and on-road driving showed differences between normal subjects and people with visual field loss in a number of driving parameters. People with central field loss tended to reduce their locomotor speed compared to those with mild peripheral field defects – presumably as a compensation mechanism. Even with this slowing there were situations where they tended to leave a smaller gap to the car in front of them compared to the control group indicating a potential problem with gap judgement and ultimately on road safety. Peripheral visual field loss was associated with more boundary crossings and difficulty maintaining lane position. However peripheral visual field loss in most patients led to an increase in scanning eye and head movements as the person attempted to compensate for their field loss. Interestingly, the people who exhibited the most scanning behaviour (and slower driving speed) were the most likely to pass an on-road test. Coeckelbergh also noted a limited association between ability and speed in a computer based dot counting task and ability to pass an on-road driving test (Coeckelbergh et al., 2002b). Bowers (Bowers et al., 2005) examined on-road driving in 28 patients with peripheral visual field loss and noted a correlation between the extent of field loss and driving abilities. On average people with more peripheral field loss showed poorer performance in maintaining lane position, changing lanes, keeping to a path around a bend and anticipating hazards.

The literature examined so far has considered the ‘pure’ effects of visual field loss – either simulated using occluding lenses, or in populations that have particular ocular deficits. Homonymous hemianopia following a stroke may have some relationship with these conditions, but it would not be surprising if additional functional problems were observed. Two studies found that almost all participants with HH following stroke failed an on-road driving assessment (Hartje, 1991; Hannen et al., 1998), however a driving simulator study using 7 people (all of whom had significant macular sparing) showed no differences in driving performance from controls (Schulte et al., 1999). A later on-road study of 20 people (13 with hemianopia, 7 with quadrantanopia) showed that there were large differences between individuals, but that at least some of the participants were safe to drive. Others were deemed potentially safe with further training and assessment (Racette and Casson, 2005). A driving simulator study which used 3 people with hemianopia and neglect and 3 with hemianopia only, highlighted problems for both visually impaired groups with maintaining lane position and stopping times, but overall performance was considered relatively good for the pure hemianopia group (Szlyk et al., 1993). A more recent on-road study with 30 people with homonymous visual field loss showed that the majority (73% with hemianopia and 88% with quadrantanopia) were able to pass an on-road test with only minor errors, despite lower ratings for certain driving skills. For example recurrent problems with maintaining lane position and gap judgement seemed to occur (Elgin et al., 2010), and these problems were more pronounced in those who failed the test (Wood et al., 2009). On average the group with visual field loss drove more slowly and cut corners less, particularly those that failed the test. Those that passed the test made more exploratory head movements into the hemianopic side and held a more stable lane position (Wood et al., 2011). Tant (Tant et al., 2002a) examined 28 people with homonymous hemianopia with a battery of pen and paper visuospatial tests and an on-road driving assessment. All of the patients had been referred for further driving assessment (and therefore not immediately had their licenses returned). Overall only 4 people passed the on-road assessment and performance was poor on average in many domains of driving ability. Importantly however, driving ability was to some extent predicted by age, driving experience, extent of visual field loss and performance on visuo-spatial testing (Tant et al., 2002a). It should be noted that the sampling of the participant population could have a huge influence over the success (or otherwise) of those tested in these studies. Because participants in the Tant study had already been referred for further assessment it is likely that they were exhibiting overt problems with various everyday tasks.

On-road assessments may be the ‘gold-standard’ measure of intact function for the purposes of driving licence retention. As a diagnostic tool for better understanding the root problem underlying driving, however, there may well be much more sensitive quantitative measures. For example Bowers (Bowers et al., 2010) theorised that people with hemianopia would hold a lane position that increased their margin for error on the unsighted side. It is difficult to measure lane position in relation to road properties (such as bends to the left or right) in real world driving. This study examined 6 people with left hemianopia, 6 people with right hemianopia and 12 controls when driving for a 2 hour period in a simulated environment (on the right hand side of the road). Those with right hemianopia drove further to the left on a straight section than controls – and tended not to move rightwards when an oncoming vehicle approached. On rightward curves they were far less inclined to cut the corner than controls, but on left curves their paths were similar to controls. On right turns their position was more rightward than controls. This behaviour would bring more of the opposite side of the road (and any approaching traffic) into their left hemifield. Those with left hemianopia had a similar path to controls on straight sections (although the authors noted that controls tended to adopt a rightward position). When a vehicle approached on the opposite side of the road those with left hemianopia tended to pull further rightwards than controls, and on left turns a more leftward position was adopted (compared to controls)which would bring any approaching traffic more quickly into their intact hemifield. Steering was more variable for hemianopes than controls with more boundary crossings (i.e. entering another lane) – but the majority of boundary crossings occurred on the opposite side to the hemianopia (Bowers et al., 2010). The same group of people with hemianopia were also assessed for their ability to detect pedestrians on the road and reaction time in sounding the horn. Detection rates and reaction times for pedestrians on the blind side were significantly reduced (with large individual differences) both on straight road sections and at intersections – although most were detected within 2.5 seconds (Bowers et al., 2009). Another study assessed 30 patients with homonymous visual field loss and 30 controls navigating a simulated busy intersection at a fixed speed – with the number of collisions as the primary outcome measure. Again a very wide spread of ability was observed in people with hemianopia, but on average the number of collisions was increased against controls – particularly at a higher difficulty level. Both age and the extent of visual field loss were associated with performance (older participant and larger field deficits associated with worse performance), but these factors alone were inadequate to predict performance (Papageorgiou et al., 2012a). Further analysis strongly suggests a link between exploratory head and eye movements and performance in the task – longer saccadic amplitudes, longer scanpaths, more gaze shifts and more fixations on vehicles (rather than the intersection) were associated with better task performance (Papageorgiou et al., 2012b). A study of 17 drivers with hemianopia and 7 drivers with quadrantanopia assessed self reported problems whilst driving via a questionnaire. Difficulties with manoeuvres requiring peripheral vision and independent mobility were most commonly expressed but worryingly the amount of self reported difficulty did not correspond with actual performance on an on-road test (Parker et al., 2011).

In conclusion, driving performance amongst people with homonymous visual field loss is extremely variable. Whilst age and extent of macular sparing may have an effect on performance, these factors alone do not reliably predict driving performance. Some people may drive well enough to be deemed safe in an on-road test even with extensive field loss. Visual field loss almost certainly affects steering stability and often leads to an increase in boundary crossings, but perhaps more importantly it seems to have an effect upon hazard perception too. There is some distinct evidence that driving performance may well correlate with ability to compensate for the visual field loss – through the use of frequent eye or head movements to scan across the visual scene efficiently. This could be important as evidence from eye movement and visual search studies suggest that a sizable proportion of people with homonymous visual field loss have problems with saccade accuracy and also difficulties with effectively using eye movements to perform tasks such as visual search. One could theorise that the people with hemianopia who have difficulty with saccadic accuracy and visual search tasks will also struggle to use compensatory eye movement strategies when driving and therefore perform less well. Testing this theory will form a central part of this thesis.

1.2 Unilateral Spatial Neglect

1.2.1 Introduction

Unilateral spatial neglect (USN) can be described as a person's failure to report, respond to, or orientate towards, novel or meaningful stimuli presented at the side opposite to the lesion (Heilman et al., 1984). These problems have higher severity and prevalence in those with right hemisphere strokes (affecting the left side of space), although the presence of right sided inattention due to a left hemisphere stroke may be masked by additional language impairments (Stone et al., 1993). The deficits described are, in essence, problems with higher functional brain regions since the patient may have no concurrent sensory or motor deficits (e.g. intact visual fields). Bisiach and Luzzatti (Bisiach and Luzzatti, 1978) demonstrated this dissociation in a striking demonstration of representational neglect: two patients with USN who were native to Milan were asked to imagine themselves standing on the steps of the cathedral looking into the city's main square, Piazza del Duomo. They were then asked to name the buildings and features around the square. Both patients named most of the features on the right side of the square and few on the left. The patients were then subsequently asked to imagine themselves on the opposite side of the square looking towards the Cathedral. This time they could name most of the features on the opposite side of the square – which now lay on the right side of their imagined viewpoint. Overall, between both tasks, the patients could recollect most of the square's features, meaning that spatial memory was intact. However, they were only able to access information from the imagined right side of their mental image. Testing imagined space rules out any behavioural interference from sensory deficits such as hemianopia (Bisiach and Luzzatti, 1978). It is important to note, however, that neglect of imagined space seems to be a relatively uncommon feature of neglect. One study showed that only 5 out of 17 patients with left visuospatial neglect showed neglect of imagined space and none of 30 left sided brain damaged patients showed right neglect of imagined space (Bartolomeo et al., 1994).

It appears, therefore, that unilateral spatial neglect is a highly heterogeneous condition. In its most severe form (often immediately after stroke), a person lies with eyes and head deviated to right and ignores any stimulus beyond the midline (Berger et al., 2006). After a period of recovery, a person may be able to hold their eyes and head centred to their midline, but the first appearance of any stimulus on the right side causes an almost immediate 'magnetic attraction' of attention, even if a stimulus is also presented simultaneously on the left side (Gainotti et al., 1991). Other striking manifestations may include the patient with USN thinking that their left limb does not belong to them, only eating food from the right hand side of their plate, or only shaving half of their beard (Unsworth, 2007). In the months after a stroke, the most prominent deficits associated with unilateral neglect may disappear, but neuropsychological testing often still reveals poorer task performance on the affected side (Unsworth, 2007).

A number of theories have been advanced to explain the features of unilateral neglect but there is no consensus as to a unifying explanation and its causal mechanisms (Harley, 1996). A variety of tests have been used to probe the nature of USN. Stone et al. (Stone et al., 1993) used a test battery to assess stroke unit admissions with confirmed stroke, 2-3 days post stroke (69 right hemisphere, 102 left hemisphere strokes). Visual neglect phenomena were found on testing in 82% of right brain and 65% of left brain strokes. Personal hemi-inattention was found in 70% of right and 49% of left brain strokes. Tactile extinction was found in 65% of right and 35% of left brain strokes and visual extinction in 23% of right and 2% of left brain strokes (Stone et al., 1993). These tests all highlight that right hemisphere strokes are more likely to lead to visual neglect phenomena. Azouvi et al. performed a visuo spatial test battery on 206 patients with right hemispheric stroke – including Bells test, line bisection, overlapping figures, clock drawing and text reading: 85% of patients had at least one abnormal test, but importantly each of the tests showed relatively high degrees of independence from each other (Azouvi et al., 2002), reflecting the heterogeneity of presentations of spatial neglect.

Visual field defects (as introduced in Section 1.1) often are strictly delineated by quadrants or hemifields (with potentially some sparing of central vision). In contrast visual neglect seems to be a phenomenon with far less distinct boundaries, and with no particular respect for the vertical midline. In left USN the chance of reporting a target diminish as a number of properties are changed, when: the target moves further left, the number of distracters increases, the complexity of distracters increases and the further right the distracters are placed (Kaplan et al., 1991). If the timing and location of target appearance is made more predictable then accuracy and speed of response will improve for both left and right visual fields, but the relative difference between the two sides does not change. This suggests that attention can be cued towards the side of the neglect, but that the neurological deficit cannot be overcome voluntarily (Smania et al., 1998).

Although a stimulus presented to the affected side of a person with hemineglect may go unreported, it may still be processed. In one study, patients with severe hemineglect were asked to categorise pictures shown on the right side of the visual field as quickly as possible. On some trials, a priming stimulus was first briefly presented on the opposite side of the screen. This priming stimulus could be incongruent, congruent or highly congruent to the target stimulus. Speed of identification increased with congruency, even when the presence of a priming stimulus was denied by the participant (Berti and Rizzolatti, 1992). These findings emphasise that there is a considerable degree of visual processing occurring, and it is high-level attentional problems that are cause the observed deficits.

1.2.2 Components of Unilateral Spatial Neglect

A range of different cognitive deficits may be observed in unilateral spatial neglect patients, and these deficits often dissociate from each other: it is quite possible for two people with spatial neglect not to share any particular deficit (Vallar, 1998). Most commonly people will exhibit a combination of deficits, but the combinations vary between patients (Buxbaum et al., 2004). This fact supports the idea that unilateral neglect is not a discrete phenomenon with a single overarching cause, but manifestations of neglect result from damage to nodes within, or connections between, a diffuse network of brain areas involved with spatial and attentional processing. With these caveats in mind, it is still possible (and useful) to identify specific deficits observed in people with spatial neglect and place them into various categories. The following sections present the main deficits observed in those with spatial neglect.

1.2.2.1 An attentional spatial bias towards the side of the lesion

Often, the most clearly observable deficit in left neglect is that a person will attend to right-sided stimuli quicker and more readily than left-sided stimuli (Gainotti et al., 1991). This is exemplified in a phenomenon known as ‘extinction’:

only right-side stimuli are reported when stimuli are presented bilaterally. This observation suggests that a key deficit in neglect syndromes is attentional bias towards the ipsilesional side.

The attentional system is usually conceptualised as a network of brain systems whose role is to maintain coherent behaviour by maintaining attention to goal-relevant stimuli whilst ignoring distractions. Attention can be ‘cued’: Posner et al. (Posner, 1980) demonstrated that object identification reaction times are improved if the object is preceded by a cue in the same visual hemifield (such as a brightening of the box in which it will appear). If the cue is in the opposite hemifield, reaction times are slowed, and the slowing happens even when the eyes and head do not orientate toward the cue – i.e. attentional orienting is covert (Posner, 1980). Section 1.1.6 introduced the importance of eye-movements for sampling useful visual information from the scene. The primary reason for moving the eye is because visual acuity is greatest at the fovea, and the visual system moves the eye to maximise the quality of data sampled, by foveating the object of interest. This is the reason why attending to an object is usually synonymous with looking at the object. It is also the reason behind the “visual grasp reflex”, whereby the sudden appearance of a peripheral object elicits involuntary eye and head movements in order to bring the object into the fovea (Fletcher and Sharpe, 1986). Neglect phenomena seem to be more dramatic and common in the visual domain compared to auditory, tactile or imagined stimuli (Stone et al., 1993; Fujii et al., 1991; Hjaltason et al., 1993). This is possibly because other sensory modalities (e.g. audition and touch) do not have the same high-acuity focal point linked to attentional orientation mechanisms. It seems likely, therefore, that a key feature of neglect is disturbance to attentional orientation rather than a general bias to the spatial world (i.e. one would expect that all sensory modalities would be affected equally by a shift in egocentric frame of reference).

People with left unilateral neglect typically orientate to right-sided objects more easily and quickly than left-sided objects. This preferential attention often seems to form a gradient from left to right: In a simple visual search task (searching for targets embedded in distracters), a person with USN would be expected to make many fixations to the far right, with progressively fewer fixations moving leftwards across the screen, with almost none left of the centre (Husain et al., 2001). Kinsbourne has long proposed an ‘opponent processor’ model of spatial attention wherein each cerebral hemisphere shifts attention towards the opposite side by inhibiting the opposite cerebral hemisphere. According to this model, healthy humans have a slight but significant tendency to orientate attention rightwards and Kinsbourne theorised that the left cerebral hemisphere has a stronger spatial orientating ability than the right. Right sided brain damage tends to further exacerbate this rightward bias, giving rise to left neglect syndromes. Right neglect is a rarer phenomenon because any downregulation of the right hemisphere is likely to first balance out the physiological rightward attention bias, before manifesting as right neglect if damage is sufficiently severe (Kinsbourne, 1993). This proposal does not match experimental findings that, during visual search, people with left spatial neglect make a peak number of fixations some way right of centre, but not at the extreme edges (Behrmann et al., 1997) as one might expect if the opponent processor model were true

1.2.2.2 Ipsilesional objects winning the contest for attentional selection

There is evidence that the neural architecture of humans is structured to support attention being oriented towards objects rather than areas of space. For instance, people can report two features of one object more easily than one feature of two objects, even if the objects lie in the same region of space (Duncan, 1984). Findlay and Walker proposed the concept of ‘salience maps’ whereby peripheral detection mechanisms in the brain identify all of the features in the perceived environment and then attentional selection of the most salient takes place through a ‘winner takes all’ competition (Findlay and Walker, 1999). In left neglect syndromes it is proposed that the salience of rightward objects is greater than leftward objects due to dampened peripheral detection mechanisms. Objects on the left therefore do not win the competition for attentional selection and are not looked at. An elegant experiment by Mark et al. (Mark et al., 1988) supports this idea. Using a whiteboard on which a number of horizontal lines were drawn, participants were asked either to draw a line through the horizontal lines, or erase the horizontal lines. As would be expected the vast majority of participants with left neglect started both tasks on the right side, but there were clear differences in progress for the two conditions. Drawing over lines on the right hand side made them even more visually salient and the participants continued to draw over these lines again and again without ever moving to the left field. In contrast when erasing the lines participants gradually moved attentional focus to the left as each salient target was removed from the right field, and so overall individuals were able to respond to a greater number of lines on the board in the removal condition (Mark et al., 1988).

1.2.2.3 A deficit in disengaging attention from the right

It has been demonstrated that people with right parietal lesions have slower reaction times for objects appearing on the left side of the screen when the target object is preceded by a cueing stimulus on the right (Posner et al., 1984). It has been proposed that the cueing stimuli shifted attention to the right side of the screen and the reduced reaction times were due to a failure in disengaging attention from that side. The argument that USN is caused by a failure to disengage, is predicated on an increased engagement with an ipsilesional stimulus. This “magnetic attraction” phenomenon is commonly observed by clinicians. For instance, when the clinician moves both hands toward a patient to administer a visual extinction examination, a patient with left neglect compulsively looks at the examiners left hand (placed on the patient’s right hand side) (Gainotti et al., 1991). In laboratory settings, if a visual target is preceded by the appearance of a box on both sides of a screen, the reaction time to contralesional targets is much increased compared to targets appearing on a blank screen. This suggests that the participants attention is drawn to the rightmost box (in people with left neglect) and they then struggle to disengage to look at the left sided target (Derme et al., 1992).

Interestingly, few of the participants in the original study exhibited the clinical signs that would have been used to diagnose actual unilateral neglect (Posner et al., 1984). A subsequent study did demonstrate that there is a relationship between the severity of neglect and the strength of this phenomenon (Morrow and Ratcliff, 1988), however, it seems unlikely that the sole cause of neglect is the failure to disengage. People with USN are no more likely to generate a saccade to a contralesional target under a gap condition (wherein the screen is rendered entirely blank for a short period prior to target appearance), than they are under normal testing conditions with an initial on screen central fixation point. Furthermore, the gap condition does not improve saccadic latency any more than using a warning condition to alert the person that the stimulus is about to appear (Walker and Findlay, 1996). So whilst a failure to disengage may contribute to and exacerbate the neglect syndrome, it is probably not a key component on its own.

1.2.2.4 Impaired representation of space

If someone with USN is asked to point straight ahead whilst sat in darkness, they commonly point off centre in an ipsilesional direction (Jeannerod and Biguer, 1987; Heilman et al., 1983). Whilst some have explained this observation as a problem with directional motor programming rather than egocentric frame of reference (Heilman et al., 1983), shifts in perceived straight ahead have been found when the judgements are made without a motor command (Chokron and Imbert, 1995), (Karnath, 1997). Karnath et al. (Karnath, 1997) studied a group of five people with unilateral neglect as they searched a dark room for a light stimulus. For controls, the direction of gaze over time formed a bell curve with a peak directly in front of them whereas for people with left neglect the bell curve peaked at around 15 degrees right of centre.

Other studies using similar methods have found no link between the egocentric frame of reference and the presence or absence of clinical features of neglect (Bartolomeo and Chokron, 1999a; Chokron and Bartolomeo, 1997; Chokron and Bartolomeo, 1998; Farne et al., 1998). Bisiach et al. (Bisiach et al., 1996) conducted an experiment using optokinetic stimulation to try to correct the egocentric frame of reference for their participants with neglect. The participants were asked to mark the endpoints of an imaginary line of a given length, the midpoint of which was marked on a piece of paper. The participants with neglect moved the line endpoints leftwards, reproducing the ipsilesional line bisection error often seen in left hemineglect. When left sided optokinetic stimulation was applied (known to temporarily improve some signs of neglect), the task error increased rather than vanishing (Bisiach et al., 1996). In another study, participants with left neglect were directed to scan a line left to right before bisecting it (people with left neglect usually scan right to left on this task) and this induced a left sided bisection error (Chokron et al., 1998). These two experimental findings suggest that interventions for those with left neglect that are said to improve use of the egocentric frame of reference are in fact affecting task performance through another mechanism – perhaps by facilitating the orientation of attention leftwards. If this is so, then a shift in egocentric frame of reference may be a feature of neglect in some people but not the key explanatory variable for some of the behaviours exhibited by people with neglect.

1.2.2.5 Non lateralised impairments of attention

Attention and processing can be affected in neglect syndromes in ways not governed by the location of a stimulus. In neglect syndromes, reaction times to stimuli are slower even for ipsilesional stimuli and reaction times increase with neglect severity (Bartolomeo and Chokron, 1999b). People with no brain damage can detect two separate visual stimuli presented in central vision only if they are separated in time by 100-450 milliseconds (Raymond et al., 1992) (the so called ‘attentional blink’). In people with significant USN this attentional blink slows considerably to around 1.5 seconds (Husain et al., 1997). Poorer performance in an auditory tone counting task also predicts severity of spatial features of neglect (Robertson et al., 1997). An auditory ‘beep’ prior to a visual stimulus appearing on a screen reduces the poor reaction times seen in neglect which has been proposed to enhance vigilance, a component part of the attentional system (Robertson, 1993).

1.2.2.6 Directional motor impairments

In addition to interfering with vigilance and attentional selection processes, it has been suggested that unilateral spatial neglect syndromes may also interfere with programming actions such as arm movements. Heilman et al. (Heilman et al., 1985) conducted an experiment wherein six people with left sided neglect were asked to move a handle as quickly as possible across a horizontal track – either left to right or right to left. The participants with neglect were slower to initiate movements from right to left than left to right which was not true of people with strokes and no neglect (Heilman et al., 1985).

These findings have not always been reproduced, however. For example, Mijovic (Mijovic, 1991) studied 40 patients with right sided brain lesions using a visual search task. A target object was to be located by moving a panel until the target appeared in a window. Search times for these individuals did not alter depending in whether the panel was moved leftwards or rightwards (Mijovic, 1991). Many experiments have tried to tease apart motor programming deficits from perceptual deficits, with mixed results. It seems that separating perception and action is extremely difficult when examining the behaviours of people with USN. For example, in order to program a leftward movement (as in Heilman's experiment) the person must first attend to the left side of the track. As previously described, people with left neglect seem 'magnetically attracted' to right lying stimuli (e.g. the right side of the track), so even in this simple experiment the cause of delay may be slow attentional selection rather than motor programming per se.

One of the better attempts to disentangle perceptual deficits from motor programming deficits in those with left neglect was conducted by Bartolomeo et al. (Bartolomeo et al., 1998). 34 people with right sided brain damage (14 with signs of left neglect and 15 controls) participated in a 'perceptual' task whereby participants made a motor response pressing a computer key in their midline, to eccentric targets appearing on one side or the other, and a 'motor' task whereby participants had to press either a left, central or right side lying computer key, depending on the nature of a visual stimulus) to targets appearing in the centre of the screen. The results showed that the participants with USN exhibited a clear deterioration in performance for left lying stimuli in the perceptual task, but no deficit for making left sided motor responses to central stimuli (although two patients with right sided lesions and no neglect did have motor problems) (Bartolomeo et al., 1998). A further attempt to demonstrate a clear deficit in programming spatial movements in left neglect was made by Mattingley et al. (Mattingley et al., 1998). This study compared directional motor responses between 6 patients with clinical signs of USN, 3 of whom had isolated lesions of the right inferior frontal lobe and 3 of whom had isolated lesions of the right inferior parietal lobe – the hypothesis being that the inferior parietal lobe is an important sensory-motor interface and lesions here should produce directional motor impairments. Participants were asked to press a light which appeared either to their left or right, but on each trial the starting position of their right hand was varied between left, central or right. Participants with inferior parietal lobe lesions were slower to initiate a response to a left sided stimulus if their hand started right of centre, whilst no directional difference was found for those with frontal lobe lesions. To rule out a cuing effect of the starting hand position, a no reach task was also tested in which participants simply pressed a button under their hand when the stimulus appeared – again the starting hand position could be either left, central or right. On this task, no effect for starting hand position was found (Mattingley et al., 1998). This gives evidence that some specific neglect causing lesions (namely right inferior parietal lobe lesions) may produce specific directional motor impairments whilst other lesions produce a pure perceptual deficit.

1.2.2.7 Effects of behaviour and action on unilateral spatial neglect

When interpreting task performance in people with neglect, one must be aware that changes in strategy and changes in the task can have huge impact on the observed behaviours. Some forms of testing are markedly affected by instructions – for example asking individuals, both with or without neglect, to reverse the direction in which they explore a horizontal line can change the direction of line bisection errors (Chokron et al., 1998). The phenomenon of actions transforming the visual scene, which then further influences future actions was demonstrated by Mark et al. in the line deletion/line overwriting tasks described in Section 1.2.2.2 (Mark et al., 1988).

Indeed, experimental conditions can cause task performance to change dramatically. When people with USN responded to a target appearing inside one of two circles: slower reaction times were observed for left-sided targets – a classic demonstration of spatial neglect. However, when the circles were connected by a line and rotated 180 degrees on the screen just before the target appears, the people with USN became quicker at noticing targets appearing on the left side of the screen – demonstrating left neglect with a frame of reference relative to the object rather than the participant (Behrmann and Tipper, 1999).

1.2.2.8 Common characteristics of unilateral spatial neglect

People with USN show a wide variety of manifestations and this may reflect anatomical differences throughout a diffuse network of attentional nodes and brain connections. However, common characteristics do emerge for most people with spatial neglect. They seem to experience an early orienting of attention ipsilesionally and have difficulty or slowness in reorienting attention contralesionally as well as a non-lateralised deficit in processing of attention-pertinent information. Further problems with other levels of sensory processing, attentional selection, vigilance and motor programming may exacerbate the problems that these people experience, varying from individual to individual.

1.2.3 Effects of Unilateral Spatial Neglect on Activities of Daily Living

Unilateral spatial neglect is a common consequence of stroke, especially in the early stages, but it seems that it is difficult to estimate its prevalence. A systematic review of epidemiology papers showed prevalence estimates from 3% to 82% of strokes (Bowen et al., 1999), and while the review concluded that it is more common after right-sided stroke than left-sided stroke, it seemed impossible to get reliable estimates because each study used a different selection of patients, a different amount of time post-stroke and different neglect criteria (Bowen et al., 1999). A comprehensive battery of visuospatial tests given to a large sample of patients with right hemispheric stroke showed that 85% of people scored in the abnormal range for at least one test (Azouvi et al., 2002), although scoring low on one test is not diagnostic of the clinical syndrome of left neglect.

Whilst obvious signs of neglect are common early after stroke (especially in right hemispheric stroke) these overt problems largely resolve in as many as three quarters of people (Kerkhoff, 2001). More detailed testing of such stroke survivors often reveals that some features of neglect are still present (Mattingley et al., 1994) that could easily have an impact on performing skilled actions in complex, real-world environments. Several studies have shown that the presence of clinical features of neglect at admission to a rehabilitation hospital has a profound effect on patient outcomes for motor, sensory and cognitive recovery, as well as return to independence, even 6 months after discharge from hospital (Katz et al., 1999). And even after a period of inpatient specialist rehabilitation, fewer than 50% of people are able to return to living independently in their own home (Giaquinto et al., 1999; Cherney et al., 2001). A key feature of USN is lack of insight into one's deficits (anosognosia) and even if some degree of recovery is seen in simple activities of daily living, the condition of unilateral neglect can pose a significant safety risk and the need for constant monitoring by families and carers (Hartman-Maeir et al., 2001). A comprehensive study of 166 people admitted to a rehabilitation facility with a single stroke demonstrated that the presence of unilateral neglect was a stronger predictor than infarct size for a variety of issues; from adverse outcome in motor, sensory, and cognitive function, through to more limited activities of daily living and increased carer burden (Buxbaum et al., 2004).

1.2.4 Driving with hemispatial neglect

The previous section demonstrated that many people with unilateral spatial neglect face large barriers in returning to independence in basic activities of daily living. The presence of observable signs of moderate neglect is almost certainly incompatible with safe driving (Tant et al., 2002a) and clinicians are highly likely to advise driving cessation. However, there are patients who present with marked visual inattention acutely after stroke but show substantial recovery. Jehkonen et al. (Jehkonen et al., 2012) described three patients who had significant neglect early after their brain injury, but months later had improved to the extent that that only minor deficits could be elicited in quite complex visual search tasks. Importantly, scoring on the Behavioural Inattention Test (BIT) was within normal limits for all three people. Although they exhibited minor problems reacting to novel situations and some slow reaction speeds were detected, all three were deemed safe to drive (Jehkonen et al., 2012). No consistent way of evaluating the complex interplay of cognitive, attentional, physical and perceptual deficits to determine driving fitness has yet been established (Galski et al., 2000), and where there is any doubt an on-road driving assessment is the usual course of action.

Whilst for the majority of patients with persisting unilateral neglect, driving a car may never be achieved, successfully piloting an electric wheelchair may give much needed freedom and independence to someone who is unable to walk. Generally people with USN in the UK are denied access to this mode of transport because of safety concerns (Dawson and Thornton, 2003; Frank et al., 2000), but some important work has been done in controlled environments to study the kind of issues that wheelchair piloting may cause. The most obvious problem with wheelchair navigation for people with USN can be frequent collisions with obstacles on the contralesional side (Webster et al., 1989; Webster et al., 1994; Webster et al., 1995; Punt et al., 2008). Whilst collisions with objects directly in front and on the ipsilesional side can also occur, this tends to be less frequent. Punt et al. (Punt et al., 2008) examined accuracy passing through doorways in seven patients with USN. The patients tended to pass through the doorway a constant distance from the ipsilesional door frame, regardless of how wide the door was. This suggested that the participants were selectively attending to the ipsilesional side of the doorway and passing through a reasonable distance from it, without attending to the contralesional side in order to judge the gap from that side (Punt et al., 2008). This study also showed that performance on pen and paper tasks of visuospatial ability did not predict behaviour in the functional task of wheelchair piloting. Such task difference were also observed in a study by Turton et al. (Turton et al., 2009) who discovered a strange dissociation between behaviour of people with unilateral neglect walking down a corridor (who tended to deviate from the centre ipsilesionally), and those piloting a powered wheelchair down the same corridor who tended to deviate course contralesionally (Turton et al., 2009). Whilst the authors were unable to explain this difference, it does suggest that navigational performance with unilateral neglect may be heavily task dependent. A study of 9 people with right hemispheric strokes walking through tight apertures by Trompe et al. (Tromp et al., 1995), found that the presence of USN strongly increased the frequency of collisions both on the left and right sides. However 2 participants with more severe USN walked straight towards the right side of the aperture and collided with it – as though this right sided stimulus was so powerful to the person that it produced an overt motor response which could not be overcome to avoid collision. The other 3 participants with USN tended to take a leftward course and collided more frequently with the left side of the aperture – perhaps staying a reasonable distance from the right sided stimulus as in the Punt et al. study above. Given that task performance for people with USN may vary widely depending on the task being performed and the strategy being used – which in itself may be driven by the specific components of spatial processing which were affected by the person’s lesion, it seems crucial to investigate further the relationship between USN deficits and locomotor steering control. Also, given that simple attentional cueing by moving the wheelchair joystick contralesionally may reduce collisions and improve ability to navigate through a doorway (Punt et al., 2011), with better understanding there me be opportunities to facilitate mobility even amongst those with USN.

1.3 Experimental Predictions and Plans

1.3.1 Homonymous visual field defects.

For people with homonymous field loss, the level of difficulty experienced in a range of tasks, from simple pen and paper tasks to complex tasks such as driving, shows a wide variation from individual to individual. Furthermore, it seems that it is not possible to predict from simply the extent of visual field loss, or degree of macular sparing alone how well someone will perform on any given task – although people with quadrantanopia generally perform better than those with hemianopia. For many tasks, a clear dichotomy appears to emerge between those with visual field loss who, perhaps through a range of compensatory mechanisms, are able to perform well on most perceptual motor tasks and those who perform poorly. There may be an anatomical basis involving lesions of white matter 'feed forward' pathways from the primary visual cortex that cause additional problems with spatial processing and therefore the ability to compensate for a primary sensory deficit such as hemianopia.

A key hypothesis tested in this thesis is that a set of people with homonymous visual field loss will naturally divide into those who perform as well as, or nearly as well as controls across a variety of measures (from pen and paper tasks through to more complex computer based tasks and simulated driving tasks) and those who experience problems across these measures and perform poorly compared to controls. It is expected that those who perform in a similar manner to controls on the driving tasks will rely upon compensatory eye movement patterns to ameliorate their visual field loss, whereas those who perform poorly will be unable to make these compensations, or will try to do so, but fail.

1.3.2 Unilateral Spatial Neglect

People with unilateral spatial neglect are expected to show deficient performance on most aspects of visuospatial testing, from simple pen and paper tests, to visual search tasks and simulated driving tasks. The phenomenon of ipsilesional attentional capture is expected to be a prominent feature leading to deficient performance in detecting stimuli on the contralesional side, judging position in lane whilst driving and spotting hazards. There may be wide variability in performance from one individual to the next because USN is a highly heterogeneous condition and even on simple pen and paper tests, individuals vary widely – this is the reason why batteries of tests are required to diagnose USN. There may be a possibility that some individuals, perhaps with milder forms of spatial neglect, may show some ability to complete the driving tasks and even compensate for their neglect.

1.3.3 Planned Experimental Work

The first stage will be to recruit a convenience sample of 6 people clinically diagnosed with left homonymous visual field loss, 6 people with right sided visual field loss and 6 with unilateral spatial neglect as well as 18 older adult, non brain damaged controls. **Chapter 2** describes a battery of clinical and pen and paper tests, as well as formal visual field testing by perimetry, to quantify the degree of visual field loss, and identify those with visual inattention as well as to gain measures of the severity of perceptual deficit and disability. **Chapter 3** then determines the accuracy of saccadic and smooth pursuit eye movements in the horizontal plane for each participant, to see whether these measures have a bearing on ability of individuals to compensate for visual field loss or inattention. **Chapter 4** determines the ability to perform a novel visual search task and this will be used to group those with visual field deficits into those that appear 'Adequately Compensated' and those that are 'Inadequately Compensated' (as per (Hardiess et al., 2010; Zihl, 1995b) **Chapter 5** then measures driving performance in a simulated 'virtual reality' setup, using measures such as car positioning accuracy as well as measures of gaze behaviour. The results of driving performance will be compared with all the previous measures to see whether particular functions seem to be more predictive of performing skilled actions successfully. **Chapter 6** will measure the ability to perceive and react to hazards whilst driving through a computer simulated city driving task. Again performance on this task will be compared with previous chapters to look for specific features of a visual disability that predicts hazard perception performance. Finally, **Chapter 7** will address broader implications of our findings with regards to fitness to drive, identify if and to what extent driving performance is predicted by pen and paper visuospatial or cognitive testing, eye movement accuracy or visual search ability and examine whether any participants showed evidence of adapted eye movements to compensate for their visual deficit, what form this took and whether compensation was effective.

Chapter 2: The Experimental Participants: Demographics, Classification of their Impairments, Visual Field Mapping and Cognitive Assessment

One of the central aims of this thesis is to systematically evaluate a cohort of people who have experienced a stroke, specifically those with homonymous field defects or unilateral spatial neglect (or both). The next series of chapters examines the performance of participants carrying out a series of tasks in order to look for commonalities that may lead to particular performance deficits with predictive utility across tasks (particularly with respect to driving).

Performance in complex tasks involving spatial exploration can be strongly affected by the strategy chosen by the individual performing the task. A simple example is the line bisection task (commonly used to measure neglect) where the direction of exploration of the line (from left to right, rather than right to left) can reverse the line bisection error, in both normal subjects and in people with neglect (Chokron et al., 1998). In more complex tasks (such as driving) it is clear that there will be a wide variety of strategies could be chosen that could have a profound effect on performance. Moreover, because the way in which spatial information is processed is only incompletely understood (both anatomically and neuropsychologically) there are no simple ways to unambiguously ‘classify’ an individual’s hemianopia or spatial neglect syndrome. It is clear that task performance can vary widely from one person to another and this undoubtedly depends on a large number of variables i.e. size and location of infarct, age, strategy and premorbid performance. The number of variables affecting task performance makes systematic (e.g. RCT) approaches completely impractical for addressing the research questions highlighted in Chapter 1, and would require resources and a sample size that would be impossible to achieve within the scope of this project. Instead, the work presented here evaluates a set of participants as a series of individual case studies, with a battery of tests that provide detailed measures across a variety of functions and behaviours.

The first step in determining the capabilities and limitations of individuals with HFVD/USN is the recruitment and assessment of potential participants. This chapter outlines the methods employed to gather groups that were as homogenous as possible, whilst providing sufficient numbers for group analysis where possible. These assessments excluded potential participants with significant motoric and/or cognitive impairments in an attempt to isolate individuals with problems linked with visual field defects and or neglect.

Broadly speaking people with homonymous field defects have been defined as being adequately or inadequately compensated (Hardiess et al., 2010) i.e. able to perform tasks with similar ability to controls or not. The difference between these groups has been suggested to be anatomical in nature, with more anterior lying strokes perhaps affecting white matter pathways conveying visual information to other parts of the brain, causing difficulties with compensatory strategies such as eye movement adaptation (Zihl et al., 2009). People with unilateral spatial neglect (USN) show very large variation in task performance between individuals (Stone et al., 1993; Azouvi et al., 2002), quite possibly reflecting the fact that spatial and attentional processing takes place throughout the brain and is integrated with many other cognitive processes. This chapter details a number of metrics that were gathered in order to be able to group the participants according to the degree of deficit as measured to a variety of visual and cognitive tests.

2.1 Recruitment

Over a 2 year period, 18 people with stroke over the age of 50 were recruited, alongside 18 non brain injured controls over the age of 50 (reflecting the age group who most commonly have strokes). The intention was to recruit a convenience sample of 6 people with left sided homonymous visual field loss, 6 people with right sided homonymous visual field loss and 6 people with unilateral spatial neglect, although we would allow small variations around these figures depending on ease of recruitment. Ethical approval for NHS patients was gained for the project using the IRAS online application system and the study was passed by a local ethical committee. We then gained local R & D permissions from several NHS trusts across West Yorkshire to recruit from local stroke services and rehabilitation services. We also gained ethical permission from the psychology ethics committee at Leeds University to recruit healthy control subjects over the age of 50. In order to help with recruitment, the study was accepted onto the Yorkshire Stroke Research Network's portfolio of adopted research studies, which allowed local stroke research nurses to actively recruit patients on our behalf.

Patients with stroke who may be eligible were screened for eligibility by the person identifying the patient and referred to us for further discussion and consent. The inclusion and exclusion are shown in Table 2.1.

Table 2.1: Inclusion and Exclusion Criteria

Inclusion Criteria	Aged 50 or over Previously driving prior to stroke Clinically has homonymous visual field defect or unilateral spatial neglect
Exclusion Criteria	Another eye condition that would affect driving i.e. bilateral maculopathy or cataracts Needs more than minor assistance to transfer Unable to consent because of cognitive or language deficit Photosensitive epilepsy Has already returned to driving

We also recruited a cohort of control, non brain damaged subjects over the age of 50 using known networks of people who had volunteered for research studies in the past or through other informal networks such as NHS employees. All of the control subjects were currently driving, able to consent, able to transfer in and out of the driving simulator, did not have photosensitive epilepsy and had no eye conditions which may affect driving. All potential recruits were formally screened for eligibility by the researchers and signed an approved consent form.

Firstly the participants were given an initial classification of control, left sided visual field loss, right sided visual field loss or left or right unilateral spatial neglect according to the clinical impression of the referrer, pending more detailed investigation of their impairments. We obtained a simple set of demographic information on each subject including age, gender, an estimate of number of miles driven each year (currently for controls or in the year prior to stroke for the subjects with stroke), year driving license obtained, handedness according to the Edinburgh Handedness Questionnaire, other stroke related impairments, Oxford Community Stroke Project Classification (Bamford et al., 1991) (OCSP - see Appendix 1) and a

Modified Barthel score (Shah et al., 1989) (see Appendix 2) as a measure of overall disability. We then went on to formally measure visual fields to assist in identifying and classifying visual field loss for each participant. Each participant completed a set of pen and paper tests in order for us to judge whether the person had evidence of unilateral spatial neglect or any other cognitive deficit that may impact on driving performance

The study group's demographics are shown in Table 2.2 (control participants) and Table 2.3 (participants with stroke)

Table 2.2: Demographics of Control Participants

Number	Type	Age	M/F	Hand	Oxford Stroke Classification	Impairments	Months since stroke at time of testing	Driving Miles/Year	Driving Other	Modified Barthel
1	control	64	M	Right	X	X	X	10000		100
2	control	69	F	Right	X	X	X	8500		100
3	control	71	M	Right	X	X	X	3000		100
4	control	51	F	Right	X	X	X	7500		100
5	control	80	F	Right	X	X	X	3000		100
6	control	62	M	Right	X	X	X	20000		100
7	control	62	F	Right	X	X	X	2500		100
8	control	71	F	Left	X	X	X	3000		100
9	control	62	F	Right	X	X	X	20000		100
10	control	72	M	Right	X	X	X	5000		100
11	control	51	F	Right	X	X	X	30000		100
12	control	79	M	Right	X	X	X	750	Prev HGV	98
13	control	80	M	Right	X	X	X	20000		100
14	control	64	M	Right	X	X	X	4000		100
15	control	57	M	Right	X	X	X	12000		100
16	control	62	M	Right	X	X	X	15000		100
17	control	74	F	Right	X	X	X	500		100
18	control	63	M	Right	X	X	X	22500		100

Table 2.3: Demographics of Participants with Stroke

Number	Type	Age	M/F	Hand	Oxford Stroke Classification	Impairments	Months since stroke at time of testing	Driving Miles/Year	Driving Other	Modified Barthel
1	LHVFD	73	M	Right	R POCI		3	6000		98
2	LHVFD	63	M	Right	R POCI		10	12000		100
3	LHVFD	51	M	Right	R PACH	L hemiparesis	10	20000		78
4	LHVFD	68	M	Right	R POCI	Ataxia	3	84000	Prev Chauffeur	98
5	LHVFD	66	M	Right	R POCI		42	10000	Prev HGV	100
6	LHVFD	74	M	Right	R POCI		3	5000		100
7	LHVFD	57	M	Right	R POCI	Mild ataxia	72	10000		100
8	RHVFD	60	M	Right	L POCI		3	3000		100
9	RHVFD	55	M	Left	L TACH	Aphasia, R Hemiparesis	45	17500	Prev rally driver	20
10	RHVFD	62	M	Left	L POCI		3	10000		100
11	RHVFD	51	F	Right	L TACI	Dysarthria, Alexia, R Hemianaesthesia	18	20000		100
12	RHVFD	67	M	Right	L POCI		36	4000	Prev HGV	100
13	RHVFD	65	M	Right	L TACI		35	6000	Pilot	100
14	LUSN	64	M	Right	R PACI	L Hemiparesis	108	20000		86
15	LUSN	57	M	Right	R PACI	L Hemiparesis	48	7500		74
16	LUSN	63	F	Left	R PACI	L Hemiparesis	18	0		43
17	LUSN	52	F	Ambi	R PACI	L Hemiparesis	12	12500		68
18	RUSN	57	M	Left	L PACI	R Hemiparesis	13	3000	Prev van driver	66

LHVFD = left homonymous visual field defect

RHVFD = right homonymous visual field defect

LUSN = left unilateral spatial neglect

RUSN = right unilateral spatial neglect

2.2 Measurement of Visual Fields

Each participant had a full optometry screen performed including calculation of refractive error, screening for glaucoma, cataract and other ophthalmic conditions and formal automated visual field analysis. A custom made set of spectacles was then made for each participant to correct their refractive error and optimise vision at 1 metre (the distance from the eye to the driving simulator screen). These spectacles were used for all of the eye movement tasks, visual search tasks and driving tasks.

Visual fields were assessed using a Humphrey Visual Field Analyser. Each eye was examined in turn using the Swedish Interactive Threshold Algorithm (SITA) and then a binocular Estermann test was also performed. Each person was also assessed by confrontation using a black hat pin as the stimulus. The Binocular Estermann is the standard used by the Driving Vehicle Licensing Authority in the UK when determining if someone has enough usable visual field to be allowed to drive. However the Binocular Estermann test is less sensitive to picking up visual field loss than the monocular testing performed on the Humphrey analyser (Ayala, 2012). Direct confrontation is extremely insensitive for picking up visual field loss (Townend et al., 2007). In the following tables I have recorded the results using each test, but when making a final assessment of the type of visual field loss and the extent of macular sparing I have used the monocular (SITA) test as the primary indicator. For each test I have recorded the type of defect (hemianopia, quadrantanopia) and the minimum degree of macular sparing i.e. how many degrees from centre was the nearest point highlighted as abnormal. Table 2.4 shows the visual field profile for those with stroke

Table 2.4: Visual Fields of Participants with Stroke

	Confrontation	Monocular		Binocular		Other	Overall
No.	Type of VFD	Type of VFD	Foveal Sparing	Type of VFD	Foveal Sparing		
1	LHH	LHH	0°	LHH	10°		LHH no sparing
2	LIQ	LIQ	8°	LIQ	8°		LIQ 8° sparing
3	LHH	LHH	0°	LHH	0°		LHH no sparing
4	LSQ	LHH	0°	LSQ	0°	Patchy LIQ + central sparing	LHH patchy LIQ sparing
5	LHH	LHH	0°	LHH	0°	L Lens replacement	LHH no sparing
6	LHH	LHH	12°	LHH	20°		LHH 12° sparing
7	L Scotoma	L scotoma	12°	Not done	Not done	Involves both L quadrants	L scotoma, to within 12°
8	RHH	RHH	6°	RHH	0°	Some RIQ sparing	RHH, 6° + RIQ sparing
9	RHH	RHH	0°	RHH	0°		RHH no sparing
10	RHH (partial)	RHH	0°	RHH	0°	RHH, patchy IQ, SQ sparing	Partial RHH
11	RHH	RHH	0°	RHH	0°		RHH no sparing
12	RIQ	RIQ	6°	RIQ	10°		RIQ, central sparing
13	RSQ	RSQ	0°	Patchy RSQ	0°		RSQ no sparing
14	Normal	Patchy LHH	14°	Patchy LHH	30°	No VFD on confrontation	LVI
15	Normal	Patchy LIQ	12°	Patchy LIQ	0°	No VFD on confrontation	LVI.
16	Normal	Patchy LHH	0°	Patchy LHH	16°	No VFD on confrontation	LVI
17	Normal	Patchy LHH	14°	Normal	°	No VFD on confrontation	LVI
18	Normal	Patchy RIQ	0°	Patchy LIQ	20°	No VFD on confrontation	RVI

LHH = Left Homonymous Hemianopia

RHH = Right Homonymous Hemianopia

LIQ = Left Inferior Quadrant **or** Left Inferior Quadrantanopia

RIQ = Right Inferior Quadrant **or** Right Inferior Quadrantanopia

LSQ = Left Superior Quadrant **or** Left Superior Quadrantanopia

RSQ = Right Superior Quadrant **or** Right Superior Quadrantanopia

All of the visual field examinations for the control group were unimpaired.

Finding homonymous visual field defects on perimetry examination is common in people with unilateral spatial neglect but does not mean that the patient actually has a hemianopia. Case studies have been described in which an apparent left hemianopic field defect is abolished when gaze is directed 30 degrees to the right (Kooistra and Heilman, 1989) – suggesting a hemispheric rather than retinotopic problem incompatible with hemianopia – and another whereby targets on the left were not seen if the central fixation cross remained onscreen, but targets were detected if the cross disappeared prior to the stimulus appearing (Walker et al., 1991). This latter case study was felt to be incompatible with hemianopia – the patient could detect the target in the left hemifield as long as no competing stimulus (i.e. the central fixation cross) lay to its right. This is highly suggestive of hemispatial neglect.

If, as I suggest in chapter 1, homonymous field loss tends to result in a fairly sharp border between areas of the visual field in which targets are detected and not detected, whereas unilateral neglect results in a far less obvious borderline, one might reasonably expect that any apparent visual field loss detected on perimetry examination for people with unilateral neglect to be quite patchy. This is exactly the pattern seen in participants 14 to 18. Combining this with the absence of an obvious visual field defect on confrontation, I took this as evidence that these patients did indeed have unilateral neglect and in each case the referring clinician felt that they did too.

2.3 Screening for Unilateral Spatial Neglect

Neglect is a highly heterogeneous condition and, despite it's likely high prevalence after stroke (Bowen et al., 1999), no consensus exists as to how to diagnose it and monitor severity after treatment (Azouvi et al., 2002; Bowen et al., 1999; Stone et al., 1992). Performance on individual tasks frequently dissociate from each other meaning that no single task alone is particularly predictive of the presence of spatial neglect – probably reflecting that neglect is a highly heterogeneous condition (Azouvi et al., 2002) (if it is a single entity at all!). Batteries of tests assessed together are generally felt to be far more predictive of the presence of spatial neglect and a number of these exist – the best known are the Rivermead Perceptual Assessment Battery (Whiting et al., 1985) and Behavioural Inattention Test (Halligan et al., 1991) Pen and paper tests of neglect certainly correlate with behavioural assessment but by no means always predict it (Azouvi et al., 2003).

Neither the Rivermead Perceptual Assessment Battery or the Behavioural Inattention Battery categorised the cohort of patients used to develop the tests as to whether they had a homonymous visual field defect or not. Neither the test batteries, nor the component tests have been standardised against groups of patients with homonymous visual field defects without neglect – so the normal ranges for people with visual field defects alone are essentially unknown. The presence of a visual field defect in addition to visual neglect can worsen performance in a line bisection task (Cassidy et al., 1999; Doricchi and Angelelli, 1999). Performance in other visuospatial tasks has been found to be unaltered by the presence of visual field defect in addition to spatial neglect (Halligan et al., 1990b).

This all makes disentangling whether each individual participant in this study had visual field defect alone, visuospatial neglect alone or both quite challenging. There is no agreed way to diagnose spatial neglect - test batteries were developed without categorising validation study participants according to whether they also had visual field defects or not. Furthermore normal ranges for task performance on visuospatial tests for hemianopic patients without neglect have not been established and visual field analysis for people with neglect but no visual field defect may still be abnormal. I have therefore taken a pragmatic approach using a battery of component tests used in previous studies to diagnose neglect, each of which is detailed below. Following this I have tabulated task performance for each trial participant with stroke and then made a judgement as to whether they have a field defect and whether they have spatial neglect.

2.3.1 Visual and Tactile Extinction

There remains some debate as to whether extinction (in which a contralesional stimulus goes undetected only when a simultaneous, ipsilesional stimulus is presented) is a form of neglect or a separate entity (Milner, 1997). Certainly double dissociations (whereby case studies are found with leftward spatial processing problems, but between whom no characteristics are shared) (Vallar et al., 1994; Geeraerts et al., 2005; Cocchini et al., 1999) exist, but severity of neglect measured on a cancellation task correlates very well with rate of extinction in a computer based task in one study (Vuilleumier and Rafal, 2000). I have therefore taken a view that the presence of extinction phenomena on examination in combination with other lateralised deficits of task performance was suggestive that the participant had unilateral spatial neglect.

Presence of visual extinction was assessed by finger wiggling. The examiner held a finger of each hand on either side of the participant’s visual field. If the participant had hemianopia, the finger in the affected hemifield was moved centrally until the participant could see it – often just past the midline. Central fixation was checked by the examiner. The participant was asked to point at which finger moved and 3 trials were done, firstly the finger on the ‘good’ side (or examiners left in controls) was moved for around 1 second. Then the other finger was moved and finally both. If there was any doubt regarding central fixation or understanding of the task, the test was repeated once. Visual extinction was taken to be present if both wiggling fingers were detected to be moving when moved alone, but only the finger moving in the ipsilesional field was reported to move in the bilateral task.

Presence of tactile extinction was measured in a very similar way. The participant was asked to close their eyes and the examiner rubbed firstly the right hand, then the left hand and then both hands for 1 second. (The order of left and right was reversed for participants with right hemispheric strokes).

2.3.2 Star cancellation task

The star cancellation task was developed by Wilson, Cockburn and Halligan in 1987 as a measure of unilateral spatial neglect (Wilson et al., 1987). A piece of A4 paper contains 56 small stars, 52 large stars, 13 letters and 10 short words. The paper is placed in the participant’s midline and they are then asked to place a line through each of the small stars whilst ignoring everything else. Neglect phenomena tend to be more manifest in the presence of distracters and therefore it was thought that this test would be more sensitive for picking up neglect than a cancellation task with no distracters such as Albert’s test. The task is scored out of 54 (56 minus 2 stars that the examiner crosses out in demonstration at the beginning of the task). A score of less than 44 is meant to indicate the presence of USN. A laterality index can be generated from the ratio of stars cancelled on the left half of the page to the total number of stars cancelled – a ratio of 0.46 or less indicates left neglect and 0.54 or more indicates right neglect.

Test-test reliability is said to be excellent (Bailey et al., 2004). A number of studies have highlighted excellent sensitivity of the test to picking up the presence of USN (Bailey et al., 2000; Marsh, 1993; Jehkonen et al., 1998; Halligan et al., 1990a). It has also been found to be a good predictor of functional outcome as measured on the modified Barthel Scale (Marsh, 1993).

2.3.3 Visuospatial Domain of the Addenbrooke's Cognitive Evaluation

The Addenbrooke's Cognitive Evaluation Revised (ACE-R) was developed as a screening tool for dementia and has very good sensitivity and specificity for diagnosing various types of dementia (Mioshi et al., 2006). It tests cognition in 5 domains – attention and orientation, memory, language, visuospatial and verbal fluency.

The visuospatial domain is tested by asking the participant to copy 2 interlocking pentagons (scored out of 1), copy a (Necker) cube shape made from 12 lines (scored out of 2) and to construct a clock face with numbers and the hands at 10 past 5 (scored out of 5). There are also 4 dot counting tasks (scored out of 4) and 4 distorted letter reading tasks (scored out of 4) – giving a total of 16 possible points.

The visuospatial component of the ACE-R has been shown to have some utility for detecting visuospatial problems following acute stroke (Morris et al., 2012) as well as adding to the predictive ability of the MMSE (mini mental state examination) to predict safe on road driving behaviour of older adults (Ferreira et al., 2012).

Failure at the interlocking pentagons copy task has been shown to correlate with severity of neglect in acute stroke patients (Lee et al., 2008). Whilst the task was designed to test for constructional apraxia, those with object centred neglect will also have problems with this task – usually failing to copy all or some elements of the left pentagon. Clock drawing has also been shown to correlate well with other tests for visuospatial neglect as well as behavioural observation of people with neglect (Azouvi et al., 2002). Dot counting tasks have also been associated with some patterns of neglect (Maeshima et al., 1997).

Whilst the visuospatial domain of the ACE-R has not been used before in screening for spatial neglect, some of the elements of it have and there does seem to be a correlation between the presence of other neglect phenomena and lower performance on the tasks at least in acute stroke. Using the ACE-R gave us the added utility of being able to screen for other domains of cognitive impairment as part of the background participant assessment which may be predictive of driving behaviour generally.

There is no defined cut off for these tasks to suggest spatial neglect. All of our control participants scored 15 or 16 out of 16 in this domain. It is feasible that participants with hemianopia may score slightly down on these tasks purely because of their hemianopia, so I have selected a cut off point of 11/16 as suggestive of neglect. I have also used a criterion of impaired placement of the clock numbers on the affected side as a separate indicator of neglect as per previous studies (Azouvi et al., 2002) as well as another separate criterion of impaired copying of the relevant pentagon out of the pair (i.e. left pentagon in right hemispheric stroke).

2.3.4 Rey-Osterrieth Complex Figure Copy Task

Simple object copying tasks are often used clinically (and mentioned in textbooks) to detect spatial neglect. More complex, multi figure complex tasks have also been used – classically a proportion of people with spatial neglect fail to copy objects on the contralesional side of the scene, or they fail to accurately copy the contralesional half of individual elements of the scene (Gainotti et al., 1972; Ogden, 1985). These phenomena can continue to occur even more than a year after a stroke (Johannsen and Karnath, 2004).

The Rey-Osterrieth figure copy task has been used as a measure of perceptual problems. The most commonly used scoring system (Lezak-Osterrieth) rates each of the 18 items of the figure copied with a score of up to 2 for accuracy and position. This gives a total score out of 0 – 36 points. One study of 61 stroke patients and 50 controls showed a score of 29 or less to have a sensitivity of 97% and a specificity of 48% for demonstrating the presence of visual neglect measured against classification using the Rivermead Perceptual Assessment Battery (Whiting et al., 1985). A cut-off of 16 or less gave a sensitivity of 81% and a specificity of 83% (Lincoln, 1998). Accuracy was improved by adding a measure of left sided omissions on the copied Rey Figure. There are 5 items of the Rey Figure that lie completely on the left side of the page. In a study of 32 right hemisphere strokes, 20 left hemisphere strokes and 20 controls, complete omission of 2 or more of these items was shown to correlate closely with a measure of neglect using a letter cancellation task. This cut off of 2 complete omissions gave a sensitivity of 97% and specificity of 100% as compared to the letter cancellation task (Rapport, 1996). It is worth noting however, that neither study of the Rey Figure in the diagnosis of neglect mentioned how many subjects had visual field defects, so it is unknown whether the measures have diagnostic worth in people with stroke and visual field defect.

For the purposes of this study, I have used 2 measures of the Rey Figure Copy task – namely a total score of 16 or less indicating neglect and 2 or more complete left sided omissions as indicating neglect.

2.3.5 Line bisection task

Ipsilesional line bisection errors are commonly demonstrated in people with unilateral spatial neglect and in some circumstances can help to discriminate between people with right hemisphere lesions and those with other kinds of lesions – presumably because many people with right hemisphere lesions will have spatial neglect (Schenkenberg et al., 1980). One study of 6 patients asked patients with neglect to bisect lines of different lengths – between 6.5 and 34cm. When the lines were placed centrally in front of the patient, the average ipsilesional line bisection error was 4.03mm.

The line bisection test is often used in conjunction with other tasks to help elucidate who has spatial neglect. One study shows that a simple line bisection has a sensitivity of 76.4% for picking up neglect (Bailey et al., 2000). Using longer lines increases the sensitivity of the task (Bisiach et al., 1983). A curious 'crossover' effect is seen when the piece of paper is placed on the patient's ipsilesional side or is made shorter, whereby the bisection error reduces and even crosses over into a contralesional line bisection error (Halligan and Marshall, 1988). Studies of gaze fixations have demonstrated that patients tend to look at the ipsilesionally portions of the line and make the line bisection without much regard as to the location of the contralesional part of the line – usually this means that the bisection error is away from the neglected side but if the line is short, or the test sheet is brought towards the better side, the cross may then fall on the opposite side. (Ishiai, 2006; Doricchi et al., 2005).

Contralesional line bisection errors in hemianopia have been known about since the late 19th century. One study showed that the mean contralesional line bisection error for someone with complete, macular splitting hemianopia was 6.15%, but for those with incomplete homonymous field defects the error was only 1.9%. The exact reasons why the direction of line bisection error is different in hemianopia than in unilateral neglect is unclear. It has been suggested that when the 2 conditions co-exist, the line bisection errors may cancel out (Ferber and Karnath, 1999).

Many different line bisection tasks are used in the literature to screen for unilateral neglect or to evaluate the effect of certain interventions. There is no agreement about which is the optimal task to use. For the purposes of this project I have used the 15 line test (+2 examples) used in Schenkenberg et al's original evaluation of line bisection errors in neglect (Schenkenberg et al., 1980) and available for free online at http://strokengine.ca/assess/. In common with Schenkenberg's paper and other research using this task, I have taken an ipsilesional average line bisection of 6mm as evidence for the presence of unilateral spatial neglect.

2.3.6 Results

The spatial neglect screening task results for the control participants are shown in Table 2.5. As would be expected performance was normal for most control participants. Control 12 seemed to have some problems (e.g. scoring below threshold on the Rey figure copy task) but they had an ACE-R score of 86/100 which is indicative of mild cognitive impairment. It is possible that some mild age related general cognitive impairment affected task performance, but in the absence of any other visuospatial defect, there is no real evidence for a classification of spatial neglect.

The results for each participant with stroke are shown in Table 2.6. Scores marked in red are suggestive of the presence of spatial neglect. In the line bisection error test, a positive number indicates a rightward bias and a negative number a leftward bias. For the Rey Figure Copy tasks, the number of left sided omissions (Rey, Left Omissions) are marked as N/A for those participants with left hemispheric strokes.

Table 2.5: Visuospatial test scores for control participants

Control number	Visual Extinction	Tactile Extinction	Star cancellation	Star laterality	ACE-R visuospatial	Pentagons	Clock numbers	Rey Copy	Rey, Left Omissions	Mean line Bisection error (mm)
1	N	N	54/54	-	16/16	Normal	Normal	36/36	0/5	0.12
2	N	N	54/54	-	15/16	Normal	Normal	Not	0/5	1.53
3	N	N	53/54	-	16/16	Normal	Normal	Not	0/5	4.35
4	N	N	54/54	-	15/16	Normal	Normal	35/36	0/5	0
5	N	N	50/54	-	16/16	Normal	Normal	34/36	0/5	1.59
6	N	N	54/54	-	16/16	Normal	Normal	36/36	0/5	-1.09
7	N	N	54/54	-	16/16	Normal	Normal	35/36	0/5	-0.24
8	N	N	54/54	-	16/16	Normal	Normal	36/36	0/5	1.53
9	N	N	54/54	-	16/16	Normal	Normal	35/36	0/5	-1.06
10	N	N	54/54	-	15/16	Normal	Normal	34/36	0/5	1.41
11	N	N	52/54	-	16/16	Normal	Normal	35/36	0/5	-5.12
12	N	N	54/54	-	15/16	Normal	Normal	21.5/36	1/5	3.06
13	N	N	54/54	-	16/16	Normal	Normal	36/36	0/5	0.12
14	N	N	54/54	-	16/16	Normal	Normal	35/36	0/5	-0.65
15	N	N	54/54	-	16/16	Normal	Normal	33/36	0/5	-1.59
16	N	N	54/54	-	16/16	Normal	Normal	36/36	0/5	-1.47
17	N	N	54/54	-	16/16	Normal	Normal	34/36	0/5	-1.35
18	N	N	54/54	-	16/16	Normal	Normal	35/36	0/5	2.65

Table 2.6: Visuospatial tests of participants with stroke

Participant number	Visual Extinction	Tactile Extinction	Star cancellation	Star laterality	ACE-R spatial	Pentagons	Clock numbers	Rey Copy	Rey, Left Omissions	Mean line Bisection error (mm)
1	N	N	53/54	-	16/16	Normal	Normal	34/36	0/5	1.24
2	N	N	54/54	-	14/16	Normal	Normal	36/36	0/5	2.82
3	Y	Y	45/54	Left	11/16	Normal	Fail	24/36	1/5	3.24
4	N	N	26/54	Left	13/16	Fail	Normal	23/36	0/5	-1
5	N	N	52/54	-	16/16	Normal	Normal	25/36	0/5	-3.32
6	N	N	51/54	-	15/16	Normal	Normal	36/36	0/5	3.29
7	N	N	46/54	-	16/16	Normal	Normal	35/36	0/5	0.53
8	N	N	54/54	-	16/16	Normal	Normal	33/36	N/A	2
9	N	N	54/54	-	6/16	Normal	N/A	11/36	N/A	-1.06
10	N	N	53/54	-	16/16	Normal	Normal	29/36	N/A	3.35
11	N	N	49/54	-	7/16	Normal	Normal	24/36	N/A	2.29
12	N	N	53/54	-	16/16	Normal	Normal	35/36	N/A	1.47
13	N	N	53/54	-	15/16	Normal	Normal	35/36	N/A	0.74
14	Y	Y	29/54	Left	12/16	Fail	Fail	22.5/36	2/5	6.59
15	Y	Y	30/54	Left	11/16	Fail	Fail	12/36	4/5	9.82
16	Y	Y	35/54	Left	13/16	Normal	Normal	21.5/36	2/5	1.59
17	N	Y	52/54	-	10/16	Fail	Fail	21/36	2/5	-4.65
18	Y	N	54/54	-	16/16	Normal	Normal	29/36	N/A	1.29

Participants with stroke 1, 2, 5, 6, 7, 8, 10, 12 and 13 scored normally on all visuospatial tasks and are easily classified as homonymous field defect only.

Participant with stroke 3 had clear visual field defects on confrontation and perimetry, but also exhibited extinction phenomena. Although the star cancellation task scored 1 point above the cut-off for suggesting inattention, all but 1 of the omissions were on the left side. The interlocking pentagon copying task was normal, but the cube copy missed elements on the left side, as did the constructing a clock. I feel this participant has both hemianopia and visual inattention.

Participant with stroke 4 is difficult to classify. They missed almost every star on the left side on the cancellation task, but all of the shape copying and construction tasks were essentially normal. There were many placement errors on the Rey copy, but they did not preferentially affect the left side. The interlocking pentagon copying task displayed a pentagon on the right and a diamond on the left – the interlocking section was correct. I feel this person has hemianopia only – the onset was relatively recent at time of testing and it is possible that they were not fully adapted to it yet.

Participant with stroke 9 scored down on the visuospatial parts of the ACE-R because of aphasia – they were unable to read letters, or write numbers on the clock face. The Rey figure was highly abnormal, the participant was not able really to place many elements at all and gave up very early. The simpler copy tasks were completely normal as was the star cancellation. I feel that this person has hemianopia only with no inattention.

Participant with stroke 11 scored down on the visuospatial part of the ACE-R purely because of aphasia. The Rey Figure copy task score was also quite low, mostly due to construction errors – only 1 element was omitted. There was no evidence at all of spatial inattention

Participants with stroke 14-17 had clear evidence of spatial inattention. Participant 18 was referred as having right inattention by his therapy team – they felt that right inattention was still present during therapy sessions. He did have visual extinction on examination, but all of the pen and paper tests were normal. This has been documented previously and visual extinction has been viewed by some as a residual form of recovering visual neglect (Driver and Vuilleumier, 2001). I have therefore classified participant 18 as having right inattention, but which is likely to have improved since his stroke.

2.4 Cognitive Assessment

The final part of the initial assessment of the participants was to perform some baseline cognitive assessment. There were two roles for this assessment – firstly to screen all of the participants to see whether there was evidence of any cognitive impairment and if so, in roughly which domains this lay. Secondly, to administer some cognitive tasks that had previously been linked with on-road fitness to drive that could give some insight into performance errors that may occur in later chapters when the participant went on to do the driving simulator tasks.

2.4.1 Cognitive Screening

A large number of tests exist that have some utility in detecting the presence of cognitive impairment after stroke. After detailed evaluation the Addenbrookes Cognitive Evaluation – Revised (ACE-R) was used. The rationale was that it is the standard screening tool used by rehabilitation medics in Leeds for this purpose, it is relatively quick to administer (at around 10-15 minutes) and it seems to have reasonable sensitivity and specificity for detecting mild cognitive impairment after stroke. One study showed a sensitivity of 83% and specificity of 73% using a cut-off of less than 94 (Pendlebury et al., 2012), whilst another study, using a cut-off of 82, found a sensitivity of 77% and specificity of only 44% (Morris et al., 2012). A further advantage of the ACE-R is that it tests 5 domains of cognition – namely attention/orientation, memory, language, verbal fluency and visuospatial functions, and that the MMSE (Mini Mental State Examination which uses a subset of these tests) can be calculated from the results. The ACE-R has been shown to have utility in detecting post stroke impairment specifically in the visuospatial, fluency and visuospatial domains (Pendlebury et al., 2012).

Control 12 scored below the cut off of 88 indicating possible mild cognitive impairment. Control 13 also scored below the threshold, but English was the second language for this participant and points were mainly dropped on the verbal fluency part of the test, so it is unlikely this individual has cognitive impairment. It should be noted that whilst the ACE-R can be used to aid the diagnosis of dementia, in order to make such a diagnosis it is necessary to document deterioration in cognition over time, so it is impossible to diagnose dementia on a single assessment. Results are shown for control participants in Table 2.7 and participants with stroke in Table 2.8.

Table 2.7: ACE-R Scores for control participants

Control No.	MMSE	Attention	Memory	Fluency	Language	Spatial	Total
1	29	18	25	12	25	16	96
2	29	18	21	12	26	15	92
3	30	18	26	13	26	16	99
4	29	18	25	11	26	15	95
5	28	18	24	10	25	16	93
6	28	17	17	13	26	16	89
7	27	17	20	12	24	16	89
8	30	18	26	14	26	16	100
9	30	18	22	14	25	16	95
10	29	18	24	9	25	15	91
11	30	18	23	14	26	16	97
12	28	17	16	13	25	15	86
13	29	18	25	7 (polish)	21	16	87
14	30	18	26	14	26	16	100
15	30	18	26	14	26	16	100
16	29	18	20	10	25	16	89
17	30	18	22	13	26	16	95
18	30	18	25	14	26	16	99

Table 2.8: ACE-R results for participants with stroke

Participant No.	MMSE	Attention	Memory	Fluency	Language	Spatial	Total
1	25	15	16	4	18	16	69
2	30	18	26	12	26	14	96
3	29	18	16	12	22	11	79
4	26	17	24	14	25	13	93
5	28	18	23	8	23	16	88
6	29	18	26	10	25	15	94
7	29	18	16	13	26	16	89
8	28	18	18	12	23	16	87
9	10	3	2	0	18	6	29
10	28	18	25	11	25	16	95
11	17	11	9	9	14	7	50
12	30	18	22	12	26	16	94
13	30	18	26	14	26	15	99
14	27	17	23	10	25	12	87
15	25	16	18	7	24	11	76
16	29	17	26	9	24	13	89
17	28	18	22	11	24	10	85
18	30	18	18	11	26	16	89

For the stroke group (Table 2.8) the totals in blue highlight scores that fall below the standard cut off point of 88 suggesting dementia, and those in red scored than 82 that are indicative of post-stroke cognitive impairment. Red is also used to mark deficits in specific domains that look well below the expected values (though there are no predetermined cut-offs for each domain). Because participants 9 and 11 had dysphasia, the results for these participants are uninterpretable since most of the assessments on the ACE-R rely on intact language function. .

Amongst those with hemianopia, Participant 1 is likely to have some cognitive impairment affecting memory and executive functions. Participants 3, 7 and 8 seem to have a degree of memory impairment.

All of those with spatial neglect (Participants 4 and 14-18) seem to have a degree of executive and/or memory impairment.

2.4.2 Cognition and Fitness to Drive

Many attempts have been made to ascertain whether a battery of pen and paper tests may be used to predict driving performance after stroke. Tools such as the Stroke Drivers Screening Assessment (SDSA) (Nouri et al., 1987) supposedly correctly predicts the result of an on road driving evaluation in 82% of cases. The validation of this tool had problems, however, with the original validation attempt scrapped due to differences in on road driving performance between the original and validation study groups. Instead of performing an independent validation test, pooled results were sampled from both new and old data. The major problem with this approach is that half of the validation data was exactly the same as that used to develop the test battery in the first place (Nouri and Lincoln, 1992). This is likely to have inflated the predictive values and rendered the validation study meaningless.

Even if the SDSA validation had been performed correctly, it would still be of limited utility since participants with hemianopia and neglect were excluded from the sample populations. This is true of many studies trying to develop tools to predict fitness to drive after stroke, which have either excluded people with hemianopia and neglect or simply not mentioned how many participants had each impairment. At the beginning of this project there were two published meta-analyses of all studies examining the issue of predicting fitness to drive post stroke – each with slightly different results but neither mentioning the proportion of people with hemianopia or neglect in the study groups (Marshall et al., 2007; Devos et al., 2011). Each highlighted the pen and paper tests that had the best predictive value and so these were the tests that were selected for use in this thesis. The aim of performing these tests was to measure broader constructs that may underlie deficits in the driving tasks used in later Chapters. The Marshall study (Marshall et al., 2007) identified the Trail Making tests A and B and the Rey Figure copy tasks as most predictive of driving capability. The Devos study (Devos et al., 2011) identified the Road Sign Recognition and Compass test components of the Stroke Drivers Assessment Battery and the Trail Making Test B as most useful. The cube copy (i.e. from the ACE-R) also seemed to be highly predictive but was supported by only a single study. The Rey Figure Copy test was identified, but already in use for neglect screening in this Chapter (Tables 2.5 and 2.6). The Devos study used cut-offs of 8.5 for the road sign recognition, 25/32 for the compass test and 90 seconds for the Trail Making Test B (Trail A). As per usual guidance a cut off of 78 seconds for the Trail A was used.

The first thing to note is that there were many Control participants that scored below the established thresholds in each task (Table 2.9).

Table 2.9: Cognitive screening and driving, control group. Red text indicates values that fall below the criterion threshold

Control No.	Trail A	Trail B	Compass	Road Sign
1	35	104	22	9
2	Not done	Not done	18	10
3	Not done	Not done	24	10
4	21	35	24	9
5	39	150	17	6
6	48	85	18	10
7	32	130	23	6
8	33	46	20	5
9	23	40	24	9
10	30	106	22	9
11	28	79	21	11
12	51	134	18	4
13	26	66	32	6
14	23	56	32	10
15	21	38	32	12
16	28	51	30	12
17	31	56	32	6
18	21	48	32	8

Table 2.10: Cognitive screening and driving, participants with stroke. Red text indicates values that fall below the criterion threshold

Participant No.	Trail A	Trail B	Compass	Road Sign recognition
1	77	abandoned	12	6
2	39	52	32	11
3	92	unable	9	5
4	95	257	11	3
5	47	101	5	9
6	62	128	19	9
7	31	56	22	12
8	38	86	Declined	Declined
9	130	330	2	3
10	41	90	30	12
11	dysphasic		4	0
12	35	55	32	6
13	33	78	32	12
14	76	227	9	5
15	96	unable	11	6
16	101	205	10	3
17	63	137	18	5
18	42	109	24	7

In the stroke group (Table 2.10), participants 2, 10 and 13 are the only stroke participants who scored in the normal range for each task. Participant 8 scored in the normal range for the trail making tasks but declined to attempt the SDSA. Every other participant's results would raise some concern as to whether they would be fit to drive based on the measures identified in the existing literature.

2.5 Final Categorisation

The primary goal of performing the various assessments on each participant was to differentiate between participants in the stroke group that had homonymous visual field loss (and if so what type), those who had spatial neglect and any individuals who had both sets of deficits. Furthermore, the tests should enable the identification of individuals with significant cognitive impairments that could impact on successful driving. Following completion of testing each participant was assigned a code that will be used as their individual label throughout the remaining Chapters. Table 2.11 shows the entire stroke group listed by their code number, along with the original participant number (1-18) and a synopsis of their stroke related impairments.

Table 2.11: Final categorisation of the impairments of the participants with stroke. The code labels (i.e. LHH1) are used to identify each participant throughout the rest of the thesis

	Code No.	Participant No.	Age	Visual impairment	Comments
HVFD	LHH1	1	73	LHH no sparing	Some cognitive impairment
	LHH2	2	63	LIQ 8° sparing	
	LHH3	4	51	LHH patchy LIQ sparing	
	LHH4	5	68	LHH no sparing	Reduced verbal fluency.
	LHH5	6	66	LHH 12° sparing	
	LHH6	7	74	L scotoma, to within	Some memory deficit
	RHH1	8	57	RHH, 6° + RIQ sparing	Some memory deficit
	RHH2	9	60	RHH no sparing	Dysphasia
	RHH3	10	55	Partial RHH	
	RHH4	11	62	RHH no sparing	Dysphasia
	RHH5	12	51	RIQ central sparing	
	RHH6	13	67	RSQ no sparing	
USN	LHHVI	3	65	LHH no sparing	Some memory and cognitive deficit
	LVI1	14	64	LVI	
	LVI2	15	57	LVI.	Some memory and cognitive deficit
	LVI3	16	63	LVI	
	LVI4	17	52	LVI	
	RVI1	18	57	RVI	Some memory deficit

Chapter 3 – Saccadic and Smooth Pursuit Eye Movement Performance

There are 4 basic types of eye movement. Saccades are rapid ballistic eye movements that transfer gaze fixation between one target and another. Smooth pursuit movements allow a person to track a moving target. Vergence eye movements allow the eyes to foveate targets at different distances and vestibulo-ocular eye movements compensate for head movements maintaining foveation of a target.

Saccades and smooth pursuit eye movements are commonly used in driving. When driving on a road with no particular features to attract gaze, a driver tends to fixate a point on the road ahead and track it using smooth pursuit eye movements until it is 1-2 seconds away, at which point a saccade is made to another point on the road ahead (Wilkie et al., 2008; Wann and Swapp, 2000; Lappi et al., 2013a; Authie and Mestre, 2011). However saccadic and smooth pursuit eye movement performance may be impaired following a stroke (Rowe et al., 2013; Zihl, 2000) and such deficits could potentially negatively impact on driving.

This chapter examines the degree to which saccadic and smooth pursuit eye-movement performance remains intact post-stroke, and in particular if there are systematic differences across the individuals identified in Chapter 2. We hypothesised that some of the participants with stroke would have impairments in the execution of these eye movements and would also show impaired performance at visual search (Chapter 4), steering (Chapter 5) and hazard perception whilst driving (Chapter 6)

3.1 Visual Saccades

Human beings gain information from the visual scene around them by moving their eyes in a sequence of step wise movements in order to sample visual information from a number of targets (often closely linked to a current or planned action) across time (Land et al., 1999; Land, 2006; Land, 2009). A key reason for this is that the central (foveal) part of vision has a much higher resolution than peripheral vision and so has an important function in sampling visual information from the scene. Under normal conditions, several saccades may be made every second (Land et al., 1999). The next object or feature to be brought into foveal vision is often selected unconsciously and reflexively (Findlay and Walker, 1999), though eye-movements can also be consciously controlled and inhibited voluntarily in most circumstances. The saccadic system uses the location of the selected target on the retina to code the direction and amplitude of the next saccade in order to foveate the target (Robinson, 1964).

Figure 3.3 shows a 3 minute saccadic scan path (taken from Yarbus, A 1967 (Yarbus, 1967)) examining a picture of a face.

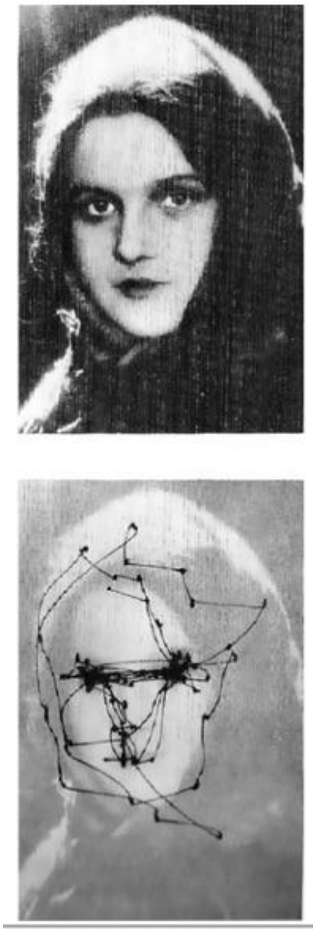

Figure 3.3: Scan path whilst viewing a face for 3 minutes (from Yarbus, A., 1967 (Yarbus, 1967))

Saccades are rapid, ballistic, eye-movements (of up to 700 deg/sec) that rotate the eyes towards a new target in the scene. Most saccades are followed up by a fixation (keeping the eye stable and directed at a point) to allow time to retrieve useful information from the target. Saccades are often reflexive (unconsciously directed to a salient target in the scene) but they can be generated voluntarily or even memory guided (rather than by an external stimulus). Irrespective of how they are generated, then tend to be remarkably similar in terms of trajectory and velocity (Bahill et al., 1975b; Bahill et al., 1975a; Collewijn et al., 1988). When making a saccade, the eye accelerates then decelerates with a peak velocity which increases as the amplitude of the saccade increases. For saccades of up to 60 degrees the relationship is fairly linear, but for saccades larger than 60 degrees the eye approaches maximum velocity at around 300 degrees per second, so the relationship tails off (Bahill et al., 1975b). The trajectory and destination of a saccade is fixed from 70 msec before it's initiation – new visual information after this time will not affect the saccade (Becker and Jurgens, 1979). However saccadic accuracy is modest – typically landing within 5-10% of the intended target (Kowler and Blaser, 1995) - and a smaller corrective saccade may then be made to correct the error. The corrective saccade typically begins after only a very brief fixation and this fact has been cited as evidence that the saccade is programmed in parallel with the previous eye movement (Walker and McSorley, 2006).

Even though the shape of the trajectory and the velocity of saccades are fairly stereotypical, the latency of a saccade (i.e. the time between a stimulus appearing and an eye movement towards it being initiated) varies widely between individuals and between trials even in an identical task. Saccade latency would typically sit around the 200ms mark in adults (Carpenter, 1988; Yang et al., 2002), but in some circumstances, saccadic latencies can be far quicker (around 120ms) and this population of saccades are termed 'express saccades'. These saccades were first observed when the central fixation target was set to disappear 200ms prior to the stimulus appearing (the 'gap' condition), producing a bimodal distribution of saccadic latencies of express saccades and fast regular saccades (Fischer and Ramsperger, 1984). More careful testing using 'catch trials' indicates that many saccadic latencies in the express range are in fact anticipatory saccades and so are not elicited by the actual stimulus. It is possible to produce a small number of genuine express saccades by increasing the stimulus luminescence (Kingstone and Klein, 1993), but even then the vast majority of visually guided saccades will have a latency in the region of 200ms.

3.2 Smooth Pursuit Eye Movements

Not infrequently, we may wish to track a moving object and to do this we use smooth pursuit eye movements. The goal of smooth pursuit eye movements is to keep a moving target centred on the fovea and if smooth pursuit is ineffective, the quality of visual information received by the brain is degraded (Bridgeman et al., 1999; Haarmeier and Thier, 1999). During smooth pursuit, the eye uses information about the difference in velocities between eye and target (Krauzlis, 2005; Lisberger and Westbrook, 1985), target location on the retina (Blohm et al., 2005) and target acceleration (Lisberger et al., 1987) to adjust the pursuit eye movements in order to keep the target foveated. In adults this process for targets moving predictably is very successful, although sometimes the target will outrun the eye and require a catch up saccade to be made – particularly if the object is moving at greater than 30 degrees per second (Leigh and Zee, 2006). The appearance of a moving target in the visual field can elicit pursuit eye movements with a latency in the region of 100-150ms (Bahill and McDonald, 1983; de Xivry and Lefevre, 2007). A similar delay is seen when the target changes trajectory and it may take further time for the velocity of the eye to come to match that of the target (de Xivry and Lefevre, 2007). In order to optimise target foveation the brain may try to overcome this processing time lag by using forward prediction of target location and velocity (Bahill and McDonald, 1983; Barnes and Asselman, 1991) or through the use of catch up saccades (de Brouwer et al., 2002).

3.3 The Interaction of Smooth Pursuit and Saccadic Eye Movements

Older research often stated that motion processing parts of the visual pathways in the brain were predominantly responsible for programming pursuit eye movements, and location sensitive areas of the brain's visual pathways programmed saccades (Petit and Haxby, 1999). However this simple model makes erroneous predictions about the case of trying to maintain foveation of a target which is moving unpredictably. Using smooth pursuit eye movements alone, generated purely from movement information would be a suboptimal strategy, as the lag in the feedback system (Bahill and McDonald, 1983; de Xivry and Lefevre, 2007) would cause the target to move off the fovea for significant portions of time whenever the velocity or direction changed. Using saccades to quickly bring the object back to the fovea would also be problematic, as by the time the saccade is programmed using purely location information, it would be executed to a point from which the target has already moved off. Furthermore, visual perception is very poor during a saccade, so use of frequent small saccades to keep a moving object on the fovea would lead to recurrent periods of absent visual processing of its features (Bridgeman et al., 1975). It is therefore unsurprising that movement information (Krauzlis, 2005; Lisberger and Westbrook, 1985) and location information (Blohm et al., 2005) provide input to smooth pursuit programming systems in the brain, and that location information (Leigh and Kennard, 2004) and movement information (de Brouwer et al., 2001) inform saccade generating systems. It is hypothesised that the brain tries to optimise the visual information received by the brain by trading off the disadvantages of saccades (absence of information during saccade execution) with those of smooth pursuit (frequent slipping of the target off the fovea) (de Xivry and Lefevre, 2007).

Because the motor systems that program and execute saccades and smooth pursuit movements are separate yet share many common input streams, it would be reasonable to expect that, in people with stroke, disorders of smooth pursuit and saccades may commonly, but not universally, co-exist. A key aim of this chapter is to establish which of our participants with stroke have deficits with either eye movement, or indeed which participants have problems with both types. Chapter 7 will examine if such eye movement problems predict steering or hazard perception abilities on the driving tasks described in Chapters 5 and 6.

3.4 Visual Saccades of People with Homonymous Visual Field Defects and Unilateral Spatial Neglect

A number of studies have shown that people with hemianopia are able to make reflexive saccades towards a target presented in the blind hemifield, although they are more likely to generate a saccade if the target is presented in the seeing hemifield (Barbur et al., 1988; Gassel and Williams, 1963a; Zihl, 1980). This ability to react to a stimulus in the blind hemifield, without conscious perception of it, may reflect some spared residual visual processing (Weiskrantz, 2004; Cowey, 2010) often termed ‘blindsight’ (Weiskrantz et al., 1974). This phenomenon is not universal to all people with postchiasmal hemianopia (Scharli et al., 1999; Blythe et al., 1987), but reflexive saccade generation towards a stimulus in the blind hemifield not consciously perceived (a form of action-blindsight (Danckert and Rossetti, 2005)) is a commonly reported phenomenon (Barbur et al., 1988; Blythe et al., 1987; Meienberg et al., 1981; Meienberg et al., 1986; Weiskrantz et al., 1974; Zihl, 1980; Zangemeister et al., 1982; Zihl, 1999). The latency of a saccade towards a target may be slower for some people with homonymous visual field than for those with normal vision (Barbur et al., 1988; Meienberg et al., 1981; Walker et al., 2000; Zihl, 1980).

As detailed in Chapter 1, many people with homonymous visual field loss will make inaccurate saccades usually falling short of the target, even when making repeated saccades between fixed targets of known location (Williams and Gassel, 1962; Zihl, 2000; Meienberg et al., 1981). (71% of those with hemianopia showed such saccadic dysmetria in the Zihl study). Latency and accuracy may improve if the person with hemianopia knows when and where the target will appear, compared to the target appearing in a random location at a random time (Meienberg et al., 1981; Zangemeister et al., 1982). When the target position is not predictable, a common response is to make a series of step-like hypometric saccades towards the target (Gassel and Williams, 1963a; Meienberg et al., 1981; Meienberg et al., 1986; Zangemeister et al., 1982), but when the target position is predictable, a smaller proportion of patients will make a hypermetric saccade followed by a saccade back to the target (Meienberg et al., 1981; Zihl, 2000),(22/90 hemianopes showed this pattern in the Zihl study). Meienberg proposed the possibility that the hypermetric pattern may be a compensatory mechanism of using a single large saccade to bring a target into the seeing hemifield to allow it then to be rapidly foveated with a second saccade (Meienberg, 1983). One of his patients tested 3 months later showed a much higher number of hypermetric saccades possibly supporting this hypothesis. Some have proposed that this strategy could be used as a form of cognitive rehabilitation to try and induce greater saccadic amplitudes in hemianopic patients through practice (Zihl, 2000; Kerkhoff et al., 1992; Kerkhoff et al., 1994). However a study of 10 children with homonymous hemianopia (who may reasonably be expected to adapt well to hemianopia), did not observe consistent use of hypermetric strategies in any participant. Moreover, one child may use different saccadic amplitudes from one trial to the next to try to find the target (Mezey et al., 1998).

In addition to the spatial saccadic errors, there also appear to be temporal delays for those with hemianopia - increased saccadic latencies even to targets presented in the ipsilesional hemifield have been reported (Walker et al., 2000; Zangemeister et al., 1982; Meienberg et al., 1981), although this finding is not universal (Barbur et al., 1988). Some studies have shown normal spatial parameters of saccades into the intact hemifield (Meienberg et al., 1981; Barbur et al., 1988), although a much larger study by Zihl showed that significant numbers of people with homonymous field loss had dysmetric saccades ipsilesionally (46/90 patients) and that the proportion of hypermetric saccades to hypometric saccades was larger when travelling ipsilesionally (Zihl, 2000). This is highly suggestive that, at least for some individuals, there is a problem in consistently programming and/or executing the spatial and temporal components of saccades – rather than simply strategically changing saccade behaviours as an adaptive process in response to the visual field loss.

Whilst problems generating saccades to single targets may be a useful indicator of likely difficulties, a number of saccades are usually strung together to enable the completion of tasks such as searching a scene for a target object. In visual scanning and search tasks similar changes to saccades have been observed in patients with hemianopia (particularly in those with slow search times) with the saccades falling short of the items in the search array. According to Poppelreuter these patients show scan paths that are disorganised and ‘fragmented’ and therefore are highly inefficient for completing the task in hand (Zihl, 2000; Poppelreuter, 1917 (Translation Zihl, J 1990); Hardiess et al., 2010). It is important to note that while the ability to generate an accurate saccade does correlate well with self reports of day to day disability, there is no clear relationship with the extent of visual field loss (Zihl, 2000). One explanation for this functional independence could be that saccadic dysmetria, visual search impairments and line bisection errors are caused by additional damage to white matter ‘feed forward’ structures anterior to the visual cortex (Zihl, 1999; Zihl, 1995b; Zihl et al., 2009) rather than the specific damage responsible for the visual field loss.

For someone with homonymous visual field loss, one could imagine that accurate scanning using saccades into the affected hemifield would be a useful way to gather visual information and compensate for visual field loss. One might also imagine that if the saccadic programming is impaired, then the ability to carry out this compensation will be limited, resulting in an increased functional deficit. In line with this argument, behaviours such as frequent eye and head movements into the affected hemifield have been correlated with better driving performance in some cases (Coeckelbergh et al., 2002a; Tant et al., 2002a). Furthermore, those with larger saccadic amplitudes, longer scanpaths, more gaze shifts and more fixations on vehicles (rather than the road or intersection), seemed better at a collision avoidance task (Papageorgiou et al., 2012b).

Visual field loss presents a challenge for successfully carrying out skilled actions such as driving, but there do seem to be potential avenues that may allow some individuals to compensate for their deficits. For those with unilateral spatial neglect, saccades towards targets in the contralesional hemifield may not occur at all, or will show increased latency and reduced accuracy almost universally through undershoot (Cochin et al., 1996; Butler et al., 2009; Girotti et al., 1983; Walker and Findlay, 1996). The actual execution of a saccade once it is initiated (i.e. in terms of the trajectory and velocity) will be normal (Behrmann et al., 2001) – the deficit seems to lie in the programming of the saccade. For ipsilesional saccades, latency may also be slower as compared to controls, although quicker than people with right brain strokes but no signs of unilateral neglect (Smania et al., 1998; Bartolomeo and Chokron, 1999b; Bartolomeo et al., 1998). More careful analysis has shown that at small eccentricities ipsilesionally (5 and 10 degrees) people with neglect can have detection rates and saccadic accuracy comparable to controls and saccadic latencies that outperform controls (Behrmann et al., 2002; Natale et al., 2007). Further left or right of this small window, detection rates, saccadic accuracy and latency were all worse than controls – with task performance dropping off more quickly in the contralesional direction.

When the visual environment is more complex – i.e. in a visual search task with distracters, people with unilateral neglect may preferentially focus on targets on the ipsilesional side and make fewer saccades into the affected hemispace (Husain et al., 2001; Gainotti et al., 2009; Behrmann et al., 1997; Mapstone et al., 2003), although this is not necessarily true for all patients, especially when a period of time has elapsed following the stroke (Harvey et al., 2002; Samuelsson et al., 2002). Patients have been shown who fixate the correct target but then fail to report it – demonstrating that the reduced accuracy in visual search tasks for people with hemispatial neglect is at least in part due impaired uptake or processing of information even when it is viewed correctly (Forti et al., 2005; Laeng et al., 2002). Other studies have shown that even when the target is located and registered, its location may not be remembered (Kristjansson and Vuilleumier, 2010; Husain et al., 2001).

3.5 Smooth Pursuit Performance of People after Stroke

Smooth pursuit deficits are well documented after stroke. A series of 915 stroke patients referred to optometry centres for visual problems revealed smooth pursuit disorders in only 37. Smooth pursuit difficulties were associated with strokes in many different locations. They were very commonly associated with saccadic dysmetria (20 out of 37 patients) and were also more common in patients with hemianopia and visual inattention (Rowe et al., 2013).

A number of different patterns of smooth pursuit difficulty have been described following stroke. They do not occur as a direct consequence of hemianopia or spatial neglect although are commonly associated with these conditions. The patterns include impaired pursuit ipsilesionally (with low gain and catch up saccades), symmetrical impaired smooth pursuit (with low gain and catch up saccades), impaired pursuit bidirectionally in the contralateral hemifield and paralysis of pursuit in the contralateral hemifield (which may be a feature of a neglect syndromes) (Sharpe and Morrow, 1991).

3.6 Eye Movement Experiments.

As described above, when people drive they tend to fixate a point on the road ahead and track it using smooth pursuit eye movements until it is 1-2 seconds in front. At this point a saccade is made to a point further ahead on the road (Wilkie et al., 2008; Wann and Swapp, 2000; Lappi et al., 2013a; Authie and Mestre, 2011). Saccades may also be used to fixate points on the road at which direction will change (Wilkie et al., 2008) and saccades into the affected hemifield during tasks such as driving may be a performance improving compensatory mechanism for some people with HVFDs (Tant et al., 2002a; Coeckelbergh et al., 2002a). However saccadic and smooth pursuit eye movement performance may be impaired following a stroke (Rowe et al., 2013; Zihl, 2000) and we hypothesised that such deficits could interfere with the normal active gaze mechanisms used in driving as well as adversely impact on compensatory gaze mechanisms that some participants may use to optimise steering performance.

Chapter 5 examines steering performance of our participant group during a simple bends task – a task anticipated to involve using the usual predictable pattern of saccade and smooth pursuit eye movements found in previous experiments (Wilkie et al., 2008; Wann and Swapp, 2000; Lappi et al., 2013a; Authie and Mestre, 2011). Chapter 6 examines the ability of our participants to make decision responses to pedestrians appearing on a city street – a task anticipated to also involve using saccades to targets (i.e. pedestrians) appearing at unpredictable locations on the road ahead, as well as the usual predictable pattern of saccades and smooth pursuit eye movements used in maintaining an appropriate steering trajectory. This Chapter therefore examines parameters of saccade and smooth pursuit performance anticipated to be relevant to the future driving tasks – namely the ability to make saccades to targets appearing at predictable locations (Experiment 3.1), the ability to make saccades to targets appearing at unpredictable locations (Experiment 3.2) and the ability to track a predictably moving target on the screen (Experiments 3.3 and 3.4 use targets moving at different velocities). Both Experiments 3.3 and 3.4 involve tracking a target moving in simple harmonic motion. During driving, if one is tracking a point on the road ahead, the velocity at which the eye must move to maintain foveation increases exponentially as the point approaches. It did not, therefore, seem appropriate to use targets moving at constant velocity for these smooth pursuit experiments.

3.6.1 Participants

Seventeen control subjects were initially tested (CONT18 could not be calibrated due to technical difficulties caused by reflections from rather thick lenses). No usable gaze data were obtained for participant LVI2 mostly due to ptosis and cognitive difficulties following the instructions that ensures consistent calibration. Fatigue related ptosis was problematic in tracking several members of the USN participant group.

Controls 4,7,8 and 13 were discounted from some analyses in experiment 3.1, and controls 10 and 13 were discounted from some analyses in experiment 3.2. In these datasets there were clear errors in the spatial calibration with the fixation direction offset by values greater than 1 degree when fixating the central target, as well as discrepancies between left and right saccades. (Because the shape of each person's eye is different, there are various parameters of the eye-tracker that need to be adjusted to ensure a good eye image is obtained. There is a definite art to getting good eye data and the skill of the experimenter improved over time, ensuring that more data was retrieved from those participants recruited later (mainly the participants with stroke). The initiation of saccades could still be determined, so saccade latency measures were taken for these participants.

Very limited data for LVI1 was obtained in experiments 2,3 and 4 mostly due to fatigue related ptosis which masks the features used by the eye tracker to monitor gaze direction. Over half of experiment 3.3 was successfully eye tracked – enough to allow an error measure to be generated, but not enough to generate a gain or lag measure (it was uncertain whether the furthest extents of the eye movements were tracked). Only a small number of saccades in experiment 3.2 were successfully eye tracked and no data were obtained for experiment 3.4. Limited eye tracking data for LVI3 was obtained during experiments 3.3 and 3.4, partly because of ptosis and partly because of head movements. There was insufficient data to be sure that the eye position was accurately being recorded rather than artefact, so no quantitative measures were calculated.

3.6.2 Apparatus

Visual fixation target stimuli were presented on a high resolution 17 inch CRT colour monitor (Vision Master, Ilyama, Japan) with 1024 x 768 pixels spatial resolution and 75Hz refresh rate with a mean luminance of 50cd/m^2. The visual target was an annulus presented on a black background consisting of a large white circle with a diameter subtending 1.5 degrees of visual angle containing a smaller black circle subtending a diameter of 0.5 degrees of visual angle. The targets were generated using Experiment Builder Software (SR Research Ltd., Canada). Participants were seated 57cm from the monitor with their chin and forehead secured on an Eyelink 5000, 1000 Hz eye tracking system (SR Research Ltd, Canada – see Figure 3.4). In this position the total screen width subtended slightly more than 37 degrees of visual angle. All experiments took place in a quiet room free of external light sources. The participants all wore their custom made spectacles for this task.

Figure 3.4: The Eyelink 1000. Left panel: the control screen showing the eye image and the features used to calibrate and measure the direction of gaze relative to the screen. Right panel: the experimental setup with a participant resting their head in the chin and forehead rest, viewing the display.

3.6.3 Procedure

Experiment 3.1: The experiment began with on screen instructions to look at each target as it appeared. Each participant then had 2 practice attempts to fixate a target on the left and on the right (a total of 4 iterations). Following this a total of 16 iterations occurred, with 8 left targets and 8 right targets presented alternately in a regular and predictable fashion. In each iteration of experiment 3.1, a target first appeared in the middle of the screen to centre the participants gaze (Figure 3.5, top panel). After 1 second this target disappeared and immediately another target appeared 15 degrees left or right of centre which the participant then had to fixate

(Figure 3.5, bottom panel). The target appeared alternately left or right on each iteration and remained on screen for 1.5 seconds after which the screen turned black for 2 seconds.

Experiment 3.2: Following on screen instructions to look at each target as it appeared, a target also first appeared in the middle of the screen to centre the participants gaze (Figure 3.5, top panel), but this stayed visible for either 1, 1.5 or 2 seconds (duration was random from trial to trial). The target would then disappear, and reappear in a position either 15 degrees left (Figure 3.5, bottom panel), 7.5 degrees left, 7.5 degrees right or 15 degrees right of centre. The target would appear in each location a total of 8 times, but the sequence in which this happened was randomly generated for each participant so both the timing to generate the saccade and the spatial location of the target was unpredictable for each trial. Experiment 3.2 was preceded by 4 unrecorded practice trials (1 at each location).

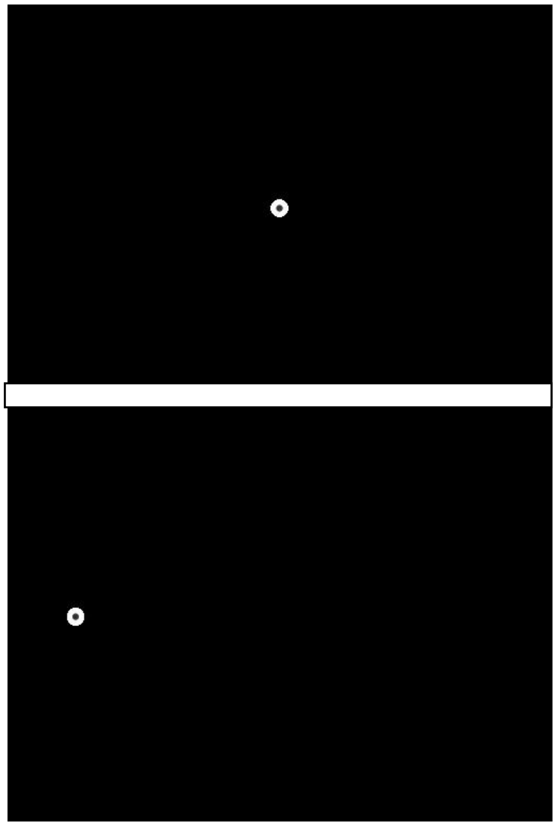

Figure 3.5: Central fixation followed by target moving 15 degrees to left

Experiment 3.3: Participants were given clear verbal and on screen instructions to track a moving target with their eye as accurately as possible. They were then given a practice run consisting of 2 complete cycles of the trial prior to each experiment. The task was to track a target horizontally across the centre of the screen moving back and forth in simple harmonic motion with an amplitude of 15 degrees (in each direction). The target made 8 complete cycles from centre to left to centre to right and back to centre again, with a frequency of 5 seconds per cycle (the trial therefore lasted a total of 40 seconds).

Experiment 3.4: The procedure was the same as Experiment 3.3 except that the target moved more quickly, so there were 10 complete cycles and the frequency was 2.5 seconds per cycle (so total trial time was 25 seconds). The maximum target velocity in the fast target trial was 37.7 degrees per second.

3.6.4 Analysis

Saccade trials (Experiments 3.1 and 3.2): The Eyelink 5000 recorded the location of the eye at 1000Hz. From these measurements the start and end location and timing of every saccade and fixation could be calculated. For each trial the first eye movement following the appearance of the target that exceeded 2 degrees in amplitude towards the target with a latency exceeded 80ms was classified as a reflexive saccade – this is the standard criteria for classifying a saccade as having been visually guided (Wenbansmith and Findlay, 1991). If the initial saccade began before 80ms, the saccade was treated as a predictive eye-movement and the trial was coded but the eye data was discounted from further analysis. Similarly any first saccade going in the wrong direction (away from the target) or any trial in which eye tracking data was lost for any reason was coded and the eye data was removed from further analysis.

Previous research would indicate that control subjects would initiate the vast majority of first saccades at around 200ms following target appearance (or perhaps a little slower given the older age of the control group compared to previously published experiments) and that the vast majority would land within 10% of the distance to the target. There was no expectation of a lateralised bias for the control participants so the results from the left and right sides of the display were collapsed together.

For participants with HVFDs or USN greater variation in task performance could be expected. Based on previous research it is likely that some saccades will not be generated, some that are generated will have longer latencies than the controls, many will undershoot the target and some may sometimes overshoot the target. It is to be expected that there may be systematic biases in saccadic performance according to whether the target lay in the affected hemifield, so results have been split accordingly.

Any first saccade missing the target centre by more than 1.5 degrees was coded as either an “undershoot” or “overshoot” if a second or third saccade found the target; whereas it was coded as a “miss” if the eye never fixated the target (Kowler and Blaser, 1995). A number of outcome measures were calculated for each participant. Medians were used rather than means because it seemed likely that there would be the odd spurious trial that could unduly bias the estimate of central tendency:

1. Median **latency** of the first visually guided saccade to the target
2. Median **error** of the first saccade (in degrees)
3. Median **bias** of the first saccade (in degrees) where negative numbers indicate an undershoot and positive numbers indicate an overshoot

4. Performance in each trial was also placed into one of the following categories:

NA: Predictive saccade made, eye tracking failed, saccade made in wrong direction or eye not on central fixation point at start of task (Discounted from analysis 1-3)

NS: No saccade of at least 1.5 degrees amplitude made towards target. (Discounted from analysis 1-3)

M: Saccade made towards target but target never fixated – i.e. at no point did the eye rest within 1.5 degrees of target. (It turns out all such saccades were undershoots).

U: Undershoot saccade which was subsequently corrected to fixate the target through 1 or more corrective saccades

O: Overshoot saccade which was subsequently corrected to fixate the target through 1 or more corrective saccades within the 2 seconds allotted for each trial

DH: Direct hit – first saccade made within 1.5 degrees of target.

An error margin of 1.5 degrees was established through exploratory analyses that examined the eye movement data of a healthy adult and an older adult volunteer. The vast majority of closest fixations to the target fell within the 1.5 degree zone, and conveniently this corresponded exactly with a previous study that had found that the vast majority of visually guided saccades to a target landed within 10% of the intended target (Kowler and Blaser, 1995).

Finally group analysis was conducted between 3 groups – the controls, the HVFD group (LHH1-6 and RHH1-6) and the USN group (LVI1-4, RVI1 and LHHVI) – for mean saccadic latencies and mean bias of first saccade. ANOVAs were conducted (one way ANOVAs for experiment 3.1 and repeated measures ANOVAs for experiment 3.2) to compare these parameters and if the ANOVA was significant, planned contrasts compared each pair of groups to elicit where the significant differences lay. As no significant difference was expected between leftward and rightward saccades for the control group, data was averaged across saccades in both directions. The entire control datasets were used to contrast with contralesional and ipsilesional saccades separately for the groups of participants with stroke.

Smooth pursuit trials (experiments 3.3 and 3.4): As previously the eye position was recorded at 1000 frames per second. For each outcome measure, the entire first cycle of the moving target was discounted from analysis (in order to give each participant a chance to have fully entered the pursuit tracking phase whilst excluding the catch-up saccades used at the initiation of movement). As previously some degree of bias was expected for the stroke group, so data were separated into whether the eye was moving in a leftward or rightward direction (control data was collapsed across eye direction since no directional biases were expected for this group). For each experiment a number of outcome measures were calculated:

1. Mean **Gain:** The ratio by which the eye undershot (gain <1) or overshot (gain >1) the positions of the target at the peak of each cycle (extreme left and right positions)
2. Mean **Lag:** The number of milliseconds that the eye was in front (-ve number) or behind (+ve number) the target at the extreme ends of the path.

3. Mean **Error:** Mean distance in degrees from eye to target.

Group analysis was conducted between the 3 groups – the controls, the HVFD group (LHH1-6 and RHH1-6) and the USN group (LVI1-4, RVI1 and LHHVI) – for mean lag, mean gain and mean error. Repeated measures ANOVAs were conducted to compare between groups these 3 parameters separately across the 2 task conditions (fast and slow) and if the ANOVA was significant, planned contrasts compared each pair of groups to elicit where the significant differences lay. As no significant difference was expected between leftward and rightward smooth pursuit for the control group, data was averaged across both directions. The entire control datasets were used to contrast with smooth pursuit in a contralesional and ipsilesional direction separately for the groups of participants with stroke.

3.6.5 Results: Experiments 3.1 and 3.2 (first saccades)

Experiment 3.1: The control group performed as expected. The mean latency to saccade initiation was 209.9 ms following target appearance (very close to the expected value of 200ms), and mean accuracy was 0.88 degrees (well within the expected 10% margin of error). On average the saccades of the control group exhibited a small amount of undershoot (-0.34deg). The control group results are given in Table 3.12. As would be expected for healthy individuals, some in the control group made accurate saccades to all targets (16 direct hits; Table 3.13), but when participants didn't achieve a direct hit, they usually made an 'undershoot' followed by a corrective saccade to perform the task (Table 3.13).

Table 3.12: Latencies and errors of the first saccade to a target appearing at 15 degrees at a predictable time and place (control group)

Participant	Med. Latency (ms)	Med. Error (deg)	Med. Bias (deg)
CONT1	227	0.99	-0.99
CONT2	241	1.12	+1.12
CONT3	246	0.6	-0.6
CONT5	195	1.12	+0.14
CONT6	159	0.62	+0.05
CONT9	193	0.97	-0.97
CONT10	200	1.14	+0.21
CONT11	196	1.13	-0.94
CONT12	280	1.39	-1.39
CONT14	180	0.44	+0.01
CONT15	187	0.53	-0.2
CONT16	181	0.66	-0.66
CONT17	329	0.66	-0.19
CONT4	179	-	-
CONT7	219	-	-
CONT8	176	-	-
CONT13	181	-	-
Range	159-329	0.44-1.39	-1.39 -+1.12

Table 3.13: Number of trials (out of a total of 16) categorised using the method 3.6.4 for each participant in the Control group.

Participant	Direct Hit	Undershoot	Overshoot	Miss	No Saccade	Not counted
CONT1	13	3	0	0	0	0
CONT2	15	0	0	0	0	1
CONT3	13	1	0	0	0	2
CONT5	15	1	0	0	0	0
CONT6	13	0	0	0	0	3
CONT9	10	6	0	0	0	0
CONT10	15	0	0	1	0	0
CONT11	11	4	1	0	0	0
CONT12	9	7	0	0	0	0
CONT14	16	0	0	0	0	0
CONT15	16	0	0	0	0	0
CONT16	15	1	0	0	0	0
CONT17	13	0	3	0	0	0

For the participants with stroke, the results were separated into targets in the affected hemifield (Table 3.14 and Figures 3.6 and 3.7), and targets in the unaffected hemifield (Table 3.57 in Appendix 3).

All entries marked in red lie outside the range of results obtained for controls (to classify the number of misses, undershoots etc. relative to controls, the highest value was taken and halved (rounding up) because left and right trials were added together for controls).

Table 3.14: Performance of participants with stroke on the predictable target simple saccade task for targets appearing in the affected hemifield. Lat = median latency to first saccade (in milliseconds); Error = median error of first fixation (in degrees); Bias = median distance of first fixation from target with negative numbers showing an Undershoot (U) and positive numbers an Overshoot (O). DH = Direct Hit; M = Miss; NS = No Saccade; NA = Not Counted.

	Participant	Lat(ms)	Error(deg)	Bias(deg)	DH	U	O	M	NS	NA
HVFD	LHH1	329	6.31	-6.31	0	5	0	3	0	0
	LHH2	212	1.18	-1.18	7	1	0	0	0	0
	LHH3	268	3.27	-3.27	2	6	0	0	0	0
	LHH4	238	1.94	-1.94	2	6	0	0	0	0
	LHH5	314	2.01	-2.01	0	8	0	0	0	0
	LHH6	214	1.26	-1.26	5	3	0	0	0	0
	RHH1	201	2.58	-1.33	2	2	1	1	0	2
	RHH2	272	9.84	-9.84	0	7	0	1	0	0
	RHH3	289	3.09	-3.09	1	3	0	2	1	1
	RHH4	637	10.64	-10.64	0	0	0	4	4	0
	RHH5	279	0.65	-0.41	7	0	0	0	0	1
	RHH6	176	0.51	-0.44	6	1	0	0	0	1
USN	LHHVI	246	11.92	-11.92	0	2	0	3	3	0
	LV1	331	6.76	-6.76	1	6	0	0	0	1
	LVI3	421	8.58	-8.58	0	2	0	3	3	0
	LVI4	191	3.37	-3.37	1	7	0	0	0	0
	RVI1	281	1.29	-1.29	6	2	0	0	0	0

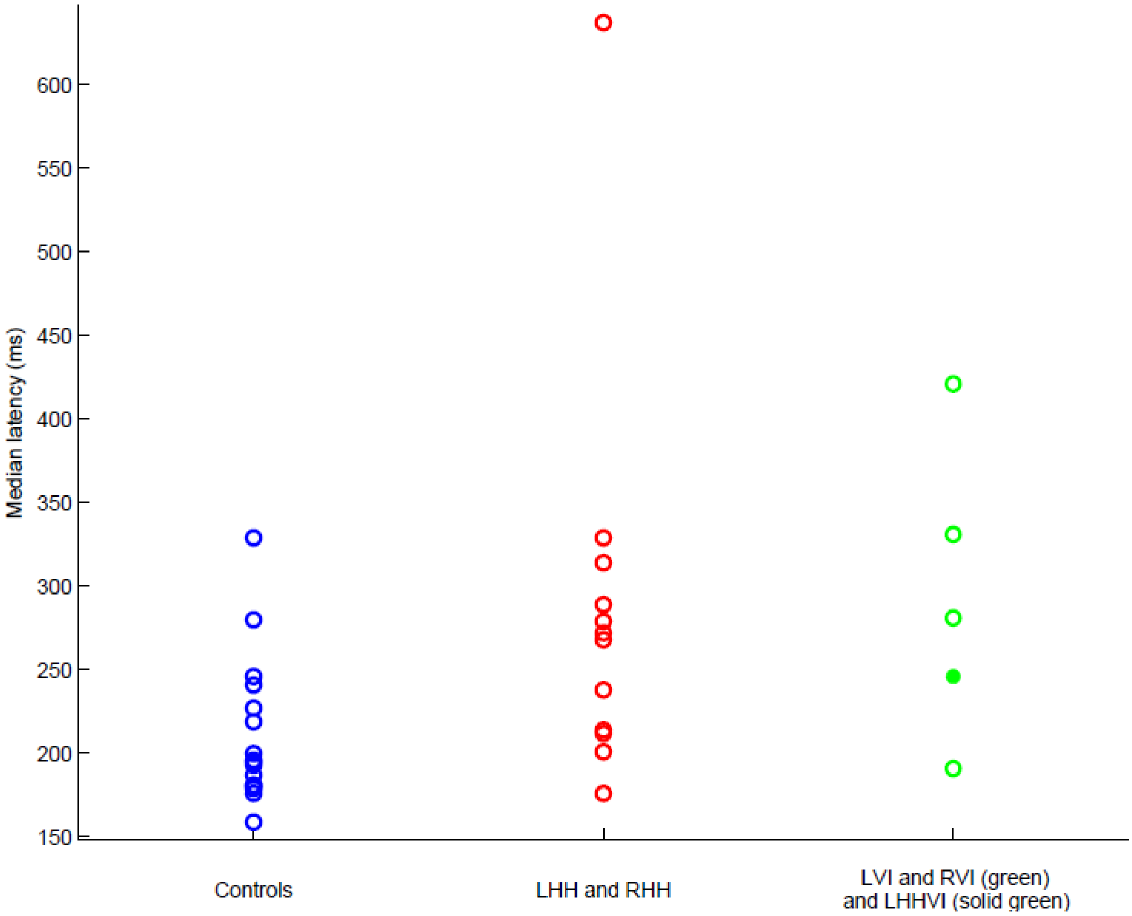

Figure 3.6: Median latencies to predictable target appearing in the affected hemifield (Saccade Experiment 3.1).

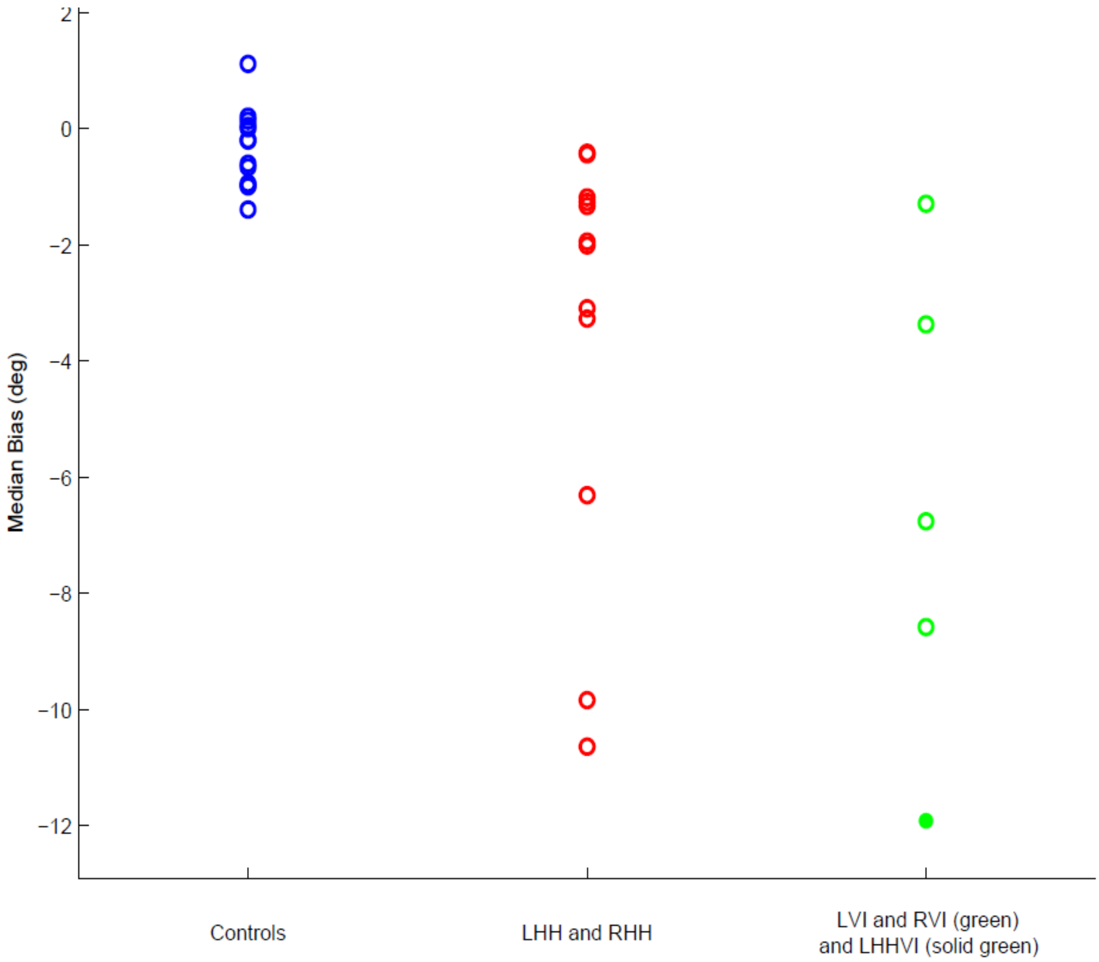

Figure 3.7: Median bias of first saccade to predictable target appearing in affected hemifield (Saccade experiment 3.1)

For saccades to target in the affected hemifield, mean (of medians) latencies were: Controls: 210ms, HVFD group: 286ms, USN group: 294ms. Levene's test showed that variance was homogenous ($p=0.246$). A one way ANOVA showed significant differences between the groups: $F(2,33) = 3.689$, $p = 0.037$. Planned contrasts showed a significant difference between the controls and the HVFD group: ($t(31) = 2.389$), $p = 0.023$, $d = 0.839$). No difference was found between the controls and USN group: ($t(31) = 1.963$), $p = 0.059$, or between the HVFD and USN groups: ($t(31) = 0.184$), $p = 0.855$.

For mean (of medians) bias of first saccade to a target in the affected hemifield were: Controls: -0.34 deg, HVFD group: -3.34 deg, USN group: -6.38 deg.

Levene's test showed that variance was not homogenous ($p = 0.002$). Welch's test detected a significant difference between groups: ($F(2,8.065) = 8.784$), $p = 0.009$. Planned contrasts (with no assumption of homogeneity of variance) showed a significant difference between the control group and the HVFD group: ($t(11.733) = -3.019$), $p = 0.11$, $d = 1.233$ and a significant difference between the control group and the USN group: ($t(4.079) = -3.20$), $p = 0.32$, $d = 2.0$. No difference was found between the HVFD group and the USN group: ($t(6.51) = -1.36$), $p = 0.219$.

For saccades to target in the unaffected hemifield, mean (of medians) latencies were: Controls: 210ms, HVFD group: 221ms, USN group: 230ms. Levene's test showed that variance was homogenous ($p=0.523$). A one way ANOVA showed no significant differences between groups: ($F(2,33) = 0.368$), $p = 0.695$.

For mean (of medians) bias of first saccade to a target in the affected hemifield were: Controls: -0.34 deg, HVFD group: -0.75 deg, USN group: -0.69 deg. Levene's test showed that variance was homogenous ($p = 0.787$). A one way ANOVA showed no significant differences between groups: ($F(2,29) = 0.798$), $p = 0.461$.

Experiment 3.2: For the control group, results for left and right sided targets were combined, producing two results – one for far targets (15 degrees left or right from centre; Table 3.15) and one for near targets (7.5 degrees from centre; Table 3.16).

Table 3.15: Control results for the unpredictable target saccade task with targets either 15 degrees left or right of centre. DH = Direct Hit; U = Undershoot; O = Overshoot; M = Miss; NS = No Saccade; NA = Not Counted

Participant	Lat (ms)	Error (deg)	Bias (deg)	DH	U	O	M	NS	NA
CONT1	245	1.18	-1.08	11	4	1	0	0	0
CONT2	261	1.49	-0.62	8	5	0	3	0	0
CONT3	295	0.91	-0.79	10	4	0	2	0	0
CONT4	178	0.74	-0.70	10	2	0	2	0	2
CONT5	201	0.98	-0.81	15	1	0	0	0	0
CONT6	220	0.55	-0.34	14	2	0	0	0	0
CONT7	227	1.16	-1.16	10	6	0	0	0	0
CONT8	192	0.98	-0.16	9	0	1	3	0	3
CONT9	196	2.16	-2.16	3	13	0	0	0	0
CONT11	196	1.60	-1.60	7	8	0	1	0	0
CONT12	248	1.63	-1.63	7	9	0	0	0	0
CONT14	188	0.43	+0.29	16	0	0	0	0	0
CONT15	215	0.64	-0.64	16	0	0	0	0	0
CONT16	176	1.19	-0.86	11	3	0	2	0	0
CONT17	337	0.82	+0.27	16	0	0	0	0	0
CONT10	191	-	-	-	-	-	-	-	-
CONT13	217	-	-	-	-	-	-	-	-
Range	176-337	0.43-2.16	-2.16-+0.29	3-16	0-13	0-1	0-3	0	N/A

Table 3.16: Control results for unpredictable target saccade task with targets appearing either 7.5 degrees left or right of centre. DH = Direct Hit; U = Undershoot; O = Overshoot; M = Miss; NS = No Saccade; NA = Not Counted

Participant	Lat (ms)	Error (deg)	Bias (deg)	DH	U	O	M	NS	NA
CONT1	224	0.38	+0.24	16	0	0	0	0	0
CONT2	229	1.25	-1.25	9	7	0	0	0	0
CONT3	263	0.46	+0.46	16	0	0	0	0	0
CONT4	171	1.16	-0.31	10	5	0	1	0	0
CONT5	193	0.42	+0.06	16	0	0	0	0	0
CONT6	210	0.67	+0.61	15	1	0	0	0	0
CONT7	188	0.48	-0.48	15	1	0	0	0	0
CONT8	191	0.91	+0.91	8	0	1	1	0	6
CONT9	206	0.52	-0.34	14	2	0	0	0	0
CONT11	178	0.42	-0.23	16	0	0	0	0	0
CONT12	229	0.19	-0.06	16	0	0	0	0	0
CONT14	178	0.72	+0.72	16	0	0	0	0	0
CONT15	199	0.58	+0.54	16	0	0	0	0	0
CONT16	129	0.73	-0.29	10	6	0	0	0	0
CONT17	351	0.52	+0.06	12	0	2	2	0	0
CONT10	199	-	-	-	-	-	-	-	-
CONT13	180	-	-	-	-	-	-	-	-
Range	129-351	0.19-1.25	-1.25-+0.91	8-16	0-7	0-2	0-2	0	-

For the participants with stroke, results were separated according to whether the target appeared 15 degrees into the affected hemifield (Table 3.17 and Figures 3.8 and 3.9), 7.5 degrees into the affected hemifield (Table 3.18 and Figures 3.10 and 3.11), 15 degrees into the unaffected hemifield (Table 3.58, Appendix 3) or 7.5 degrees into the unaffected hemifield (Table 3.59, Appendix 3). Results in red lie outside the range of the control group.

Table 3.17: Results for the unpredictable saccade experiment where targets appeared 15 degrees into the affected hemifield. DH = Direct Hit; U = Undershoot; O = Overshoot; M = Miss; NS = No Saccade; NA = Not Counted

	Participant	Lat.(ms)	Error(deg)	Bias(deg)	DH	U	O	M	NS	NA
HVFD	LHH1	406	11.27	-11.27	0	0	0	7	1	0
	LHH2	191	1.19	-1.19	5	3	0	0	0	0
	LHH3	311	6.24	-6.24	2	5	1	0	0	0
	LHH4	265	2.70	-2.70	2	5	1	0	0	0
	LHH5	325	2.39	-2.39	0	7	0	1	0	0
	LHH6	288	1.75	-1.75	3	5	0	0	0	0
	RHH1	271	11.72	-11.72	0	3	0	2	0	3
	RHH2	459	6.47	-6.47	0	4	0	2	0	2
	RHH3	298	3.39	-3.39	2	5	0	0	0	1
	RHH4	-	-	-	0	0	0	0	8	0
	RHH5	282	1.08	-0.95	6	1	0	1	0	0
	RHH6	281	1.15	-0.46	7	1	0	0	0	0
USN	LHHVI	314	12.59	-12.59	0	0	0	3	5	0
	LV1	211	9.6	-9.6	0	1	0	0	0	7
	LVI3	784	7.29	-7.29	0	0	0	2	6	0
	LVI4	188	2.91	-2.91	1	7	0	0	0	0
	RVI1	284	0.60	-0.32	6	1	1	0	0	0

RHH4 made no saccades towards any target 15 degrees to the right. LVI1 was extremely difficult to eye track as he had a degree of ptosis and his eyelids kept blocking the eye camera’s view of the eye.

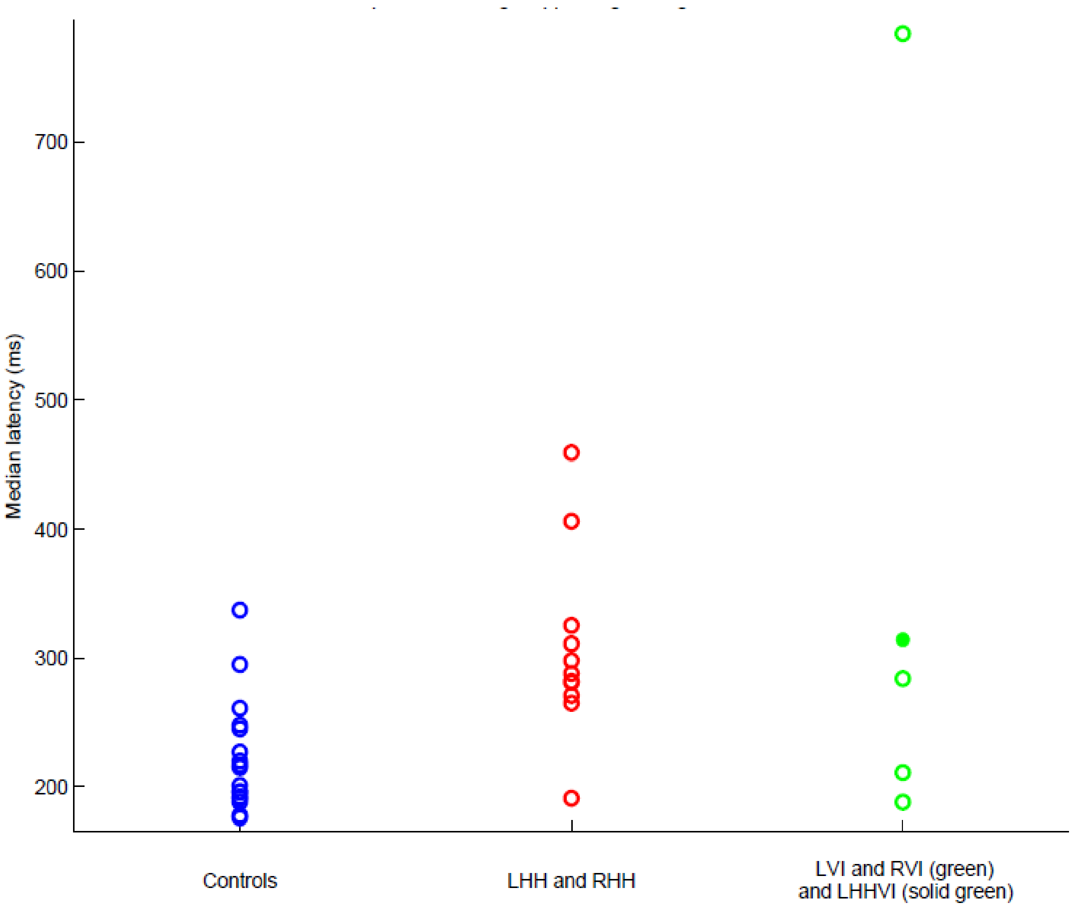

Figure 3.8: Median latency of first saccade to unpredictable target appearing 15 degrees into affected hemifield.

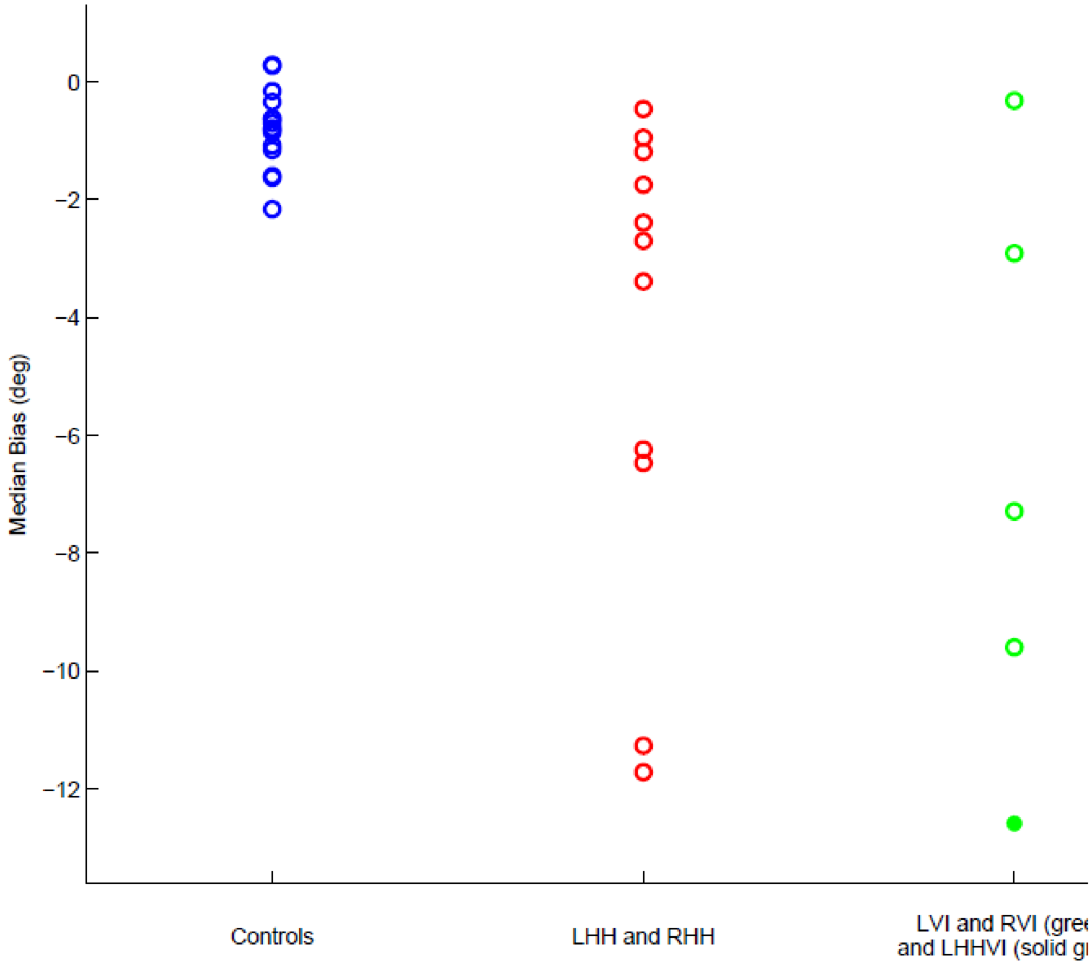

Figure 3.9: Median bias of first saccade to unpredictable target appearing 15 degrees into affected hemifield

Table 3.18: Results for the unpredictable saccade experiment where targets appeared 7.5 degrees into the affected hemifield

	Participant	Lat(ms)	Error(deg)	Bias(deg)	DH	U	O	M	NS	NA
HVFD	LHH1	303	2.09	-2.09	0	5	2	0	1	0
	LHH2	197	0.15	+0.10	8	0	0	0	0	0
	LHH3	322	3.11	-2.98	1	3	1	2	0	1
	LHH4	258	0.94	+0.03	8	0	0	0	0	0
	LHH5	235	0.41	-0.08	8	0	0	0	0	0
	LHH6	274	0.58	+0.43	8	0	0	0	0	0
	RHH1	229	1.99	+0.14	3	1	2	0	0	2
	RHH2	440	1.88	+0.91	2	2	0	1	3	0
	RHH3	242	2.77	+0.46	2	1	4	1	0	0
	RHH4	900	2.34	-2.34	0	0	0	2	6	0
	RHH5	149	3.03	-3.03	2	5	1	0	0	0
	RHH6	222	1.13	+1.13	5	0	3	0	0	0
USN	LHHVI	296	4.92	-4.92	0	0	0	2	6	0
	LV1	260	2.09	-2.09	0	1	0	0	0	7
	LVI3	271	3.46	-3.46	0	3	0	4	1	0
	LVI4	179	0.59	+0.59	8	0	0	0	0	0
	RVI1	233	0.69	+0.46	8	0	0	0	0	0

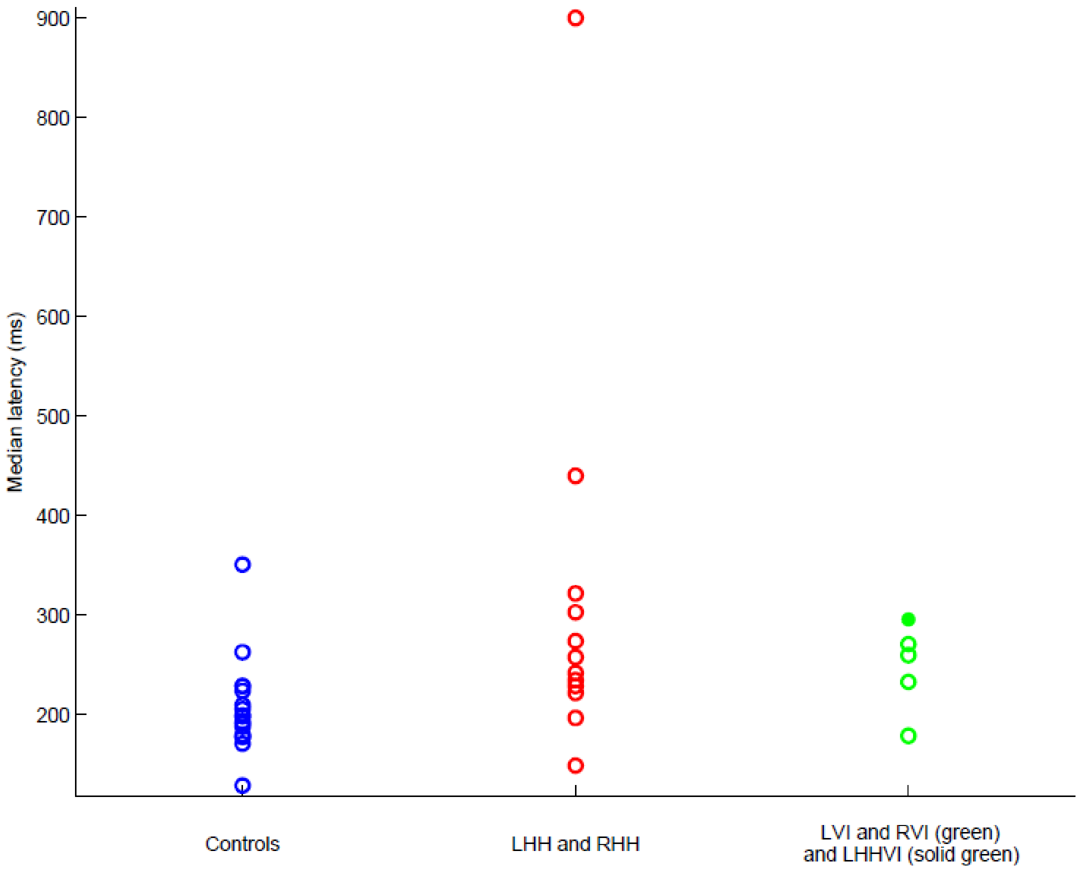

Figure 3.10: Median latency of first saccade to unpredictable target 7.5 degrees into affected hemifield

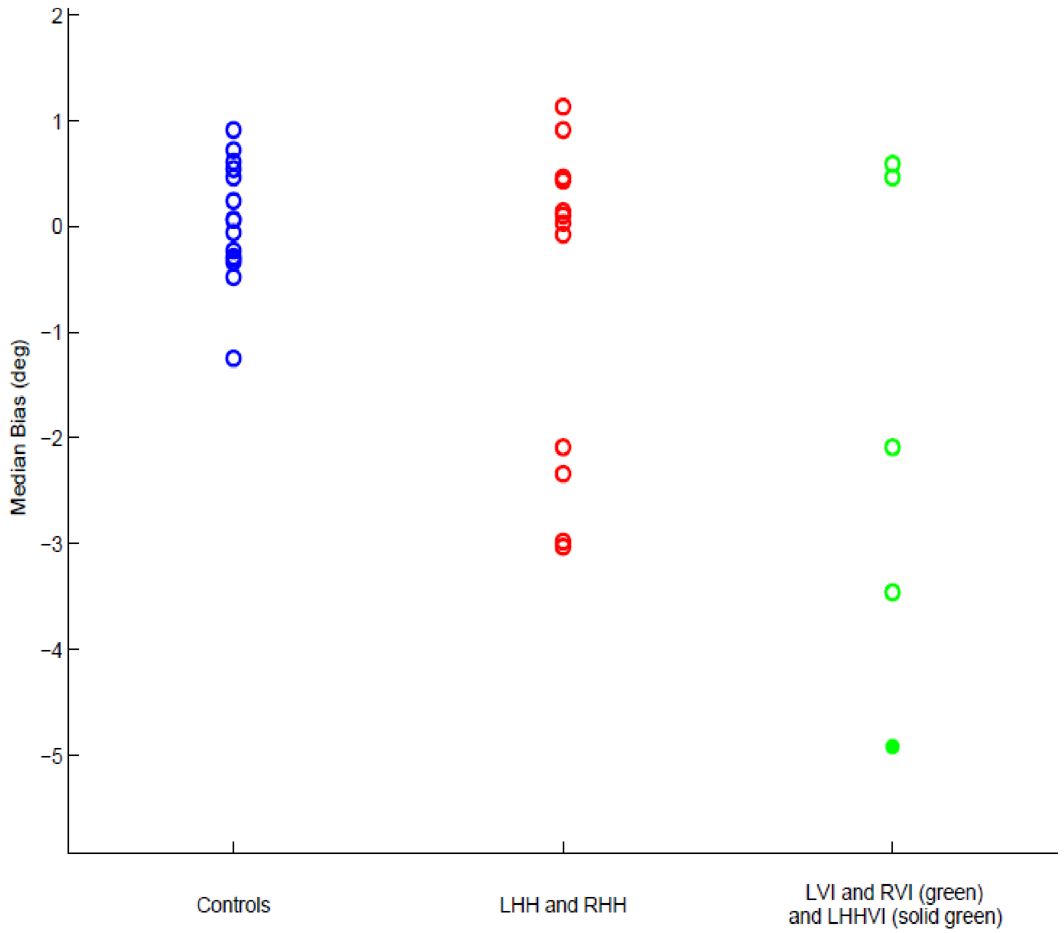

Figure 3.11: Median bias of first saccade to unpredictable target appearing 7.5 degrees into affected hemifield

Repeated measures ANOVAs were performed separately for ipsilesional and contralesional targets to analyse the effect of group (control, HVFD or USN) and of eccentricity of target (7.5 degrees or 15 degrees) on saccadic latency and bias of first fixation. For saccades to contralesional targets, mean (of medians) saccadic latencies for 15 degree targets were as follows: Controls: 223ms, HVFD group: 307ms, USN group: 356ms. Mean saccadic latencies to contralesional targets at 7.5 degrees from midline were: Controls: 207ms, HVFD group: 261ms, USN group: 248ms. A repeated measures ANOVA found a significant difference in latency between task conditions (i.e. 7.5 degree targets or 15 degree targets): $F(1,30) = 10.452$, $p = 0.003$, partial eta squared = 0.258. There was also a significant difference between groups: $F(2,30) = 4.667$, $p = 0.017$, partial eta squared = 0.237. There was no significant interaction between group and condition: $F(2,30) = 2.145$, $p = 0.135$. Post hoc Bonferroni analysis was performed to try and distinguish where the group differences lay, but no comparison reached statistical significance: Comparison between control and HVFD group: $p = 0.053$, between control and USN group: $p = 0.67$, between HVFD and USN group: $p = 1$.

For saccades to contralesional targets, mean bias of first saccade for 15 degree targets were as follows: Controls: -0.8 deg, HVFD group: -4.41 deg, USN group: -6.54 deg. Mean first saccade bias to contralesional targets at 7.5 degrees from midline were: Controls: +0.04 deg, HVFD group: -0.45 deg, USN group: -1.88 deg. A repeated measures ANOVA found a significant difference in bias between task conditions (i.e. 7.5 degree targets or 15 degree targets): $F(1,28) = 35.24$, $p < 0.001$, partial eta squared = 0.557. There was also a significant difference between groups: $F(2,28) = 8.213$, $p = 0.002$, partial eta squared = 0.370. There was also a significant interaction between group and condition: $F(2,28) = 6.183$, $p = 0.006$, partial eta squared = 0.306. Post hoc Bonferroni analysis demonstrated a significant difference between the control and HVFD group: $p = 0.041$ and between the control and USN group: $p = 0.001$, but no difference between the HVFD and USN groups: $p = 0.105$. Looking at the raw data it seems that the control group had accurate saccades to all targets, the HVFD group had reduced saccadic accuracy to targets 15 degrees into the hemianopic field but not targets 7.5 degrees into the affected hemifield. The USN group had inaccurate saccades to both types of contralesional targets.

For saccades to ipsilesional targets, mean (of medians) to targets at 15 degrees were: Controls: 223ms, HVFD group: 255ms, USN group: 267ms. Mean saccadic latencies to targets at 7.5 degrees from midline were: Controls: 207ms, HVFD group: 219ms, USN group: 194ms. A repeated measures ANOVA found a significant difference in latency between task conditions (i.e. 7.5 degree targets or 15 degree targets): $F(1,31) = 27.461$, $p < 0.001$, partial eta squared = 0.470. There was no significant difference between groups: $F(2,31) = 0.905$, $p = 0.415$. There was, however, a significant interaction between group and task condition: $F(2,31) = 4.0$, $p = 0.029$, partial eta squared = 0.205. This interaction is presumably driven by differences for the 2 groups of participants with stroke. Controls showed little difference in latency between 15 degree and 7.5 degree targets (difference = 16ms). For the HVFD group the difference was 36ms and for the USN the difference was 71ms.

For saccades to ipsilesional targets, mean bias of first saccade for 15 degree targets were as follows: Controls: -0.8 deg, HVFD group: -0.65 deg, USN group: -1.10 deg. Mean first saccade bias to contralesional targets at 7.5 degrees from midline were: Controls: +0.04 deg, HVFD group: +0.12 deg, USN group: -0.37 deg. A repeated measures ANOVA found a significant difference in bias between task conditions (i.e. 7.5 degree targets or 15 degree targets): $F(1,28) = 32.05$, $p < 0.001$, partial eta squared = 0.534 (although the mean differences are very small in absolute terms – less than 1 degree of visual angle). There was no significant difference between groups: $F(2,28) = 1.051$, $p = 0.363$, and no significant interaction between group and condition: $F(2,28) = 0.06$, $p = 0.942$.

3.6.6 Discussion: Experiments 3.1 and 3.2 (Saccades)

As expected in our control group, the majority of saccadic latencies were close to the 200ms mark and the majority of saccades landed within 1.5 degrees of the target. There were some exceptions – CONT17 showed very high median saccadic latency in experiment 3.2 (337ms and 351ms depending on target location). In experiment 3.2 median error of first saccade to target was beyond the expected maximum of 1.5 degrees for 3 controls for the 15 degree saccades (CONT 9, 11 and 12). Whilst one may reasonably expect greater variability in older controls, it is notable that CONT11 was only 51 years old at the time of testing. Most controls did perform within expected parameters however, and it is extremely noticeable that, whilst corrections of initial undershoots are quite common, trials in which the target was never fixated are very rare (maximum was 3/16 in experiment 3.2) and there were no occurrences of no saccade toward the target at all.

At a group level, both the HVFD and USN groups showed longer saccadic latency and reduced accuracy of saccades to contralesional targets in comparison to controls, but no difference in saccadic latency or accuracy to ipsilesional targets. There were no significant differences found between the HVFD group and the USN group. Interestingly, for targets appearing 7.5 degrees ipsilesionally, the USN group showed faster saccadic latencies than controls, in keeping with the findings of other authors (Behrmann et al., 2002; Natale et al., 2007).

The main reason for measuring the performance by the control group was to provide a measure by which to classify potential abnormal saccade performance in the stroke group. After some deliberation the clearest way to identify potentially abnormal results was to highlight each measure falling beyond the range of control performance. The tables of results highlight in red each measure that exceeded the maximum performance value of control participants. The main purpose of the saccade experiments was to find a measure that could dichotomise the HVFD stroke group as into high performing or low performing subgroups as per previous research (Zihl, 1995b; Hardiess et al., 2010).

There were four HVFD participants that performed the saccade task quite well: LHH2, LHH6 and RHH6 all performed within the range of Controls for latency and accuracy of saccades to targets in the affected hemifield, and RHH5 came very close to control performance (although they tended to make hypometric saccades towards the nearer targets on the right during the unpredictable saccade task). Saccadic latencies in the unpredictable task for far targets on the affected side were somewhat slower for LHH6, RHH5 and RHH6, but still within reference range. It is notable that all 4 of these participants had a fair degree of visual field sparing despite HVFD (either quadrantanopias or a paracentral scotoma in the case of LHH6) and had also scored within the normal range on the ACE-R cognitive test and the trail making tests.

Three HVFD participants were apparently worse than controls, but were still able to saccade to the target using corrective saccades: LHH4, LHH5 and RHH3 had high median error rates for targets on the affected side, but these were no more than double the worst performing control and the vast majority of targets were subsequently fixated within the allotted 1.5 seconds. Saccades to 7.5 degree offset targets were normal. LHH5 had significant central sparing and RHH3 and significant peripheral sparing, whereas LHH4 had complete hemianopia. Total scores on ACE-R were within normal limits, although the time taken for the Trail Making B test was raised for LHH5 and RHH3.

Two HVFD participants (LHH3 and RHH2) had grossly abnormal results, with very hypometric saccades, although they still managed to subsequently fixate the majority of targets. Both had hemianopia to midline although LHH3 had some patchy sparing in the left inferior quadrant. LHH3 scored well in the ACE-R but had hemianopia of relatively recent onset (around 3 months ago).

The remaining three HVFD participants (LHH1, RHH1 and RHH4) all demonstrated very poor performance at this task. Interestingly RHH1 had fairly accurate saccades in the predictable target task but was extremely poor in the unpredictable target task. RHH1 had some central sparing, but the others had complete hemianopia. All 3 demonstrated some evidence of cognitive deficits as well as visual field loss.

Task performance for the participants with USN was quite variable. RVI1 scored normally in all saccade tasks – and did so in the pen and paper tasks of neglect. LVI4 generally used hypometric saccades to targets on the affected side which were then corrected and latencies were surprisingly rapid. LVI1 had greater error values of first saccades, but still corrected the majority (although only very limited data was obtained for experiment 3.2). LVI3 showed small saccadic amplitudes and many targets were not fixated. Participant LHHVI with both hemianopia and USN performed unsurprisingly poorly, commonly making no saccade at all to a leftward target, or using a series of very small saccades on the occasions the target was reached.

Performance of all of the participants with stroke for reaching targets on the unaffected side was usually very good regardless of visual deficit. Many participants made a few corrected undershoots and there were a very small number of corrected overshoots. The number of hypermetric saccades seems less than that found by Zihl et al (Zihl, 1995b). (See Appendix 3)

3.6.7 Results: Experiments 3.3 and 3.4 (Smooth Pursuit)

Experiment 3.3 (Slow moving target): Most control participants were able to pursue the slow moving target with a good degree of accuracy (Figure 3.12, top left panel). They achieved on average a gain of 1.05, a temporal lag of 21.4ms and a spatial error of 1.5 degrees (Table 3.19). What seems noticeable is that the oldest control participants showed the worst performance (CONT5, 12, 13 and 17). Participants 5 and 13 showed some instances where a large intrusive saccade was made with the eye moving ahead of the target and then either waiting for the target to catch up (CONT17) or making a smaller saccade or saccades back to the target to resume smooth pursuit (CONT5; (Figure 3.12, top right panel). CONT12 showed near total failure of smooth pursuit, instead predominantly using repeated small saccades in front of the target with a pause to catch up – giving the graph a sawtooth like appearance, but maintaining significant accuracy of eye position to target (Figure 3.12, bottom left panel). CONT13 also showed near total failure of smooth pursuit eye movements, but much larger saccades were used in front of the target, with a mixture of fixations and saccades back to the target resulting in very poor accuracy of eye position (Figure 3.12, bottom right panel).

Table 3.19: Control smooth pursuit performance for slow moving target

Participant	Gain	Lag (ms)	Error (deg)
CONT1	1.06	49	0.54
CONT2	1.13	-135	0.97
CONT3	0.97	3	0.60
CONT4	1.01	12	1.55
CONT5	1.07	18	2.69
CONT6	1.00	50	0.58
CONT7	1.09	-41	1.17
CONT8	1.11	-132	1.06
CONT9	1.05	-38	1.09
CONT10	1.03	48	1.15
CONT11	1.00	-8	0.84
CONT12	1.04	-59	2.12
CONT13	1.03	-190	6.47
CONT14	1.00	39	1.06
CONT15	1.11	68	0.84
CONT16	1.01	19	1.32
CONT17	1.11	-67	2.22
MEAN	1.05	21.4	1.5

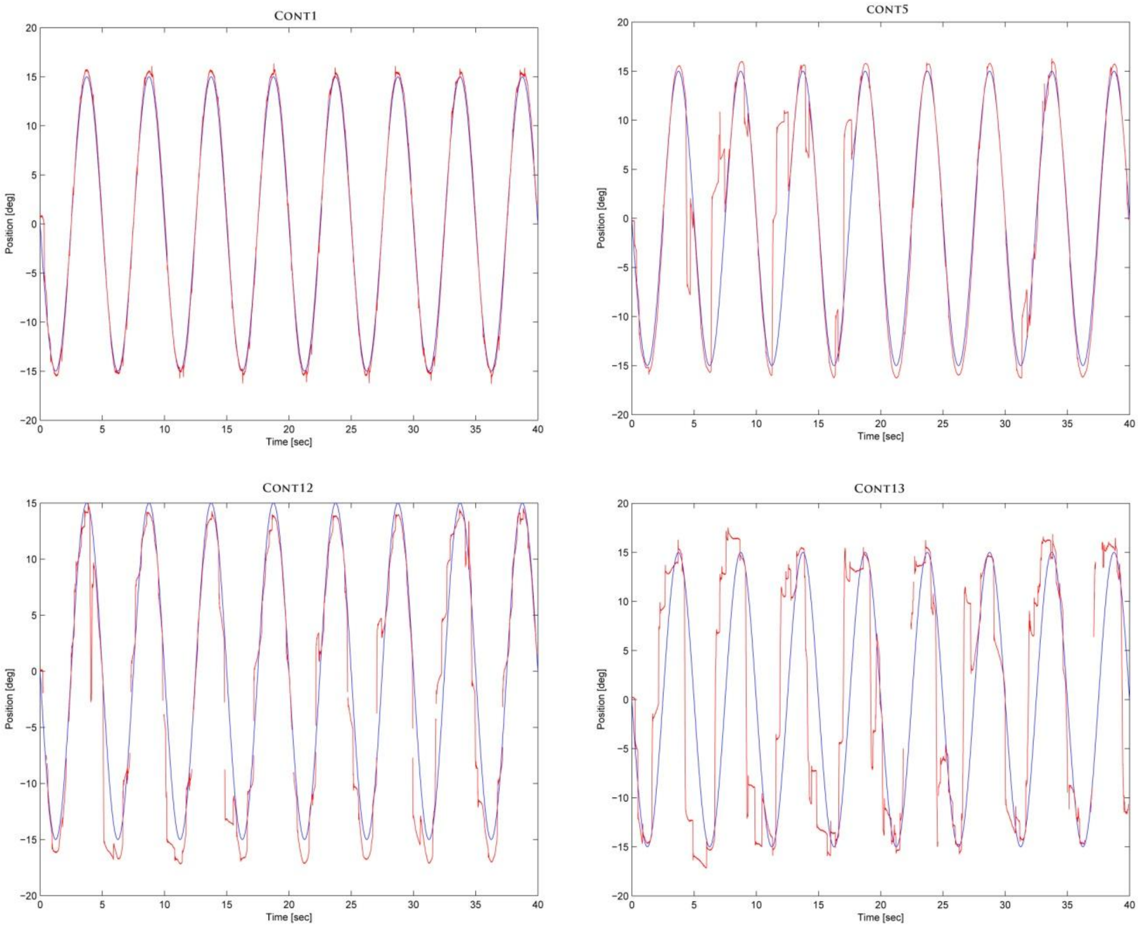

Figure 3.12: Smooth pursuit tracking performance over time. Example control participant performance (Control 1, 5, 12, 13) in the slow target smooth pursuit task (Experiment 3.3). Blue lines indicate target location and the red line indicates eye position.

Several participants with HVFD had normal smooth pursuit eye movements (Table 3.20; LHH2 (Figure 3.13, top left panel), LHH6, RHH2, RHH5 and RHH6). Most of the others showed either very occasional saccades in front of target (LHH5 and RHH4) in the direction of their field loss, or frequent saccades in front of target – with either a waiting fixation or saccade back to target (LHH3, LHH4, RHH1, RHH3, Figure 3.13, top right panel). The only participant with HVFD who showed problems in both directions was LHH1 – again the problems took the form of saccades in front of target, although accuracy travelling towards the field defect was worse than towards the ‘good’ side (Figure 3.13, bottom left panel). Nevertheless this participant did show at least some genuine smooth pursuit movement in both directions. (N.B. LHH3, despite an average error of 2.15 degrees with rightward pursuit, was very accurate in this direction. The error measurement mostly occurs because of overshoot at extreme leftward gaze and some time to catch up as the eye began to move right again.

In the USN group, LHHVI showed a very large overshoot at the end of rightward gaze, but otherwise pursuit was remarkably accurate (although the very first leftward movement of the target was not pursued at all). LVI1 showed total smooth pursuit failure in both directions (Figure 3.13, bottom right panel). The eye lagged behind and made repeated small catch up saccades to maintain an eye position remarkably close to target. RVI1 did lose some eye tracking but smooth pursuit seemed accurate and LVI4 showed accurate smooth pursuit as well.

Table 3.20 shows results for all of the participants with stroke

Table 3.20: Participants with stroke slow pursuit performance, slow moving target

		Affected Hemifield			Unaffected Hemifield		
	Participant	Gain	Lag (ms)	Error(deg)	Gain	Lag(ms)	Error(deg)
HVFD	LHH1	1.24	-361	4.16	0.97	-65	1.97
	LHH2	1.02	17	0.59	1.08	11	0.34
	LHH3	1.16	74	4.28	1.03	-33	2.15
	LHH4	0.98	-79	1.54	1.05	-7	0.66
	LHH5	0.97	-60	1.19	1.08	2	0.67
	LHH6	1.01	-48	0.76	1.07	-56	1.05
	RHH1	1.07	-205	3.65	1.12	68	1.07
	RHH2	1.10	44	1.25	0.99	-78	1.05
	RHH3	1.12	-43	2.49	1.02	-61	1.03
	RHH4	0.94	44	0.83	1.08	49	0.71
	RHH5	1.05	42	0.69	1.04	37	0.66
	RHH6	1.02	33	1.15	1.16	56	0.79
USN	LHHVI	1.00	74	2.80	1.20	25	2.55
	LVI1	N/A	N/A	1.66	N/A	N/A	1.91
	LVI3	N/A	N/A	N/A	N/A	N/A	N/A
	LVI4	0.95	47	1.00	1.06	98	0.52
	RVI1	0.98	-85	0.64	N/A	N/A	0.87

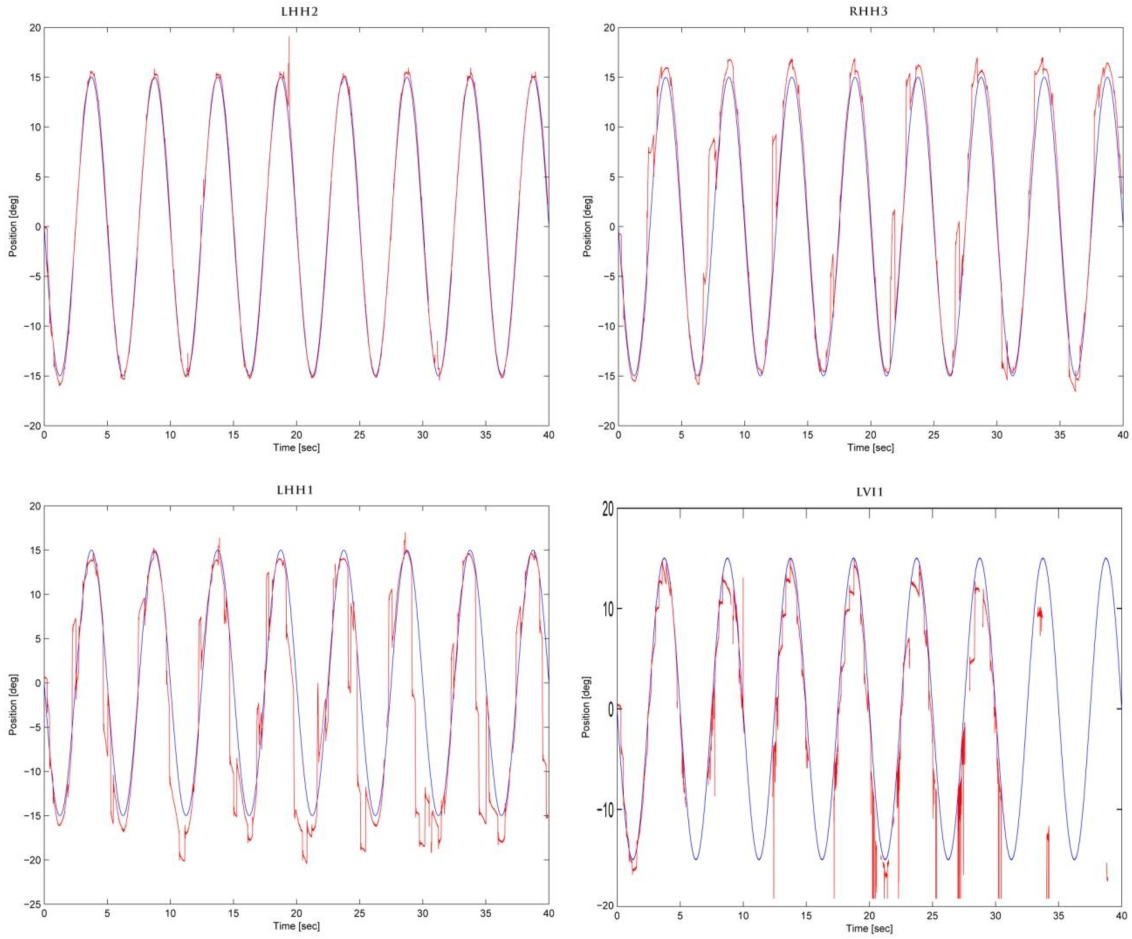

Figure 3.13: Examples of smooth pursuit performance for four participants with stroke (LHH2, RHH3, LHH1, LVI1) tracking a slow moving target. The blue line shows target location in degrees at each time and the red line shows the angle of the eye at each time point. Vertical lines in the red trace indicate intrusive saccades.

Experiment 3.4 (Fast moving target): Increasing the speed of the oscillating target made almost no difference to performance for the control group (Table 3.21). The majority remained able to pursue the target accurately (Figure 3.14, top left panel). CONT5 (Figure 3.14, top right panel) and CONT17 continued to show a few saccades ahead of target with pauses or saccades back to refixate the target. CONT12 (Figure 3.14, bottom left panel) and CONT13 (Figure 3.14, bottom right panel) showed total failure of smooth pursuit – both participants used large saccades to near the far end of the extent of the target movement range, and then waited for the target to catch up.

Table 3.21: Control smooth pursuit performance, fast moving target

Participant	Gain	Lag (ms)	Error (deg)
CONT1	1.05	11	0.88
CONT2	1.17	25	1.76
CONT3	1.02	-61	1.32
CONT4	1.03	20	1.76
CONT5	1.06	32	1.99
CONT6	1.00	33	1.00
CONT7	1.06	-47	1.02
CONT8	1.07	-22	1.43
CONT9	1.05	16	1.26
CONT10	1.04	-19	1.43
CONT11	1.02	31	0.94
CONT12	1.04	64	6.70
CONT13	0.92	-205	7.01
CONT14	1.01	35	1.04
CONT15	1.11	28	1.34
CONT16	1.01	38	1.27
CONT17	1.14	63	3.80
MEAN	1.05	2	2.11

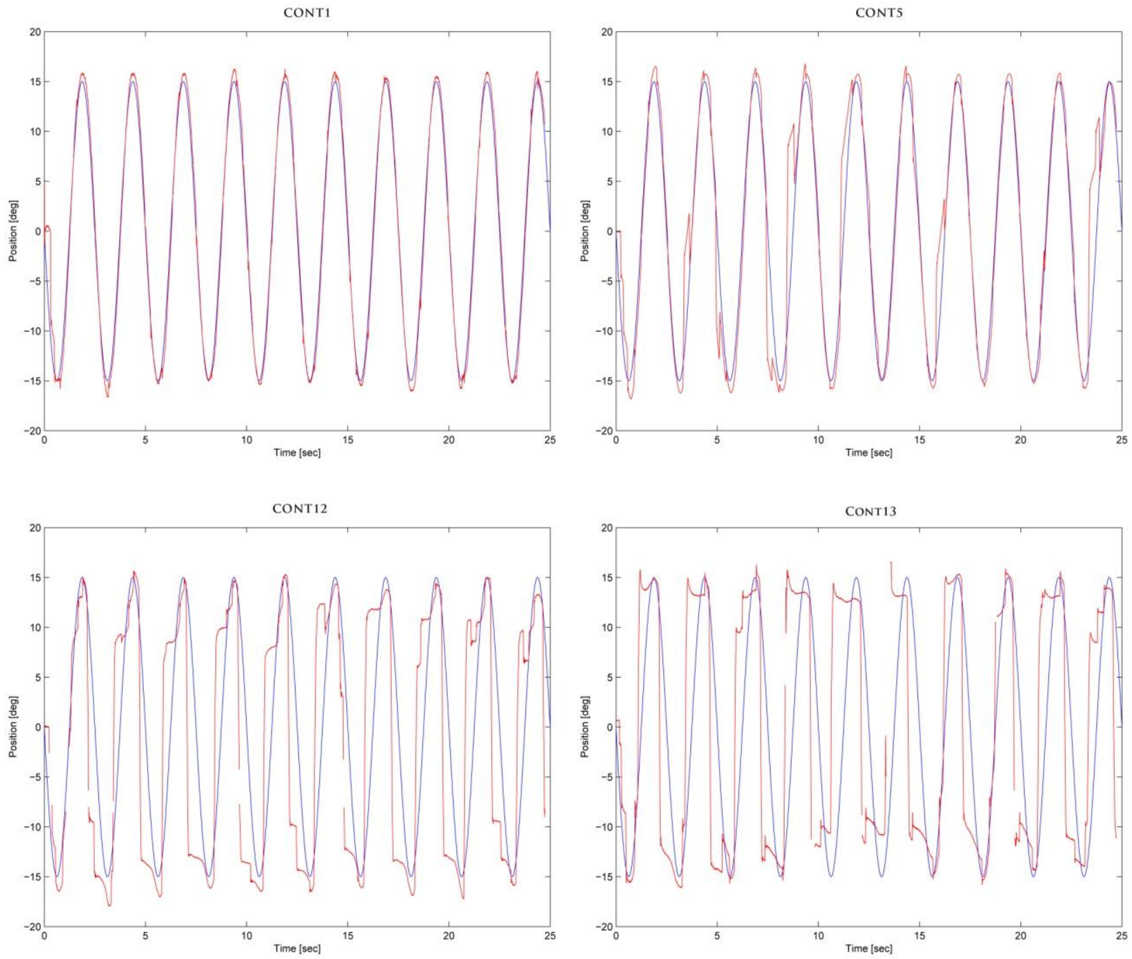

Figure 3.14: Smooth pursuit of fast moving target for selected control participants. The blue line shows target position (degrees) across time (seconds) and the red line shows eye position (degrees) across time (seconds).

Increasing the target speed made little difference to smooth pursuit performance for the group with HVFD. Those that performed very well in the slow target task (LHH2 (Figure 3.15, top left panel), LHH5 (Figure 3.15, top right panel) LHH6, RHH2, RHH4, RHH5 and RHH6) performed well with a faster target. LHH5 was a slight exception to this, having shown a single saccade in front on the slow task but 2 or 3 small saccades in front in both directions with a faster target (although overall smooth pursuit was very accurate). LHH4 again showed a few small saccades on this task but accuracy was again good. LHH3, RHH1 and RHH3 (Figure 3.15, middle left panel) showed several saccades ahead of target in the direction of visual field loss on both slow and fast tasks. LHH1 (Figure 3.15, middle right panel) had short periods of successful smooth pursuit but mostly used a strategy like CONT12 and CONT13 – with large saccades in front of target and fixations waiting for the target to catch up and the far extent of the target range.

In the USN group, LHHVI (Figure 3.15, bottom right panel) took 5 iterations of the fast trial to reach the furthest extent left of centre pursuing the target – on each of the first 4 iterations, pursuit halted closer each time to the far left of the target path, 15 degrees left of centre. Overall accuracy was otherwise good, with a small number of saccades in front of the target in both directions. LVI4 (Figure 3.15, bottom left panel) showed poorer performance in later cycles, in leftward pursuit and as the target moved left of centre – pursuit tended to fall behind and catch up saccades were made. Also in the latter half of the trial, gaze did not get to the furthest left extent of the target trajectory, 15 degrees left of centre. RVI1 showed the same problems throughout the experiment – gaze falling behind target in rightward pursuit with catch up saccades being required and the eye failing to reach the furthest rightward extent of target trajectory. Interestingly RVI1 showed significant overshoot in leftward pursuit.

Results for the participants with stroke are shown in Table 3.22

Table 3.22: Participants with stroke smooth pursuit performance, fast moving target

		Affected Hemifield			Unaffected Hemifield		
	Participant	Gain	Lag(ms)	Error(deg)	Gain	Lag(ms)	Error(deg)
HVFD	LHH1	1.23	-118	7.78	0.99	-37	3.59
	LHH2	1.02	35	0.83	1.04	23	0.58
	LHH3	1.07	23	3.09	1.08	7	2.20
	LHH4	1.01	34	1.52	1.03	28	0.88
	LHH5	0.95	34	2.32	1.12	33	1.35
	LHH6	1.02	77	1.07	1.05	-26	1.14
	RHH1	1.09	-25	2.33	1.11	37	0.90
	RHH2	1.09	58	1.09	0.95	59	1.90
	RHH3	1.10	24	3.04	1.00	42	1.53
	RHH4	0.92	41	1.04	1.03	59	0.87
	RHH5	1.05	-10	0.61	1.03	29	1.39
	RHH6	0.96	16	1.65	1.12	15	1.04
USN	LHHVI	0.87	102	3.52	1.22	25	2.91
	LV1	N/A	N/A	N/A	N/A	N/A	N/A
	LVI3	N/A	N/A	N/A	N/A	N/A	N/A
	LVI4	0.92	7	2.44	1.06	36	1.09
	RVI1	0.92	52	2.97	1.12	43	1.14

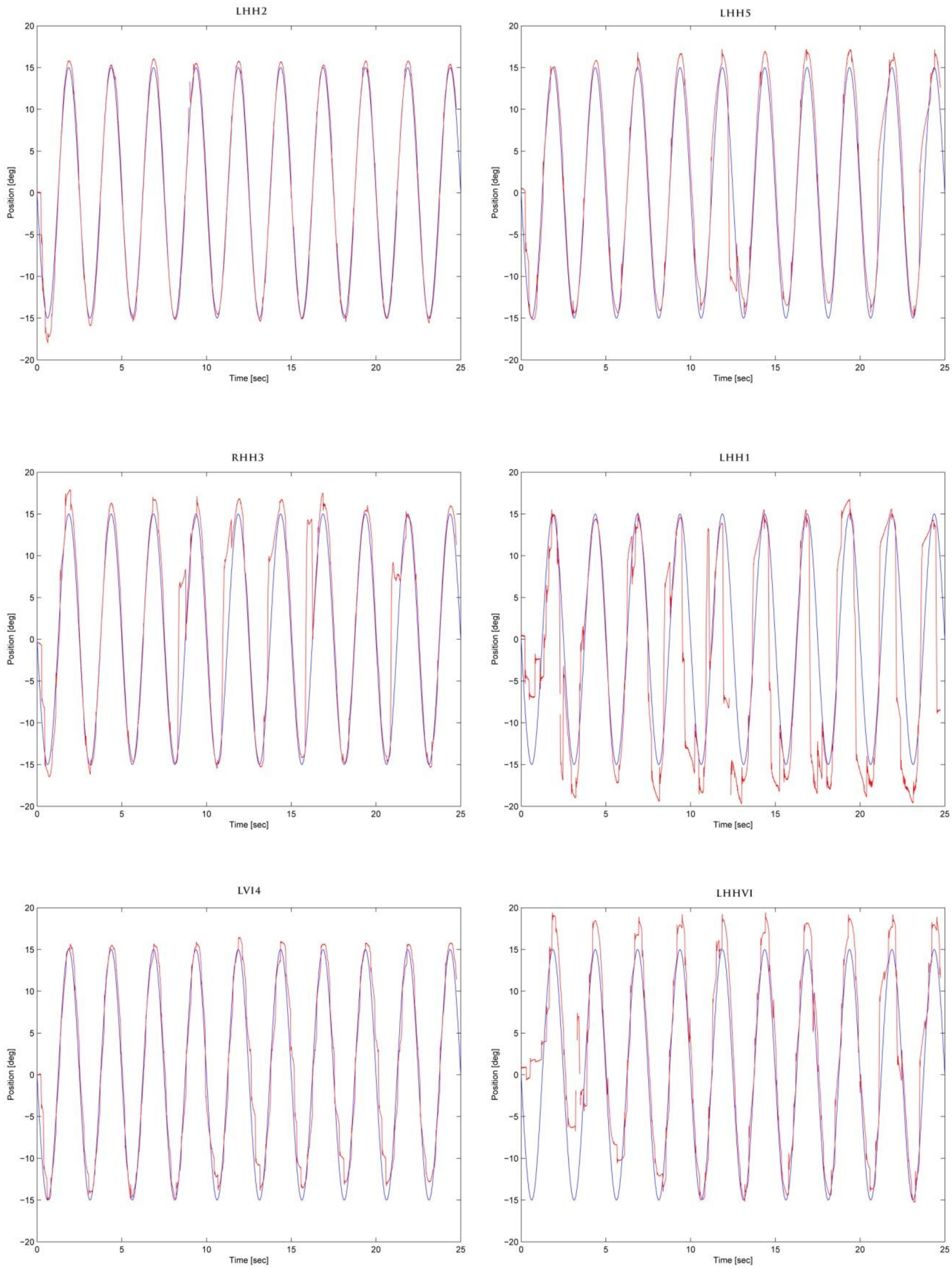

Figure 3.15: Smooth pursuit of fast moving target for selected participants with stroke. The blue line shows target position (degrees) across time (seconds) and the red line shows eye position (degrees) across time (seconds).

Repeated measures ANOVAs were performed separately for smooth pursuit in an ipsilesional and contralesional direction to analyse the effect of group (control, HVFD or USN) and of task condition (slow or fast) on smooth pursuit gain, lag and mean error. For contralesional smooth pursuit, mean gain for the slow moving targets were as follows: Controls: 1.05, HVFD group: 1.06, USN group: 0.98. Mean gain for the fast moving targets were: Controls: 1.05, HVFD group: 1.04, USN group: 0.90. A repeated measures ANOVA found a significant difference in mean gain between task conditions (i.e. slow and fast moving targets): $F(1,29) = 12.576$, $p = 0.001$, partial eta squared = 0.302. There was also a significant difference between groups: $F(2,29) = 4.015$, $p = 0.029$, partial eta squared = 0.217. There was a significant interaction between group and condition: $F(2,29) = 5.062$, $p = 0.013$, partial eta squared = 0.259. Post hoc Bonferroni analysis was performed to distinguish where the group differences lay. There was no significant difference between the control and HVFD group: $p=1.00$. There was however a significant difference between the control and neglect group: $p=0.033$, and between the HVFD and neglect group: $p=0.035$. It should be noted however that mean gain was only obtained for 3 participants in the neglect group so normal distribution cannot be assumed.

For smooth pursuit in a contralesional direction, mean lag for the slow moving targets were as follows: Controls: -21ms, HVFD group: -45ms, USN group: +12ms. Mean lag for the fast moving targets were: Controls: +2ms, HVFD group: +16ms, USN group: +54ms. A repeated measures ANOVA found a significant difference in mean lag between task conditions (i.e. slow and fast moving targets): $F(1,29) = 5.189$, $p = 0.03$, partial eta squared = 0.152. There was no significant difference between groups: $F(2,29) = 0.575$, $p = 0.569$. There was no significant interaction between group and condition: $F(2,29) = 0.745$, $p = 0.483$.

For contralesional smooth pursuit, mean error for the slow moving targets were: Controls: 1.55 deg, HVFD group: 1.88 deg, USN group: 1.48 deg. Mean error for the fast moving targets were: Controls: 2.11 deg, HVFD group: 2.20 deg, USN group: 2.98 deg. A repeated measures ANOVA found a significant difference in mean error between task conditions (i.e. slow and fast moving targets): $F(1,29) = 8.832$, $p = 0.006$, partial eta squared = 0.233. There was no significant difference between groups: $F(2,29) = 0.122$, $p = 0.866$ and there was no significant interaction between group and condition: $F(2,29) = 1.239$, $p = 0.304$.

For ipsilesional smooth pursuit, mean gain for the slow moving targets were: Controls: 1.05, HVFD group: 1.06, USN group: 1.13. Mean gain for the fast moving targets were: Controls: 1.05, HVFD group: 1.05, USN group: 1.14. A repeated measures ANOVA found no significant difference in mean gain between task conditions (i.e. slow and fast moving targets): $F(1,28) = 0.011$, $p = 0.918$. There was no significant difference between groups: $F(2,28) = 2.463$, $p = 0.103$ and there was no significant interaction between group and condition: $F(2,28) = 0.527$, $p = 0.596$.

For ipsilesional smooth pursuit, mean lag for the slow moving targets were: Controls: -21.4ms, HVFD group: -6.4ms, USN group: +61.5ms. Mean lag for the fast moving targets were: Controls: +2.5ms, HVFD group: +22.4ms, USN group: +30.5ms. A repeated measures ANOVA found no significant difference in mean gain between task conditions (i.e. slow and fast moving targets): $F(1,28) = 0.192$, $p = 0.665$. There was no significant difference between groups: $F(2,28) = 1.279$, $p = 0.294$ and there was no significant interaction between group and condition: $F(2,28) = 0.816$, $p = 0.453$.

For ipsilesional smooth pursuit, mean error for the slow moving targets were: Controls: 1.55 deg, HVFD group: 1.01 deg, USN group: 1.31 deg. Mean error for the fast moving targets were: Controls: 2.11 deg, HVFD group: 1.45 deg, USN group: 1.71 deg. A repeated measures ANOVA found a significant difference in mean error between task conditions (i.e. slow and fast moving targets): $F(1,29) = 5.151$, $p = 0.031$, partial eta squared = 0.151. There was no significant difference between groups: $F(2,29) = 0.793$, $p = 0.462$ and there was no significant interaction between group and condition: $F(2,29) = 0.101$, $p = 0.904$.

3.6.8 Discussion: Experiments 3.3 and 3.4 (Smooth Pursuit)

Group analysis showed no difference in mean lag or mean error between the control, HVFD or neglect groups in either task condition. There did seem to be a difference in gain between the neglect group and the others – when the target moved contralesionally, the participants with neglect showed lower gain suggesting than the target was not tracked to the full extent of its contralesional path. The ANOVA performed does assume a normal distribution which, with only 3 data points, the neglect group did not in fact demonstrate. This result should therefore be interpreted with caution, however all 3 individuals with neglect did show gains of below 1. Whilst there was no significant difference in gain between groups tracking the target ipsilesionally, the raw mean gain was higher for the neglect group suggesting that their gaze overshot the end of the target's path more than the other groups did.

By far the most common error in smooth pursuit performance during experiments 3.3 and 3.4 were intrusive saccades that moved gaze ahead of the target, followed by a fixation to wait for the target to catch up, or a saccade that directed gaze back to the target. This was seen in some of the older control participants (and very occasionally in some of the 51-70 age group too) but, despite the lack of statistically significant differences in mean error between groups, in the HVFD group this pattern does appear to occur more frequently and in the vast majority of cases this occurred as the target moved in the direction of the affected hemifield. This abnormal interruption of smooth pursuit patterns has not been documented in people with stroke before. Previous research has described low gain and catch up saccades consistent with lagging behind the moving target (Rowe et al., 2013) but in our participant cohort, this pattern was only observed in those with USN.

3.6.9 Eye Movements - Final Discussion

Whilst saccades ahead of target were observed in many participants with HVFD, accuracy of pursuit was good for many of them (LHH2, LHH4, LHH5, LHH6, RHH2, RHH4, RHH5, RHH6). On the whole these were the same participants that had performed well during the saccade tasks (Experiments 3.1 and 3.2), with the exception of RHH2 and RHH4 who showed severely impaired performance during the saccade tasks but very good performance on the pursuit task (both of these participants had complete hemianopia). LHH3, RHH1 and RHH3 did have somewhat impaired pursuit performance – LHH3 and RHH1 (but not RHH3) also had impaired performance at the saccade tasks. LHH1 had severe impairment of saccadic accuracy and smooth pursuit in both directions – as well as a complete hemianopia.

Overall, for those with HVFDs, examples of good saccade performance but impaired smooth pursuit were observed and vice versa, as well as examples where both saccades and smooth pursuit were intact and where both were impaired. This is consistent with theoretical perspectives of eye-movement control that suggest that some parts of the saccadic and smooth pursuit pathways are independent whilst other parts are closely intertwined (de Xivry and Lefevre, 2007; Grossberg et al., 2012).

The extent of visual field loss also did not determine saccade or smooth pursuit performance. Whilst LHH1, for example, had a complete hemianopia and very abnormal saccadic and smooth pursuit performance, LHH4 also had a complete hemianopia but normal smooth pursuit performance and only mildly impaired saccadic performance. RHH1 showed significant central and peripheral visual field sparing but demonstrated impaired smooth pursuit and saccadic performance.

Unfortunately the data available from those with USN was sparse. Using eye tracking techniques with people who experience USN proved problematic. USN is widely known to commonly co-exist with impairment of global attention and concentration (Husain et al., 1997; Robertson et al., 1997) and we commonly found that our participants suffered eyelid droop whilst sitting in the darkened room – especially those with more severe USN (LVI1, LVI2, LVI3). Where data was sufficiently reliable there was a similar dissociation between saccade and smooth pursuit performance. LHHVI showed extremely impaired saccades, but near normal pursuit performance. RVI1 had normal saccadic accuracy but clearly some problems with smooth pursuit. All of the USN participants showed some smooth pursuit palsy when pursuing in a contralesional direction, necessitating the use of catch-up saccades.

It remains to be seen whether poorer performance on the saccade or pursuit tasks are useful predictors of impaired performance in more complex tasks such as steering a car or detecting hazards whilst driving. The following chapter examines performance in a visual search task, in an attempt to gain further insight into whether any of the visual impairments that have been discovered in the stroke group translate into an actual visual disability.

Chapter 4: Visual Search Performance

Perception is a dynamic process whereby the eyes are moved within the visual environment in order to gather and update information about the world (Tsotsos, 1990). So far this thesis has measured and assessed the control of saccadic and smooth pursuit eye movements when performing simple fixation and tracking tasks. These eye-movement tasks could be considered unusual in that they merely required that the target was looked at. Of course eye-movement functions usually subserve a further goal such as searching for or retrieving useful information. One task that has been used to investigate these broader goals is ‘visual search’. This is the familiar task of trying to find a particular object amongst a set of distracters – such as trying to find a pen on a cluttered desk, or spot a friend’s face in a crowd. When performing a visual search task of sufficient complexity, the eyes will commonly be directed to different regions of the visual scene through a series of saccades followed by fixations on objects, with the visual attention network selecting the area to foveate (Wolfe, 1998; Wolfe and Horowitz, 2004; Treisman and Gelade, 1980). Tasks such as object recognition can be carried out with far greater efficiency if the object (or small group of objects) are attentionally selected and foveated first (Goldsmith, 1998). Whilst it is possible to attentionally select objects covertly without looking at them, this is unusual and only possible when the objects are visually salient (as discussed in the next paragraph).

Hazard perception whilst driving can be considered as a form of visual search task whereby the driver continues to look for potential hazards whilst also attending to the demands associated with controlling the direction of the vehicle and navigating a course through the world. It is perhaps not surprising that visual search performance of a static array of objects has been found, at least to some degree, to be a predictor of simulated driving performance (i.e. steering accuracy) in people with a range of visual field problems (Coeckelbergh et al., 2002a; Tant et al., 2002a).

When one looks at a visual scene with no particular goal in mind, some objects will tend to attract attention because they have certain characteristics that render them visually salient (Findlay and Walker, 1999) – i.e. attention is captured and saccades generated by bottom up processing. One can make certain items in a visual search task more visually salient by given these items features that are shared by the target object, e.g. when searching for a green triangle, green squares will be more likely to capture your attention than red squares (Blaser et al., 1999; Bichot and Schall, 1999). This selectivity is often useful. However having a particular search goal in mind can cause you to ignore some otherwise salient objects in the visual scene (Williams, 1985) though not all (Remington et al., 1992; Theeuwes, 1994).

The impact of visual salience is that visual search times are likely to be quickest when searching for a target that is very different from the distracters – an example might be trying to find a red square in amongst blue triangle distracters. In a simple task like this, the target will immediately 'pop out' for attentional selection and reaction times for people with normal vision will not differ regardless of the number of distracters, revealing a form of parallel processing (Treisman and Gelade, 1980). Differences in target features such as colour, size, orientation and motion are all capable of being searched for in this way (Wolfe and Horowitz, 2004). The 'pop out' effect can be eliminated and search made less efficient by varying the distracters i.e. a conjunction search such as finding the green square in amongst red squares or green triangles (Treisman and Gelade, 1980), or reducing the amount of difference between the target and distracters (i.e. searching for a target that is only subtly different in size or hue) (Duncan and Humphreys, 1989). If the target has to be actively searched for (i.e. no ‘pop out’), search times for a single target increases linearly with the distracter set size typically around 20-40ms per additional distracter object (Wolfe, 1998). For searches that use basic object properties such as colour or shape, errors tend to be rare. However, in more difficult search tasks with subtle object differences, error rates may become a useful measure (Palmer et al., 2000) and have been shown to vary with set size more closely than search times (Dukewich and Klein, 2005), presumably in a form of speed-accuracy trade-off.

In this chapter a visual search task is used to see if performance is related to the simple eye-movement performance measured in Chapter 3. The goal will also be to test the predictive power of this measure in explaining steering accuracy and hazard detection performance whilst driving during the tests outlined in Chapters 5 and 6.

4.1 Visual Search with Homonymous Visual Field Defects

If a homonymous heminaopia is simulated on an otherwise healthy adult (for instance using semi-opaque contact lenses), visual search performance is initially poor but rapidly improves as the participant develops compensatory search strategies (Simpson et al., 2011). Over the first 5-7 trials performance improves very rapidly as the participant learns to fixate a greater number of points in the hemianopic field. Following that, performance then improves further, but more slowly, more efficient searching techniques are learnt, until performance is generally on a par with controls (Simpson et al., 2011). When looking at simple shapes, controls tend to look predominantly at the middle of the shape, whereas people with hemianopia (and no neglect) make a number of saccades into the impaired hemifield and therefore spend more time looking at the contralesional side of the shape (Ishiai et al., 1987).

Compensatory behaviours through changes in dynamic visual sampling have been observed in many studies. Those with HVFDs may spend more time searching in the affected hemifield, using saccades of lower amplitude (especially when searching the affected hemifield) and exhibit scan patterns that look qualitatively different to that of controls (Kerkhoff, 1999; Pambakian et al., 2000; Tant et al., 2002b; Zangemeister et al., 1982; Zihl, 1995b; Zihl, 2000; Zihl, 1999). It should be noted that although Zihl et al. found that scan paths looked different, the saccadic amplitudes and fixation dwell times were actually the same as controls. Some studies of the visual search performance of people with HVFDs have found not only shorter saccades, but also shorter fixation durations (Machner et al., 2009; Chedru et al., 1973). Several studies of hemianopic participants have found a higher number of 're-fixations' whereby a proportion of individuals will repeatedly return fixation to a point that has already been fixated during the search (Hardiess et al., 2010; Machner et al., 2009; Zihl, 1995a; Zihl, 1995b). A high number of refixations may reflect a co-existent problem with spatial memory but refixation rates are higher in people with longer scanpaths, so they may simply be a function of the number of fixations made and the number of objects in the array that could be fixated.

In a similar fashion to saccadic accuracy (as described in Chapter 3), performance in visual search for people with HVFDs following stroke is highly variable and is not predictable from the amount of visual field loss alone. A proportion of those with a homonymous visual field defect (HVFD) can have search times that are equivalent to a control group, whilst others may have very prolonged search times (Gassel and Williams, 1963a; Zihl, 1995b). This dichotomy was first reported by Poppelreuter in 1917, who showed that 7 out 28 hemianopic patients exhibited search times indistinguishable from controls and seemed to be using a more effective gaze strategy to achieve this. He described the other patients as demonstrating 'characteristically clumsy' scan paths, which were 'fragmented' with low amplitude saccades and a high number of fixations (Poppelreuter, 1917 (Translation Zihl, J 1990)).

Because of the variable function of those with a HVFD, some researchers have found it useful to categorise people with homonymous visual field loss based on their performance in a simple dot counting task. When comparing performance with a control group categories such as 'pathological hemianopia' or 'normal hemianopia' have been used (Zihl, 1995b; Zihl, 2000), and when comparing performance to other hemianopes, categories such as 'adequately compensated' or 'inadequately compensated' hemianopia have been applied (Hardiess et al., 2010). The latter Hardiess et al. trial (Hardiess et al., 2010) categorised their study group using a simple dot counting task and then examined performance on a far more demanding spot the difference task spanning 120 degrees of visual angle. The adequately compensated group were slightly slower than the control group but seemed to be using a compensatory strategy of using a series of small saccades to take in a proportion of visual scene, accurately saccading across to the other side and using spatial memory to perform an accurate comparison. The inadequately compensated hemianopia group appeared to attempt to do the task in a similar manner, but inaccurate eye movements and problems with spatial processing and memory meant that compensation attempts broke down and failed.

4.2 Visual Search with Unilateral Spatial Neglect

People with unilateral spatial neglect who perform a visual search task unsurprisingly have been shown to spend more time searching, and make more fixations on the ipsilesional half of the screen, in contrast to controls and in contrast to people with hemianopia (Husain et al., 2001). One detailed study showed that people with USN were more likely to begin their search on the ipsilesional side of the screen. They made more fixations on the ipsilesional side and their average fixation duration was longer (Behrmann et al., 1997). Careful analysis showed that the peak area of fixations was not on the extreme right of the screen (in contrast to opponent processor theory (Kinsbourne, 1993), but rather the peak area of search was deviated to the right by a few degrees, in keeping with previous findings of impaired representation of space in unilateral spatial neglect (Karnath, 1997).

Some researchers have found that visual search performance is only impaired when the search is attentive (i.e. when search time increases when number of distracters increases), but not when the task is pre-attentive (i.e. when reaction time in controls does not vary with number of distracters – simple tasks such as finding a red circle in amongst blue circle distracters, where the target ‘pops out’ – see section 4.1) (Aglioti et al., 1997). Other studies, including larger and more detailed ones have found that USN can impair pre-attentive search as well – to a lesser degree than attentive search and not in all people with USN (Erez et al., 2009; Esterman et al., 2000; Behrmann et al., 2004). Behrman et al. found impaired performance in pre-attentive and attentive search in people with strokes without neglect, although performance was further impaired by USN or HVFD (Behrmann et al., 2004). One patient had a persistent impairment of visual search even after their USN had overtly seemed to have resolved (Harvey et al., 2002).

Refixations of previously foveated distracters are common when someone with USN performs a visual search task, although the exact reasons for this are unknown. One participant with severe left neglect, barely searched past midline at all and frequently refixated targets on the right, prompting the author of the study to infer a spatial memory deficit (Husain et al., 2001). It is, however, a common feature of neglect that attention is almost magnetically attracted to items on the ipsilesional side. It is possible that ipsilesional items are deemed so visually salient in comparison to those on the contralesional side, that they were unable to endogenously override the exogenous bottom up attraction of attention to items on the unaffected side. One study used shifting distracters to demonstrate that spatial memory on the affected side was impaired rather than spatial memory on the right (Kristjansson and Vuilleumier, 2010). Other studies have concluded that items on the affected side may only be partially processed – i.e. a person with USN may look at the item but then fail to report it (Forti et al., 2005), or may fail to report the target but nevertheless make responses that suggest that they were influenced by its presence (Laeng et al., 2002).

4.3 Visual Search Task

So far in this thesis, we have been identifying the deficits that our participant group have at an impairment level i.e. visual field loss, spatial neglect, saccadic dysmetria and smooth pursuit palsy. Real world tasks such as driving require that visual perception, visual processing and eye movement systems work effectively together at speed in order that correct motor responses can be generated. Many researchers have found it very difficult to use measures of impairment (e.g. amount of visual field defect) to predict the degree of functional disability that someone has during tasks (Warren, 2009; Poppelreuter, 1917 (Translation Zihl, J 1990); Gassel and Williams, 1963a; Zihl, 1995b). For this reason we wished to test our participants in a more complex visual task in order to gain insight into the extent of their actual visual disability.

4.3.1 Task Design

We chose to use a visual search task in order to gain a measure of actual visual disability in a more complex visual task. We chose this type of task partly for pragmatic reasons – visual search tasks are relatively easy to construct and analyse and there is already a large body of research into visual search which would aid interpretation. Also some authors have suggested a link between visual search performance and some aspects of driving (Coeckelbergh et al., 2002a; Tant et al., 2002a) for people with visual field defects. Currently in the UK people with anything other than a very mild amount of homonymous visual field loss are censured from driving (Colenbrander and De Laey, 2006), although a small minority may regain their license through an 'exceptional circumstances' application and a successful on road assessment (Elliott and Newman, 2013). The DVLA guidance for unilateral spatial neglect, as for other cognitive tests, states that no test exists to predict safe driving and recommends judicious use of on road assessments. Due to the number of people who have strokes each year and the resources needed for an on road assessment, it is clearly not practicable to offer one to everyone. If simpler surrogate measures were accurate enough perhaps to identify people who were very unlikely to be able to drive safely, this would be of enormous clinical use – on road tests and perhaps driving rehabilitation could be targeted to those with the greatest potential to resume driving.

When we designed the visual search task we wanted to incorporate a number of features. Firstly we wished the task to be fairly demanding with the targets embedded in a large number of distracters. We felt that driving was a task which placed very significant demands on the visual system and we wished to identify a high performing subgroup of our HVFD who might have a reasonable chance of also performing well on the driving tasks. We therefore intended to use this visual search task, in a not dissimilar manner to Hardiess et al. (Hardiess et al., 2010) (although they used a dot counting task) to dichotomise our HVFD group into an adequately compensated (AC) subgroup, with visual search accuracy and speed within the control reference range and an inadequately compensated (IC) group with poorer visual search accuracy or speed.

We decided to use a size discrimination task because optical size could be important for detecting approaching objects. Human sensitivity to optic expansion information (the change in optical size) is limited, so detecting the movement of small fast vehicles (e.g. motorbikes) that are far away can be difficult (Gould et al., 2012). In some cases detecting size differences could be crucial to identifying the vehicle that is approaching or receding. We also wished to include some trials which were pre-attentive, whereby the target would appear to ‘pop out’ easily on screen for control subjects at least, and some more difficult targets which required active search to identify.

The design of the visual search task was influenced by pilot work carried out with 2 older healthy adults (both aged in their 70s). We tried a number of different designs with these individuals. They favoured a display of blue squares on a black background as they felt that the targets were easy to see with minimal glare causing eye strain. They also found that targets with a very different side length to the distracters (namely targets with 20% or 180% side length of the distracters) tended to pop out and were usually seen immediately at the beginning of each trial, whereas targets with subtly different side lengths (namely 80% or 120% side length of the distracters) had to be actively searched for, but were usually identifiable within 10 seconds (not always – we did not wish the task to have a ‘ceiling effect’).

4.3.2 Participants

Seventeen control subjects were initially tested (CONT18 could not be calibrated due to technical difficulties caused by reflections from thick lenses). LVI2 could not be calibrated due to fatigue related ptosis so no data was obtained. Full data sets for the other 13 participants with stroke were obtained.

4.3.3 Apparatus

The apparatus used was identical to that used in the saccade and smooth pursuit tasks detailed in chapter 3.

Visual fixation target stimuli were presented on a high resolution 17 inch CRT colour monitor (Vision Master, Ilyama, Japan) with 1024 x 768 pixels spatial resolution and 75Hz refresh rate with a mean luminance of 50cd/m^2. Stimuli were generated using Experiment Builder Software (SR Research Ltd., Canada) and consisted of an array of blue squares which subtended 1.45 degrees of visual angle on the screen, and a target which differed by +/-20% or +/-80% in side length (Figure 2a). Subjects were seated 57cm from the monitor with their chin and forehead secured on an Eyelink 1000 eye tracking system (SR Research Ltd, Canada). In this position the total screen width subtended slightly more than 37 degrees of visual angle. All experiments took place in a quiet room free of external light sources. The participants all wore their custom made spectacles for this task.

4.3.4 Procedure and Analysis

For each iteration of the visual search task, the participant was first presented with a central fixation cross, followed by a black screen containing 32 blue squares (Figure 4.16). The location of the centre of each square remained constant between trials and the position of the target varied amongst some of these locations. There were 104 predefined trials, which were presented in a random order, with a comfort break midway. There were 8 catch trials that contained no target to ensure participants did not merely guess the target size. In each of the remaining 96 trials a single target square of a different size was presented in amongst the remaining 31 distracter squares. The target could be present at one of 24 locations – 6 of which were located in each quadrant of the screen (there were 8 blue distracter squares whose position was never used for the target square). To vary task difficulty the target square could be 4 different sizes: much smaller (side length 20% of distracters), slightly smaller (80% side length), slightly larger (120% side length) or much larger (180% side length).

In each task, the participant was instructed to locate the ‘odd one out’ using 2 buttons – one to indicate that the ‘odd one out’ was larger and the other that it was smaller. If no response was made in 10 seconds, the trial timed out and returned to a central fixation cross for 2 seconds before the next trial commenced. In each trial we recorded whether the participant made a correct, incorrect or no response along with the reaction time.

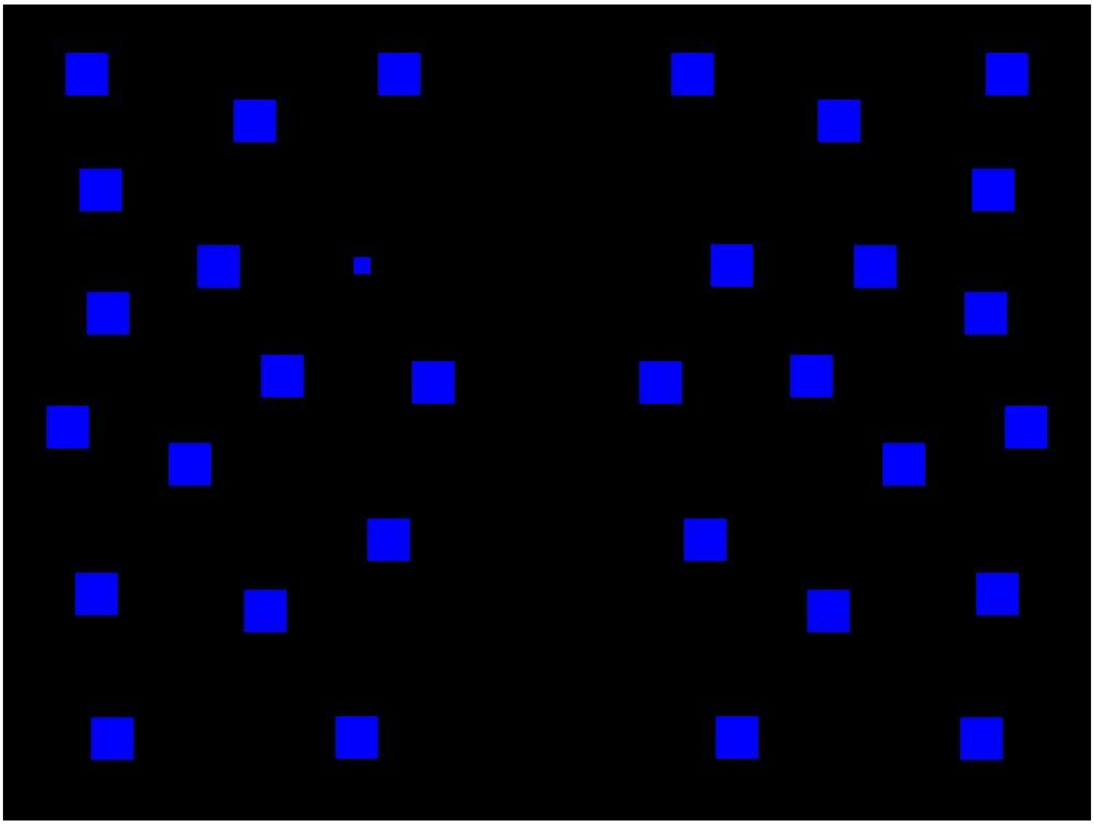

Figure 4.16: Visual search task showing a target with 20% side length of the distracters on left hand side

For each of the 96 trials in which a target was present the reaction time to a correct response was calculated, alongside whether the correct button response was made. Results were then separated into the 48 ‘easy’ trials (where the target was much larger (180% side length) or smaller (20% side length) of the distracters) and the 48 ‘hard’ trials (where the target had either 80% or 120% side length of the distracters). For the participants with stroke the results were also separated depending if the target was in the affected or unaffected hemifield. Average search times for each participant with stroke were not calculated across easy and hard trials, because this would have misrepresented overall performance – some participants correctly identified very few hard targets, so an average would mainly be taken from easy trials where faster search times would be expected.

Group analysis was conducted between the 3 groups – the controls, the HVFD group (LHH1-6 and RHH1-6) and the USN group (LVI1, 3 and 4, RVI1 and LHHVI) – for mean search time and accuracy. Repeated measures ANOVAs were conducted to compare between groups these 2 parameters separately across the 2 task conditions (hard and easy targets) and if the ANOVA was significant, planned contrasts compared each pair of groups to elicit where the significant differences lay. As no significant difference was expected between targets on the left or right of the screen for the control group, data was averaged across both directions. The entire control datasets were used to contrast with contralesional and ipsilesional targets separately for the groups of participants with stroke.

4.3.5 Results: Visual Search Performance

Table 4.23 shows descriptive statistics of the reaction times and percent of targets correctly identified by the control group in both easy and hard visual search conditions (Table 4.60, Appendix 4 shows the full data set). The mean Control reaction time for Easy targets was over 2 seconds and for difficult targets was 4.6 seconds. This can be compared with performance of an older adult group (mean age 72 years) carrying out a visual search task with some shared features, looking for a target at a random location amongst 18 items that reported search times of 0.8 seconds (Trick and Enns, 1998). It seems that the task used in this present Chapter was non-trivial even for the control group with search times between 2x and 4x longer than published work (Trick and Enns, 1998), and detection rates did not reach 100%. In the control group, only CONT13 scored more than 1 standard deviation from the mean in both accuracy and reaction time scores. At 80 years old, this participant was joint oldest control participant and notably had the poorest accuracy in the smooth pursuit task in Chapter 3 though unfortunately the saccade data was not available for this participant.

Table 4.23: Descriptive statistics for visual search by the Control Group

	Reaction Time (ms)		% Correct		
	Easy	Hard	Easy	Hard	Total
Mean	2064	4600	94.1	71.9	83.0
Median	1902	4472	97.9	72.9	83.3
S.D.	440	668	6.9	11.9	8.3
Range	1514-3018	3696-5933	77.1-100	41.7-87.5	60.4-92.7

Table 4.24: Visual search results for participants with stroke for targets in affected hemifield. N/A = Not available

		Search Time (ms)		% Correct		
	Participant	Easy	Hard	Easy	Hard	Mean
HVFD	LHH1	2217	1978	91.7	4.2	47.9
	LHH2	2054	4314	100	95.8	97.9
	LHH3	3280	5422	58.3	20.8	39.6
	LHH4	3779	4418	79.2	29.2	54.2
	LHH5	2342	4649	91.7	58.3	75
	LHH6	2441	5892	100	58.3	79.2
	RHH1	3261	6028	100	66.7	83.3
	RHH2	3135	6869	83.3	58.3	70.8
	RHH3	2786	3987	95.8	41.7	68.8
	RHH4	4604	5639	79.2	37.5	58.3
	RHH5	1818	4514	100	79.2	89.6
	RHH6	2156	4541	95.8	75	85.4
USN	LHHVI	3927	7408	75	12.5	43.8
	LVI1	4918	5700	62.5	33.3	47.9
	LVI3	7594	N/A	29.2	0	14.6
	LVI4	2585	7015	100	12.5	56.3
	RVI1	3746	5814	95	41.2	70.3

Table 4.25: Visual search results for participants with stroke for targets in unaffected hemifield

		Search Time (ms)		% Correct		
	Participant	Easy	Hard	Easy	Hard	Mean
HVFD	LHH1	2984	6222	87.5	12.5	50
	LHH2	1342	5132	95.8	79.2	87.5
	LHH3	2021	7335	75	12.5	43.8
	LHH4	2660	5878	100	12.5	56.3
	LHH5	2442	4650	83.3	45.8	64.6
	LHH6	2889	5912	87.5	70.8	79.2
	RHH1	2845	5244	95.8	54.2	75
	RHH2	2849	7650	83.3	33.3	58.3
	RHH3	2608	5184	91.7	50	70.8
	RHH4	4515	6567	83.3	50	66.7
	RHH5	1907	4546	100	79.2	89.6
	RHH6	2154	4243	100	79.2	89.6
USN	LHHVI	2202	4549	100	12.5	56.3
	LVI1	3575	5266	66.7	33.3	50
	LVI3	4877	7794	58.3	12.5	35.4
	LVI4	2302	6652	100	12.5	56.3
	RVI1	2305	5210	94.1	52.6	72.2

Table 4.24 and 4.25 show results for the participants with stroke separated by search task difficulty, and whether the target lay in the affected and unaffected field respectively. In these tables the results marked in red lie outside of the range found in the control group, whereas those marked in blue lie outside of a single standard deviation from the mean for the control group. The first observation that can be made of the HVFD group performance, is that there is certainly no clear dichotomy between successful and unsuccessful participants. Rather, (similarly to Chapter 3) a spectrum of performance is apparent from performance similar to controls through to highly impaired performance. This is more clearly shown in Table 4.26 that converts the measures into Z-scores based on control group performance (signs were adjusted so that longer search times and lower accuracy were both negative). There were three participants in the HVFD group with search times and search accuracy indistinguishable from the control group (LHH2, RHH5, RHH6). A further 3

participants had many scores within the range of performance seen in the control group, but nearer the lower range for search time (LHH6), accuracy (LHH5) or a combination of the two (RHH3). These participants (LHH2, LHH5, LHH6, RHH3, RHH5, RHH6) will be included within the Adequately Compensated group (AC). Interestingly all of these participants had partial HVFDs with some sparing on the affected side. The other 6 participants in the HVFD group all scored poorly in both speed and accuracy domains (LHH1, LHH3, LHH4, RHH1, RHH3 and RHH4). These individuals all had more extensive HVFDs with the exception of RHH1 who had both peripheral and central sparing. This group will make up the Inadequately Compensated group (IC).

The USN group showed a wide spectrum of performance, but all showed impaired search speed and accuracy on the affected side in comparison to controls. Surprisingly the difference in performance between the affected and unaffected side was not great.

Table 4.26: Performance by the HVFD group converted to Z-Scores (in relation to Control group performance). Assignment into IC and AC groups was according to the average visual search performance. The USN group were identified by the criteria outlined in Chapter 2. A colour spectrum is used to indicate performance from green (higher values) than indicates good performance in relation to the control group through yellow and orange, down to red (lower values) that indicate poor performance relative to the Control group.

		Search Time		Accuracy		
	P	Easy	Hard	Easy	Hard	Average
AC	LHH2	0.81	-0.18	0.54	1.27	0.61
AC	RHH5	0.44	0.10	0.83	0.59	0.49
AC	RHH6	-0.20	0.30	0.54	0.42	0.26
AC	LHH5	-0.72	-0.07	-0.94	-1.62	-0.84
AC	RHH3	-1.40	0.02	-0.05	-2.13	-0.89
AC	LHH6	-1.33	-1.89	-0.05	-0.60	-0.97
IC	RHH1	-2.18	-1.50	0.54	-0.94	-1.02
IC	LHH1	-1.18	0.73	-0.64	-5.19	-1.57
IC	LHH4	-2.55	-0.80	-0.64	-4.17	-2.04
IC	RHH2	-2.05	-3.86	-1.53	-2.13	-2.39
IC	RHH4	-5.51	-2.18	-1.82	-2.30	-2.95
IC	LHH3	-1.29	-2.58	-3.89	-4.51	-3.07
USN	RVI1	-2.12	-1.32	0.06	-2.04	-1.36
USN	LVI4	-0.84	-3.24	0.83	-4.85	-2.03
USN	LHHVI	-2.21	-2.00	-0.94	-4.85	-2.50
USN	LVI1	-4.82	-1.28	-4.18	-3.15	-3.36
USN	LVI3	-9.21	/	-7.13	-5.36	-7.23

Repeated measures ANOVAs were performed separately for ipsilesional and contralesional targets to analyse the effect of group (control, HVFD or USN) and of task difficulty (easy or difficult target) on search time and accuracy. For contralesional targets, mean search times for easy targets were as follows: Controls: 2.06 secs, HVFD group: 2.82 secs, USN group: 3.79 secs. Mean search times for difficult contralesional targets were: Controls: 4.60 secs, HVFD group: 4.85 secs, USN group: 6.48 secs. A repeated measures ANOVA found a significant difference in search time between task conditions (i.e. easy or difficult targets): $F(1,30) = 146.518$, $p < 0.001$, partial eta squared = 0.830. There was also a significant difference between groups: $F(2,30) = 12.30$, $p < 0.001$, partial eta squared = 0.447.

There was no significant interaction between group and condition: $F(2,30) = 1.230$, $p = 0.307$. Post hoc Bonferroni analysis was performed to try and distinguish where the group differences lay. There was no difference between the control and HVFD group ($p = 0.159$), but there was a significant difference between the controls and USN group ($p < 0.001$) and between the HVFD and USN group ($p = 0.006$). With only 4 members of the USN group normality of distribution of data cannot be assumed so these results need cautious interpretation.

For contralesional targets, mean search accuracy for easy targets was as follows: Controls: 94.1%, HVFD group: 89.6%, USN group: 72.3%. Mean search accuracy for difficult contralesional targets were: Controls: 71.9%, HVFD group: 52.1%, USN group: 19.9%. A repeated measures ANOVA found a significant difference in search accuracy between task conditions (i.e. easy or difficult targets): $F(1,31) = 127.678$, $p < 0.001$, partial eta squared = 0.805. There was also a significant difference between groups: $F(2,31) = 13.34$, $p < 0.001$, partial eta squared = 0.463. There was also a significant interaction between group and condition: $F(2,31) = 7.111$, $p = 0.003$, partial eta squared = 0.315. Post hoc Bonferroni analysis was performed to try and distinguish where the group differences lay. There was no difference between the control and HVFD group ($p = 0.089$), but there was a significant difference between the controls and USN group ($p < 0.001$) and between the HVFD and USN group ($p = 0.030$). With only 5 members of the USN group normality of distribution of data cannot be assumed so these results need cautious interpretation. In terms of the interaction between group and factor, the control group saw a fall in accuracy between task conditions (easy and difficult) of 22.2%, the HVFD group saw a fall of 37.5% and the USN group saw a fall of 52.4%.

For ipsilesional targets, mean search times for easy targets were as follows: Controls: 2.06 secs, HVFD group: 2.60 secs, USN group: 3.05 secs. Mean search times for difficult ipsilesional targets were: Controls: 4.60 secs, HVFD group: 5.71 secs, USN group: 5.89 secs. A repeated measures ANOVA found a significant difference in search time between task conditions (i.e. easy or difficult targets): $F(1,31) = 311.878$, $p < 0.001$, partial eta squared = 0.910. There was also a significant difference between groups: $F(2,31) = 7.224$, $p < 0.001$, partial eta squared = 0.318. There was no significant interaction between group and condition: $F(2,31) = 1.742$, $p = 0.192$. Post hoc Bonferroni analysis was performed to try and distinguish where the group differences lay. There was a significant difference between the control and HVFD group ($p = 0.015$) and a significant difference between the controls and USN group ($p = 0.012$). However there was no significant difference between the HVFD and USN group ($p = 1.00$). With only 5 members of the USN group normality of distribution of data cannot be assumed so these results need cautious interpretation.

For ipsilesional targets, mean search accuracy for easy targets was as follows: Controls: 94.1%, HVFD group: 90.3%, USN group: 83.8%. Mean search accuracy for difficult ipsilesional targets were: Controls: 71.9%, HVFD group: 48.3%, USN group: 24.7%. A repeated measures ANOVA found a significant difference in search accuracy between task conditions (i.e. easy or difficult targets): $F(1,31) = 132.899$, $p < 0.001$, partial eta squared = 0.811. There was also a significant difference between groups: $F(2,31) = 12.26$, $p < 0.001$, partial eta squared = 0.442. There was also a significant interaction between group and condition: $F(2,31) = 9.407$, $p = 0.001$, partial eta squared = 0.378. Post hoc Bonferroni analysis was performed to try and distinguish where the group differences lay. There was a significant difference between the control and HVFD group ($p = 0.015$), a significant difference between the controls and USN group ($p < 0.001$), but no significant difference between the HVFD and USN group ($p = 0.080$). With only 5 members of the USN group normality of distribution of data cannot be assumed so these results need cautious interpretation. In terms of the interaction between group and factor, the control group saw a fall in accuracy between task conditions (easy and difficult) of 22.2%, the HVFD group saw a fall of 42.0% and the USN group saw a fall of 59.1%.

The reason that performance was averaged across the affected and unaffected hemifields to assign groupings in Table 4.26 was that for almost all of the HVFD group, speed and accuracy for targets in the unaffected hemifield was no better than for the affected hemifield (see Tables 4.24 and 4.25), and in some cases performance was actually worse: e.g. accuracy rates for LHH5 were worse for the right field and for LHH1 search times were slower for the right field. One possible explanation is that the participants were compensating and initiating their search on the affected side, so spent more time searching the affected hemifield - this is the most common adaptive behaviour described in the literature. To investigate this hypothesis the total number of fixations and total time searching each half of the screen was calculated. Only the no target trials were included in the analysis since these trials provided more consistent viewing conditions, whereas the data from trials where there was a target may have been biased by the properties of the search that led to target detection (i.e. happening to search the side containing the target).

Some researchers have identified “refixations” of previously examined targets as a useful metric. Numbers of refixations is likely to vary with number of fixations. Our experiment did not control for number of fixations (or any related variable such as search time), so refixation numbers were not collected as this measurement was unlikely to provide useful information about an individual's search performance.

4.3.6 Results: Gaze Tracking Data during Visual Search Task

As would be expected the Control group searched the visual fields with no clear or systematic bias towards either side (on average 50.3% of fixations fell in the Left field, with 50.0% of time spent looking at the Left field) with the largest asymmetry observed in a single Control participant being 61.8% of fixations and 60.4% of time spent looking into the Left field. To gain a representative reference range of asymmetries from the Control group the side with the greatest number of fixations and longest search times were taken for each participant and used as a measure of "visual search asymmetry" (Table 4.27. N.B. Table 4.61, Appendix 4 shows the full control data set).

Table 4.27: Visual search asymmetry across control participants

	Number of Fixations	Total Time Spent Searching
Mean	53.52%	53.34%
Median	53.09%	53.03%
Standard Deviation	2.80%	2.69%
Min/Max	50.19% - 61.79%	50.11% - 60.44%

For the participants with Stroke the number of fixations and time spent searching the affected or unaffected hemifield were calculated (rather than by left or right field) and sorted by the proportion of fixations falling in the affected side (Table 4.28). LHH3 spent little time searching the contralesional side of the screen, which suggests little adaptation to the visual deficits. This is consistent with the conclusions of Chapter 2 which suggested that LHH3 had a fairly new hemianopia which had not yet been adapted to. Despite this, the number of targets correctly identified by LHH3 was similar regardless of which side of the screen they occurred on, although reaction time was slower on the left. RHH2 and LHH4 spent a greater amount of time searching on their symptomatic side suggesting a degree of adaptation to their visual field defect. The other participants with HVFDs spent roughly equal times exploring each side of the screen

Table 4.28: Proportion of fixations and proportion of time spent searching the affected side each half of screen by the HVFD and USN groups.

	P	Fixations in Affected Side	Time Searching Affected Side	Fix. Duration (Affected side)	Fix. Duration (Unaffected side)
AC	LHH2	50.9%	48.2%	194.9	205.3
	RHH5	47.2%	45.8%	160.6	173.2
	RHH6	54.0%	54.7%	211.8	218.2
	LHH5	50.0%	52.9%	214.4	208.4
	RHH3	50.4%	50.8%	231.8	222.5
	LHH6	51.2%	50.4%	214.2	228.4
IC	RHH1	53.9%	53.4%	201.3	205.4
	LHH1	52.4%	50.9%	199.6	204.2
	LHH4	65.5%	65.9%	228.1	235.5
	RHH2	67.8%	68.2%	272.3	281.3
	RHH4	50.0%	49.9%	259.5	264.1
	LHH3	16.2%	15.9%	174.1	191.5
USN	LHHVI	57.1%	50.7%	170.4	180.4
	LVI1	76.9%	80.7%	194.6	230.3
	LVI3	47.9%	45.9%	299.0	313.7
	LVI4	46.5%	51.7%	299.5	271.9
	RVI1	36.8%	33.5%	289.3	255.0

Individuals in the USN group showed a spectrum of performance in the visual search task (Table 4.24, 4.25 and 4.26). This was not unexpected given the heterogeneity of spatial neglect syndromes, but all participants showed at least some measures lying outside of the control range and all had diminished performance for targets in the affected hemifield. The difference between search performance in the two fields was, perhaps, not as great as one might perhaps expect, and may be explained by the search strategies. The prior evidence suggested that they should be less able to bring their attention over to the affected hemifield, but in fact only LVI3 showed this preference towards the ipsilesional side (Table 4.28). LVI4 and, to a lesser extent RVI1, in fact showed a greater time spent searching the contralesional half of the screen – again suggesting an attempt to overcome their impairment.

Prior research suggested that a proportion of people with a HVFD would exhibit abnormal search characteristics such as shorter fixation durations, and shorter saccades. Table 4.28 shows mean fixation durations for each participant with stroke and Table 4.29 summarises fixation durations for the control group.

Table 4.29: Control group fixation duration parameters during visual search task

Control Group	Fixation Duration (ms)
Mean of means	211.7
Median of means	209.6
Standard Deviation of means	26.72
Min/Max of means	149.4 – 275.7

For the participants with HVFDs (LHH1-6 and RHH1-6), the mean fixation duration was 218.0ms (217.9ms on the affected side, 218.1ms on the unaffected side as compared to 210.8ms for controls), median 209ms, standard deviation 120.9ms. No single HVFD participant showed a convincing difference between fixation durations on the left and right side of the screen (Table 4.28). For the participants with USN (LHHVI, LVI1, LVI3, LVI4 and RVI1), fixation duration was long at least for 3 participants (Table 4.28, Gray shaded, highlighted in red). CONT3 was the slowest control with a dwell time average of 275.7ms – LVI3 and LVI4 both exceeded this and RVI1 was only a little faster. LVI1 had fixation durations well within normal range and LHHVI had faster than average fixation duration. There were 3 participants with USN that had shorter fixation durations on the affected side but there were 2 others that were slower. This is all in line with USN being a highly heterogeneous condition.

At a group level mean fixation durations on the contralesional side of the screen were: Controls: 208.6ms, HVFD group: 213.6ms, USN group: 250.6ms. A one way ANOVA found no significant difference in fixation duration between groups: $F(2,33) = 3.154$, $p = 0.057$. Mean fixation durations on the ipsilesional side of the screen were: Controls: 208.6ms, HVFD group: 219.8ms, USN group: 250.3ms. A one way ANOVA did show a significant difference between groups: $F(2,33) = 3.878$, $p = 0.031$, partial eta squared = 0.200. Planned contrasts revealed no difference between the control and HVFD groups ($p = 0.320$), no difference between the HVFD and USN groups ($p = 0.061$), but a significant difference between the control and USN group ($p = 0.009$).

Several previous studies have shown that people with hemianopia use shorter saccades during visual search (see section 4.2). To examine whether this was the case for the HVFD group the saccade amplitude was calculated during the 8 trials without targets (to ensure consistency of number and type of saccade). The mean saccade amplitudes for the Control group were 7.62 degrees (Min: 5.13 degrees, Max: 10.94 degrees). Saccade amplitudes for each individual in the Stroke group are presented in Table 4.30. The mean saccade amplitude for the HVFD group (7.42 degrees) was similar to Controls and each individual showed mean saccade amplitude within the range exhibited by controls. The individuals with USN were heterogeneous (Table 4.30, grey shading) but LHHVI and LVI3 seemed to use very short saccades whilst searching the screen. LHHVI had very short saccade amplitudes when moving to the left, although LVI3 had slightly shorter saccades when heading right. LVI4 and RVI1 had saccadic amplitudes which were well within the range seen in the control group. There were some eye tracking artefacts when testing LVI1 with the eye tracking camera picking up reflections from moisture on the eye which caused oscillations that disrupted this measure since it caused a high number of very short artefact saccades to be recorded.

At a group level mean saccadic amplitude for saccades heading in a contralesional direction were: Controls: 7.63 deg, HVFD group: 7.22 deg, USN group: 5.36 deg (with LVI1 excluded). A one way ANOVA found a significant difference in fixation duration between groups: $F(2,32) = 5.490$, $p = 0.009$, partial eta squared = 0.268. Planned contrasts showed no significant difference between the control and HVFD groups ($p = 0.391$). There was a significant difference between the control and USN groups ($p = 0.002$) and between the HVFD and USN groups ($p = 0.014$). Mean saccadic amplitudes for saccades heading in an ipsilesional direction were: Controls: 7.63 deg, HVFD group: 7.90 deg, USN group: 6.42 deg. A one way ANOVA found no significant difference between groups: $F(2,32) = 1.686$, $p = 0.202$.

Table 4.30: Mean Saccade (Sac.) Amplitudes (in degrees) for participants with stroke towards the Affected Side (AS) or Unaffected Side (US).

	P	Sac. Amplitude towards AS	Sac. Amplitude towards US	Mean Sac. Amplitude
AC	LHH2	6.22	8.42	7.22
	RHH5	7.3	6.45	6.83
	RHH6	7.62	6.83	7.22
	LHH5	8.14	8.27	8.21
	RHH3	6.35	9.81	7.78
	LHH6	6.51	6.14	6.33
IC	RHH1	7.27	7.37	7.32
	LHH1	6.83	7.89	7.33
	LHH4	9	11.09	9.91
	RHH2	5.18	8.86	6.67
	RHH4	6.26	8.31	7.24
	LHH3	9.98	5.33	7.06
USN	LHHVI	6.45	6.93	6.68
	LVI1	6.87	9.02	7.67
	LVI3	3.28	5.41	4.18
	LVI4	3.37	6.45	4.68
	RVI1	4.85	4.32	4.55

4.3.7 Discussion

This experiment was designed to determine whether individual visual search performance could be linked to visual impairments. In particular the measures taken were used to see whether there was any evidence of qualitatively different search patterns amongst individuals or groups which could represent the effects of pathology or adaptation (or indeed, maladaptation) to visual impairments. The first noticeable feature of the visual search task was that there was a wide variability in performance even among the control group – CONT13 only correctly identified less than half of the difficult targets (i.e. less than the score he could have got by guessing before the experiment timed out). It is clear that this search task was challenging compared to many search tasks reported in the existing literature.

At a group level it does seem that the control group were both faster and more accurate at identifying targets than the HVFD who in turn were faster and more accurate at finding targets than the USN group – even though statistical significance was not always reached (the sample size is small). Analysis of individuals reveals a more complex picture.

When considering the performance amongst people with HVFD, previous research would lead one to presume that a neat dichotomy would emerge between well adapted and poorly adapted individuals, and so could be clearly grouped into those who are very good at visual search tasks, and those who are markedly impaired. The data presented in this Chapter do not reflect this pattern, with a spectrum of performance evident across individuals (Tables 4.24, 4.25 and 4.26). It is clear, however, that 6 individuals were the most successful in the visual search task and overall performed within the range of Control participants: LHH2, RHH5 and RHH6 had scores which were within the control range throughout and often better than Controls; and whilst LHH5, LHH6 and RHH3 scored nearer the bottom of the reference range for a number of measures, there were no scores outside of the reference range from Control participants. These individuals were therefore placed within the Adequately Compensated (AC) group (Table 4.26). The remaining individuals with HVFD generally performed worse than the AC group and outside of the reference range provided by Controls and so were placed in the Inadequately Compensated group (IC). There was widespread variability amongst these individuals: at one extreme, RHH1 was similar to Controls on accuracy measures but with considerably slower search times, whereas at the other extreme LHH3 showed severely reduced performance in both accuracy and speed in virtually all conditions.

Unsurprisingly the participants with USN were, in the main, extremely impaired at this visual search task. Even amongst this group, however, there was considerable variation. RVI1 identified virtually all of the easy targets correctly, although accuracy at identifying difficult targets was impaired on both sides, and reaction times were much longer for both easy and hard targets in the affected hemifield. LVI4 also successfully identified virtually all of the easy targets – with normal reaction times on the right and low normal reaction times on the left. Success with difficult targets was extremely impaired on both sides (worse than RVI1). Performance dropped off further from LHHVI (who at least identified all of the easy targets on the right hand side of the screen) to LVI1 who was impaired in all parameters to LVI3 who was even more impaired in all parameters.

Another striking feature of the results is that, for most of the people with HVFD, performance was not radically different when targets were presented in the affected hemifield compared to when they were presented in the unaffected hemifield. Even for those with USN, only 2 of the 5 participants showed a marked drop in accuracy for the affected side (although all are slower to find easy targets on the affected side). Table 4.31 compares performance in terms of total accuracy and search time for easy targets (search time to hard targets was often a less useful measure because the accuracy was often so poor) as well as percentage of fixations made on the affected side. It may have been expected that those in the HVFD group who showed increased numbers of fixations in the affected field would have performed better in the search task, but this was not the case, for either search times or percent correct identification. If anything, the participants who performed best seemed to exhibit fairly symmetrical search patterns. Amongst the USN group, those with a greater number of fixations on the affected side did show more accurate performance on the affected side.

Table 4.31: Comparing visual search times, proportion correct and symmetry of search (percent fixations made in the affected field) for the Stroke Group. Red text indicates results outside of the control reference range. Blue text indicates results more than 1 standard deviation from mean control result

		Search Times (ms) (Easy Task)		Percent Correct		% fixations
	P	Affected	Unaffected	Affected	Unaffected	Affected
AC	LHH2	2054	1342	97.9	87.5	51%
	RHH5	1818	1907	89.6	89.6	47%
	RHH6	2156	2154	85.4	89.6	54%
	LHH5	2342	2442	75	**64.6**	50%
	RHH3	**2786**	**2608**	**68.8**	**70.8**	50%
	LHH6	2441	**2889**	79.2	79.2	51%
IC	RHH1	**3261**	**2845**	83.3	75	54%
	LHH1	2217	**2984**	**47.9**	**50**	52%
	LHH4	**3779**	**2660**	**54.2**	**56.3**	**65%**
	RHH2	**3135**	**2849**	**70.8**	**58.3**	**68%**
	RHH4	**4604**	**4515**	**58.3**	**66.7**	50%
	LHH3	**3280**	2021	**39.6**	**43.8**	**16%**
USN	RVI1	**3746**	2305	**70.3**	**72.2**	**57%**
	LVI4	**2585**	2302	**56.3**	**56.3**	**77%**
	LHHVI	**3927**	2202	**43.8**	**56.3**	48%
	LVI1	**4918**	**3575**	**47.9**	**50**	46%
	LVI3	**7594**	**4877**	**14.6**	**35.4**	**37%**

Previous researchers have compared groups of people with hemianopia and demonstrated that more fixations were made on the affected side of the screen compared to the unaffected side (Kerkhoff, 1999; Pambakian et al., 2000; Tant et al., 2002b; Zangemeister et al., 1982; Zihl, 1995b; Zihl, 2000; Zihl, 1999). It has been proposed that this may be an adaptive behaviour, however a possible alternative explanation could be that some people with hemianopia misjudge 'straight ahead' to be offset slightly toward the hemianopic side. The data presented in this Chapter shows that only two participants seem to exhibit increased fixations on the affected side than the other, possibly indicating a degree of compensation. Although judgements of straight ahead were not explicitly measured, none of the HVFD group showed abnormal line bisection, which would suggest that asymmetric searches of the affected hemifield were more likely to be adaptive behaviours than simply a misperception of straight ahead. In any case it seems likely that the group differences previously reported are being driven by a minority of individuals who show this asymmetrical pattern of visual search. For one participant (RHH2) it is possible that increased numbers of fixations on the affected side adversely affected performance on the unaffected side. In comparison, for the USN group, only one individual showed the expected reduced number of fixations on the affected side, whereas two individuals showed a greater number of fixations on the affected side consistent with adapted gaze patterns. Such adaptations in those with USN have not previously been reported for visual search. These two individuals seemed to use the adaptation to perform the search task accurately but they were not able to maintain the same speed of visual search.

Visual search pattern performance has previously been examined through the calculation of additional fixation duration and saccade amplitude metrics. In the data presented here neither of these measures systematically varied across the control group or the HVFD group at an individual or group level. Even amongst Controls it was sometimes apparent that large differences between leftward and rightward saccade amplitudes occurred, presumably caused by different search strategies. The USN group did exhibit differences in these measures, however, with LHHVI and LVI3 (and possibly LVI1) tending to exhibit very short saccades and LVI3, LVI4 and RVI1 showed lengthy fixation durations. There is no single clear explanation for these patterns. It is possible that slowed visual processing speeds lead to longer fixation durations. Relating these findings to the saccade measures taken in Chapter 3, both LHHVI and LVI3 showed very hypometric saccades to the affected side , and LVI3 even showed slightly hypometric saccades to the unaffected side, so it is possible that these participants struggled to generate large saccades. This explanation does not hold for the participants with HVFDs since those who performed worst in the saccade tests reported in Chapter 3 still managed to make normal sized saccades in the visual search task in the current chapter.

Whilst this chapter has mainly examined visual search performance in relation to the eye-movement performance in Chapter 3, there was an additional purpose for performing the visual search, namely to determine whether visual search measures can be predictive of steering accuracy and hazard perception whilst driving. This question will be addressed in detail in the following chapters that gain additional measures of steering performance and hazard detection performance under simulated driving conditions.

Chapter 5: Performance in Steering Around Simple Bends

This chapter will examine the effect of visual field loss and visual neglect on steering and gaze during a simple simulated task of driving around a bend. Much is known about how humans plan, execute and maintain control over a range of perceptual motor tasks including driving.

A key concept in the study of visual field loss after stroke is that of **compensation** i.e. – a concept which is frequently discussed in academic literature, clinical discussions and DVLA guidance. Someone who is adequately compensating for a HVFD is usually described as using dynamic gaze strategies which are effective at gathering the necessary visual information for a particular task in a timescale which makes them able to complete the task with similar speed and effectiveness to a control subject with intact visual fields. The extent of visual field loss has been shown to only be one of a number of factors which affect performance in visual tasks such as searching and reading – the ability to use compensatory active gaze strategies to overcome visual field defects may be a more crucial factor. People with spatial neglect may have very limited ability to compensate for their impairment. They may well have intact visual fields but may not be able to drive attention into the affected hemifield in order to fixate targets (Husain et al., 2001), and if they do then the visual information may still not be processed effectively (Forti et al., 2005).

This chapter will review the current understanding of how people maintain control whilst driving and cornering and how visual field loss or neglect can impact on driving. I will then generate some hypotheses as to what we would expect in a simple cornering task for our control and patient groups and then test these hypotheses.

5.1 Patterns of gaze in motor tasks

Humans can perform motor tasks with remarkable consistency in a range of contexts even when the visual and sensory information available is highly variable. The brain is seemingly able to reliably flexibly weight information according to circumstances in order that the motor task is performed optimally (Ernst and Banks, 2002). Sampling this information requires eye movements. What a person looks at during a task varies little between individuals and the selected targets are almost always relevant to the task in hand (Land et al., 1999; Pelz and Canosa, 2001; Tatler et al., 2011).

A common type of fixation made during a task is a 'guiding fixation (Mennie et al., 2007)' (or 'just in time fixation (Ballard et al., 1995)'. Such fixations relate to the exact part of the task currently being undertaken and usually target an object which is being manipulated, or the part of space in which action is about to take place. They commonly occur ahead action by around a second or so, and by the time an action is completed the eye is already looking ahead to the next part of the task (Land, 2006). Guiding fixations have been observed in tasks such as making tea (Land et al., 1999), piano playing (Land and Furneaux, 1997) and sandwich making (Hayhoe et al., 2003).

Gaze fixations are also made in a way which anticipates future parts of the task. For instance, during hand washing, the soap is likely to be fixated ahead of the time in which it will be used (Pelz and Canosa, 2001). These 'look ahead fixations' are likely used in order to optimise performance in future parts of the task (Hayhoe et al., 2003; Mennie et al., 2007) – for instance in the hand washing task, the location and orientation of the soap can be stored in short term memory and the information retrieved just before the soap is needed.

It seems probable that different amounts and types of information are used at different times even during the same task. For instance, in the example given above, the look ahead fixation which recorded the spatial location of the soap would probably give enough feedforward information to initiate a rapid reaching movement towards the soap. In such an unconstrained action, feedback information is of more limited use and the delays inherent in waiting for and processing feedback information would introduce unnecessary delay. However once the (probably slippery) soap starts to be grasped, visual and haptic feedback information would rapidly become of crucial importance in maintaining a grip on the soap. Studies on reaching tasks do support this idea that the initial rapid reaching movement is predominantly guided by feedforward (open loop) systems, but the grasp phase requires feedback (closed loop) processes to maintain a smooth action (Keele, 1968; Hollerbach, 1982). In reality though several studies support the more complex idea that feedback and feedforward systems are online and in use simultaneously and feedforward processes are constantly being updated by feedback information. The generation of smooth, rapid actions requires both systems to be functioning at all times (Desmurget and Grafton, 2000).

As steering a car is a complex motor task, one would expect to find evidence of feedback and feedforward information being used during driving from guiding and anticipatory gaze fixations. We would also expect that steering accuracy would be impaired in predictable and logical ways when access to particular pieces of visual information is impaired. The next sections examine the evidence for this.

5.2 Eye movements and car steering

During walking or riding a bicycle, human gaze is primarily directed to points on the path ahead in the intended direction of travel, or to specific points at which direction will change (Bernardin et al., 2012; Vansteenkiste et al., 2013; Imai et al., 2001). The same is true when driving a car, for instance in a simulated slalom driving, gaze was primarily directed at the next slalom gate until it was 1-2 seconds ahead, at which point gaze moved to the next slalom gate (Wilkie et al., 2008).

When approaching or turning into a bend on which there is no specific waypoint to look at, drivers will look towards the inside of the bend (Land and Lee, 1994; Underwood et al., 1999; Land and Tatler, 2001; Chattington et al., 2007; Kandil et al., 2009; Kandil et al., 2010; Lappi and Lehtonen, 2013; Lehtonen et al., 2013; Lehtonen et al., 2012; Marple-Horvat et al., 2005; Authie and Mestre, 2011). One of the earliest studies which demonstrated this phenomenon noted that drivers seemed to be extensively fixating the tangent point of the bend i.e. the apparent apex of the bend as observed by the driver (Land and Lee, 1994). A subsequent study also noted extensive tangent point fixation (Kandil et al., 2009). It was proposed that the curvature of the bend could be calculated by the brain from the location of the tangent point from which appropriate steering could be programmed. The tangent point would also provide a relatively stable fixation point for the eye (as opposed to points on the road which would rapidly be approaching the driver). However a number of problems have since been found with this single key road feature model. Firstly is the theoretical criticism that the tangent point model is not generalisable – it would not apply in situations where there is no tangent point (consider turning into a parking space in a large car park), where the tangent point lies at a very large eccentricity from the driver (i.e. turning right in the UK on a very wide road with few road markings), or where the tangent point is obscured for some reason (Wilkie et al., 2010). Other studies have found that the tangent point was rarely fixated, rather people looked at the road ahead or somewhere between the centre of the road and the inside edge of the bend (Robertshaw and Wilkie, 2008; Wilkie and Wann, 2003b). This produces a characteristic observed eye movement behaviour of smooth pursuit of the fixated point on the road, until that point is 1-2 seconds in front, followed by a saccade to a further point ahead (Wann and Swapp, 2000; Lappi and Lehtonen, 2013; Authie and Mestre, 2011; Wilkie et al., 2008) (this pattern has been termed optokinetic nystagmus). The tangent point may appear to be fixated when approaching a bend on a trajectory intended to cut the corner to some degree (Robertshaw and Wilkie, 2008; Wilkie et al., 2010). Fixating the tangent point deliberately brought either no advantage to steering accuracy (Robertshaw and Wilkie, 2008) or a deterioration in steering accuracy (Mars, 2008) (Another study showed improvement in steering accuracy with deliberate tangent point fixation (Kandil et al., 2009), but their comparator of 'gaze sampling' was not a natural one). Very careful studies directly comparing the 'tangent point' and 'future path' models have recently been published. The observation was made that the points at which one would predict the driver to be looking at any moment in time according to either of these models were often very close to each other. By interpreting, frame by frame, whether gaze was closest to the point at which the tangent point or future path model would predict gaze to be, it was concluded that the tangent point was not likely to be a particularly important gaze target (Lappi et al., 2013a). Another study compared the eye movement properties predicted by each model with observed data and concluded that the future path models produced a far better fit (Lappi et al., 2013b).

An alternative theory of how humans use gaze to control steering is the 'active gaze' model (Wilkie and Wann, 2003a; Wilkie and Wann, 2002). This is essentially a future path model as outlined above – the person fixates areas on the road ahead and tracks them for short periods. Information gleaned from this includes visual angle to the future point, retinal flow information (i.e. the movement of visual features across the retina) and extra-retinal information (i.e. direct information fed back on the position and movement of the eyes), all of which have been demonstrated to improve steering (Wilkie and Wann, 2003a; Wilkie and Wann, 2002; Wilkie and Wann, 2003b; Wilkie and Wann, 2005; Wilkie et al., 2008). It has been conceptualised that the visual (and non visual) angular and rotational information is used to generate 'point attractors' to guide steering (Wilkie et al., 2008).

5.3 Peripheral Visual Information and Steering

Other steering models have proposed that peripheral near point information is also important in steering, as a provider of feedback as to one's current position in the road (Donges, 1978; Salvucci and Gray, 2004) with far point information being more important in generating feedforward information to guide steering. One study found that removing near road segments from the simulator screen produced smooth steering but increased position errors relative to the road, whereas removing far road sections adversely impacted on steering smoothness, but position in lane was much better (Land and Horwood, 1995). The importance of near point road edge information has been demonstrated in studies of driving through a series of waypoints (Wilkie et al., 2008) as well as driving on smooth open bends (Robertshaw and Wilkie, 2008).

The importance of road edge information was examined in a series of experiments of driving around smooth bends with faded or absent road edges (Kountouriotis et al., 2012). When driving in the centre of the road, fading or absence of either road edge did not adversely affect steering error. However if the driver was asked to drive round a bend in a line closer to one edge than the other, and that road edge was absent on the screen, steering error significantly increased (although bias did no alter – suggesting that the person could keep to the correct course on average, but steering was less accurate). On a second experiment the drivers were asked to fixate a target on the screen which appeared centrally or eccentrically past one of the road edges. When road edge information was intact, fixating a central target did not cause the driver to drift towards where their gaze was targeted as presumably peripheral road edge feedback kept their driving line intact. However, if the road edge was faded, lessening the feedback signal, the drivers did indeed drift towards where the fixation target was.

It is not just road edge information that provides error feedback whilst steering. One experiment has shown an effect on steering feedback for the ground plane texture and optic flow from the sides of the road (Kountouriotis et al., 2013). It was shown that if the ground plane texture was coarser on one side of the road than the other, drivers would steer towards the smoother texture – an effect which was explained as an attempt to partially equalise optic flow. Similarly participants steered towards a side of the bend which had a blank ground texture. Finally the participants drove round a series of bends which had one side apparently moving more quickly than the other relative to the driver. Drivers were biased towards the road edge which was apparently moving more slowly, a phenomenon which was again explained as an attempt to equalise optic flow data between the road edges.

5.4 Anticipatory Saccades

We have so far seen empirical evidence that information from at least 2 points on a curve are important for successful steering – a far point for guidance (feedforward) and a near point for stabilisation (feedback) (Salvucci and Gray, 2004). We have also seen evidence that many types of visual and non visual information can be used to control steering (Wilkie et al., 2008; Wilkie et al., 2010). All of these models have looked at online steering – i.e. sensory information that is translated immediately into steering responses. One author describes a model of steering which incorporates online steering, but also a hierarchical structure with tactical driving decisions lying above online steering control, and strategic driving decisions on a higher level still (Michon, 1985). A tactical driving decision could be choosing a speed at which to enter a curve, or drifting outwards on approach to allow a greater racing line to be taken. A strategic driving decision might be the time of departure and therefore the time allowed for to make a journey, or the route taken. In essence higher levels of driving control set goals to be accomplished through actions taken by lower levels of the driving control hierarchy (Grafton and Hamilton, 2007; Cooper and Shallice, 2000; Land, 2009).

In the case of driving around a corner, the trajectory to be taken (in terms of the speed as well as the exact path) could be seen very much as a tactical driving decision. In order to plan a trajectory, the nature of the bend and other road users will constrain which trajectories are possible (Fajen and Warren, 2003), as will the characteristics of the vehicle and the person driving it (Lehtonen et al., 2014).

A key function of trajectory planning is to choose a suitable speed at which to enter and drive around a bend (Charlton, 2007; Cruzado and Donnell, 2010; Hassan and Sarhan, 2012). It is also very important to plan a trajectory which will avoid hazards such as oncoming cars (Lehtonen et al., 2012).

In order to achieve a suitable trajectory visual information from the road ahead and emerging potential hazards (such as oncoming traffic) is needed. Gaze fixations which look further into the curve beyond what is usually fixated for online steering guidance have frequently been reported (Cohen and Studach, 1977; Shinar et al., 1980; Land and Horwood, 1995; Lehtonen et al., 2013; Lehtonen et al., 2012; Mars and Navarro, 2012; Underwood et al., 1999; Kandil et al., 2010), sometimes termed as ‘look ahead’ fixations to deliberately tie them in with anticipatory fixations found in other perceptual-motor tasks (Pelz and Canosa, 2001; Mennie et al., 2007). More recently it has been demonstrated that drivers with greater experience invest more time in anticipatory saccades than novices, perhaps because, with experience, steering guidance becomes more ‘automised’ and can rely on peripheral vision to a greater extent, leaving more time for trajectory planning (Lehtonen et al., 2014). Alternatively, when cognitive load is increased, drivers make fewer anticipatory saccades perhaps reflecting conflicting pressures on the total attentional resource (Lehtonen et al., 2013).

5.5 Other Biases to Steering on a Bend

In the experiments detailed below, participants have been asked to drive around bends either in the centre of the road, or in a position halfway between the centre and inside or outside road edge. These conditions, simply of themselves, have previously been shown to introduce significant steering biases which one would expect to be repeated here. Firstly, when asked to drive around the corner in a position offset from the centre, people are able to stay on the correct side of the road, but tend to drive closer to the centre than the line they are asked to take (Kountouriotis et al., 2012; Kountouriotis et al., 2013). Also there is a general tendency to oversteer and cut the corner (Kountouriotis et al., 2012; Kountouriotis et al., 2013; Robertshaw and Wilkie, 2008) – which adds to oversteer from a central heading tendency when on the outside of the bend, but is antagonistic to the centralising tendency when on the inside of a bend.

Driving with eccentrically fixated gaze may also introduce steering biases – a fact which may be important if our participants with stroke use compensatory gaze shifts into the affected visual hemifield. One study demonstrated that when driving down a straight road with eccentrically fixated gaze, drivers tended to drift towards the direction of gaze. They then made corrective steering adjustments to prevent themselves leaving the road (Readinger et al., 2002). These corrections are in line with what others have found regarding the use of near point peripheral road edge information to maintain lane position (Kountouriotis et al., 2012; Salvucci and Gray, 2004). The same steering biases were found even if the steering wheel was mapped in reverse, ruling out biomechanical factors to explain the bias.

When driving around a bend, eccentric gaze direction can bias steering trajectory towards the direction of gaze, but only when peripheral feedback information is poor – either because the road is wide and the relevant road edge is far from the car position (Robertshaw and Wilkie, 2008), or if the road edge visibility is degraded (Kountouriotis et al., 2012).

5.6 Steering with a Homonymous Visual Field Defect

As detailed in Chapter 1, driving performance for those with a HVFD is highly variable from person to person, with some studies reporting that most failed an on road driving examination (Hannen et al., 1998; Hartje, 1991), some reporting that a few individuals were competent enough to pass an on road assessment (Tant et al., 2002a; Racette and Casson, 2005) and at least 1 study suggesting that the majority could pass (Elgin et al., 2010) – the variation may simply reflect selection criteria.

A key theme reported in several studies is that, even when driving performance is otherwise good, people with a HVFD had trouble with crossing boundaries and holding lane position on straights and bends (Bowers et al., 2005; Coeckelbergh et al., 2002a; Coeckelbergh et al., 2002b; Szlyk et al., 1993; Elgin et al., 2010; Wood et al., 2009).

One study reported that most boundary crossings were on the opposite side to the hemianopia. They also reported that right hemianopes tended to drive further left in their lane, did not move over for oncoming traffic (they were driving on the right) and did not cut corners on right bends, but did on left bends. A similar pattern was seen for left hemianopes although the differences from controls were less pronounced (Bowers et al., 2010). The authors theorised that, unable to see the road edge in their hemianopic field, they simply increased the margin for error and stayed away from it. They also reported increased boundary crossings.

These findings would fit very neatly with what is known about steering control at an operational level. In a study using faded or absent road edges to reduce peripheral vision feedback used in lane keeping, steering became more errorful when driving near the degraded road edge (Kountouriotis et al., 2012). Homonymous hemianopia could also potentially reduce the availability of near point lane position data used in maintaining a smooth lane position, which could therefore increase boundary crossings. A deliberate strategy of driving closer to the road edge one can see may improve visual feedback information, but could also consequently reduce margin for error in the ipsilesional direction, again increasing the number of steering errors and boundary crossings.

5.7 Steering with Unilateral Spatial Inattention

Most clinicians would recommend that people with significant spatial inattention be censured from driving – for the obvious reason that not knowing what you don’t notice is very much a key feature of the syndrome and therefore hazard detection is highly likely to be critically impaired.

Impairment in the judgement of ‘straight ahead’ does seem to be impaired at least in some people with USN (Jeannerod and Biguer, 1987; Heilman et al., 1983; Chokron and Imbert, 1995; Karnath, 1997) and deviations from the intended path have been seen in walking and wheelchair driving (sometimes in opposite directions depending on which form of locomotion was being used!) (Turton et al., 2009). Collisions with objects on the contralesional side are common (Webster et al., 1989; Webster et al., 1994; Webster et al., 1995; Punt et al., 2008). One author noted that, regardless of the width of a doorway, a person with USN piloting an electric wheelchair tended to pass through the door the same distance from the ipsilesional doorway (Punt et al., 2008).

In terms of steering a car, this all might suggest that the driver with USN is likely to have significant problems with steering accuracy – their ability to control the car in a straight line or around a bend may be directly impaired by the USN and their ability to correct lane position with peripheral feedback may be very impaired as feedback information from the contralesional side may be ignored altogether. The driver may try to maintain a driving line a particular distance from the ipsilesional road edge, regardless of the road width or oncoming hazards.

5.8 Experiment: Steering around a Bend with a Homonymous Visual Field Defect or Visual Inattention

We wished to explore the behaviour of our participants with stroke when driving around a bend. In particular we were interested in whether their visual impairment affected visual feedback with an adverse effect on steering accuracy – and whether they were able to use a compensatory gaze strategy. The experiment detailed below is almost identical to the faded road edge experiment detailed above (Kountouriotis et al., 2012), with the exception that, rather than directly creating stimuli containing faded or absent road edges, the participants with stroke had a visual impairment instead. The experiment used simulated bends of a constant curvature with a sparse ground texture (fig 16) in order that targets for look ahead, anticipatory fixations would not appear – and therefore gaze would be expected to mostly lie on the path ahead (i.e. guidance fixations).

For people with a HVFD, one might hypothesise that, when asked to drive a course close to a road edge in their affected hemifield, a bias may be created away from the road edge as they attempt to balance completing the task as asked with the desire to maintain a reasonable margin for error in avoiding leaving the road. Alternatively (or in addition) steering variability may be increased. One could theorise that the participant may attempt to compensate by either using gaze shifts to fixate the road edge in their affected hemifield, or even to fixate the opposite road edge instead. Such eccentric gaze shifts may then also create a steering bias in the direction of the gaze shift, which may or may not be counterbalanced by corrective steering when the road edge is subsequently fixated.

For people with USN, one might hypothesise that the road edge on the affected side may be ignored entirely and both steering and gaze may be biased in the ipsilesional direction.

In order to test these hypotheses the experiment was designed to answer the following questions regarding the participants with stroke in comparison to the control group.

1. Does the impairment create a steering bias or increase steering error?
2. Is the error or bias only apparent when driving close to one side of the road, but not the other?
3. Is there any evidence of any participants using a compensatory driving tactic or gaze tactic?
4. If any compensatory techniques are observed, what effect does this have?

5.8.1 Participants

All 18 controls and all 18 participants with stroke attempted this experiment but usable data was only obtained on a proportion of them.

Steering data was obtained for 14 controls, all 6 left HVFDs, 5 right HVFDs and all of the participants with USN (including participant LHHVI with left hemianopia and neglect). CONT5 abandoned the task due to fatigue and severe difficulty with the eye tracking. CONT13, CONT17 and RHH4 experienced nausea on practicing the experiment so the experiment was terminated. CONT18's data was unusable – the data was not recorded correctly by the software for unclear reasons.

Eye tracking data was obtained for 13 controls (data was corrupted for CONT11 as the head tracker was malfunctioning),4 LHVFDs (LHH4 and LHH5 had eye tracking data of insufficient quality primarily due to calibration failure), 5 RHVFDs and 4 participants with USN (including participant LHHVI. We were unable to calibrate RVI1 and LVI1 so the eye tracking data was unusable).

5.8.2 Apparatus

The apparatus used was very similar to that used by Robertshaw and Wilkie in 2008 and Kountouriotis et al. in 2012 (Kountouriotis et al., 2012; Robertshaw and Wilkie, 2008). The experiment took place in our static, fixed base driving simulator (see figure 5.17). Participants sat in an Elap rotating driving seat which could be rotated to 90 degrees to allow an easier transfer from a wheelchair. The seat could then be rotated into the driving position and locked into place. The seat was mounted on a scissor lift so the participant could then be raised up to the correct eye height for which the driving simulator and eye tracker were calibrated.

The experiment was run on a PC (Intel i7 950 3.07 GHz) running Windows XP, Direct-X graphics libraries and custom software designed for the purpose. Images were generated at 60Hz and projected onto a back projection screen 1.98m x 1.43m using a Sanyo Liquid Crystal Projector (PLC-XU58). The participant's eye was 1 metre from the screen which then subtended a visual angle of 89.4 x 71.3 degrees. The screen was located in a matt black viewing booth in order that it was the only source of light. The participant controlled their steering with a force feedback steering wheel (Logitech Momo Racing) which could rotate between -32.8 and 32.8 degrees. There was no head or body restraint. Eye tracking data was recorded at 60 frames per second from a remote ASL (Applied Science Laboratories) 504 gaze monitoring system using a pan-tilt mechanism.

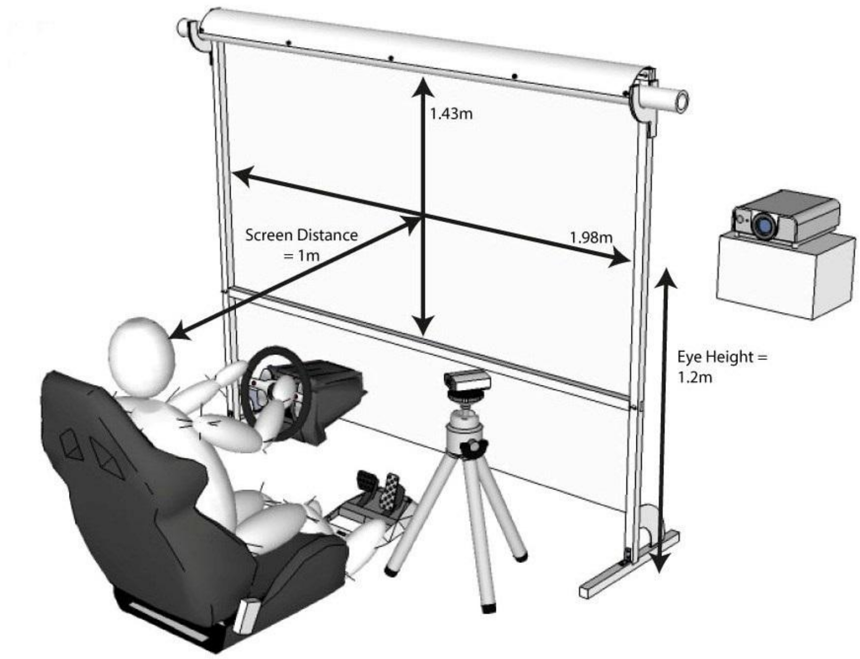

Figure 5.17: Driving Simulator Layout (Image created by Callum Mole for a forthcoming paper in the British Journal of Occupational Therapy)

5.8.3 Stimuli

The computer simulated environment consisted of a textured ground plane of a seamlessly tiled gravel surface, ending at 80 metres distance (giving a false horizon 1 degree below the true horizon). In keeping with previous studies (Kountouriotis et al., 2012; Robertshaw and Wilkie, 2008), the roadway was 2 white edges superimposed onto the ground plane. It began with a 16 metre straight section (to allow people time to react to the upcoming curve) and then entered a bend which had a constant curvature with a radius of 60 metres (to the centre of the roadway) (See Figure 5.18). The roadway was 3 metres wide. In 1/3 of trials the driver initially started in the centre of the roadway (1.5 metres from either edge). In 1/3 of trials the person started nearer to the inside edge of the bend (0.75 metres from the inside and 2.25 metres from the outside) and in 1/3 of trials the person started 0.75 metres from the outside road edge. In each trial the driver was asked to maintain their starting line as they drove around the bend (i.e. if they started 0.75 metres from the inside road edge, they should try to drive around the bend 0.75 metres from the inside road edge). There were 3 trials of each starting position with a left bend and 3 trials of each with a right bend making a total of 3 trials x 2 directions x 3 starting conditions = 18 trials. The trials were presented to the participant in a random order.

Participants had no control over their speed (in keeping with previous similar studies (Kountouriotis et al., 2012; Robertshaw and Wilkie, 2008; Wilkie et al., 2010), which ramped steadily up to 13.8 m/s (50km/h) over the course of 1 second on the straight section and stayed constant thereafter around the curve (with the final second of each trial ending with a ramped deceleration to zero).

Prior to the experiment each participant was given at least 3 unrecorded practice runs until they were happy that they were able to perform the experiment properly and understood the instructions.

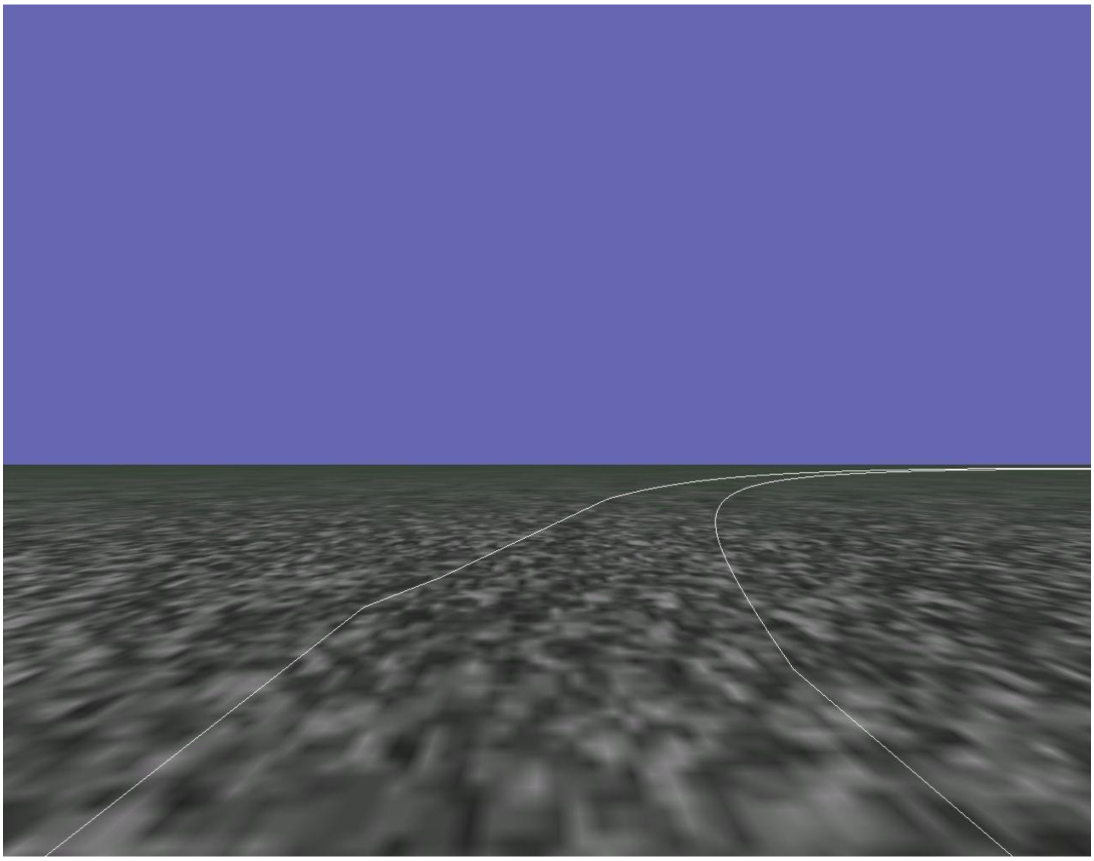

Figure 5.18: A right hand bend on the driving simulator screen

5.8.4 Analysis

We calculated 3 main measures from which to interpret our results and answer our experimental questions. **Steering bias** was calculated as the mean car distance from the (invisible) centre line of the road – the distance from car to centreline was calculated for each frame and then averaged). Positive values indicated a mean position closer to the inside edge of the curve (i.e. oversteer if the participant was intending to drive in the centre) and negative values indicated a mean road position nearer to the outside edge of the curve.

Bias gives a marker for the average position of the car during each iteration of the task but provides little information about steering variability – i.e. a bias of zero could indicate perfect central driving every frame or a very unsteady veering course around the bend which happened to average out at a bias of zero. We therefore also calculated the standard deviation of the steering bias (**steering variability**). A small steering variability would indicate that the car stayed near the mean bias position for the majority of the time. A larger value would indicate that the position was variable around the mean (note that this does not indicate the jerkiness of steering i.e. a high steering variability may indicate that the car was steadily slipping from one side of the road to the other as the bend was traversed, or that the car was being steered wildly, perhaps crossing the mean bias many times).

We also calculated mean **gaze bias**. For each frame the 2 dimensional co-ordinates of the eye on the screen were mapped to a 3 dimensional point on the road ahead. The bias was then read as the distance from centre towards a road edge for each frame and then averaged across the task.

For the purposes of analysis participants were grouped into controls, HVFDs and USNs. Subgroup analysis divided the HVFD group into adequately compensated (AC) and inadequately compensated (IC) based on their performance in the visual search task in Chapter 4 (see table 25 in chapter 4).

For the participants with stroke individual results were analysed based on the direction of the curve (and starting position) to capture whether the curve was in a contralesional direction (i.e. bending into the visually impaired hemifield) or an ipsilesional direction. This means that the results for left bends for people with left sided HVFDs are collapsed with right bends from people with right HVFDs. There was no reason to expect any difference between left and right bends for controls, therefore full datasets for left and right bends were used for both contralesional and ipsilesional bend analysis as if all corners taken by the controls were in that direction.

5.8.5 Results

5.8.5.1 Results – Steering Bias

Steering bias is an error measurement indicating the mean driver position in relation to the unmarked centre line during each condition. This measurement was used to gain insight into whether the participants (at a group level or individual level) were able to perform the task successfully by following the task instructions. Driving nearer the outside road edge causes negative bias and when driving nearer the inside edge bias causes positive bias. The instructed goal was to achieve a constant bias of -0.75 metres for the outside driving condition, 0 for the central condition and +0.75m for the inside edge condition. Wilkie et al. (Wilkie et al., 2010) found mean biases as follows: -0.55m for the outside condition, 0.14m for the central condition and 0.62m for the inside condition. (for Kountouriotis et al.

(Kountouriotis et al., 2012) the results were -0.45m, 0.11m and 0.62m respectively). We would expect therefore, as per these previous studies, a centralisation bias and an oversteer bias. Table 5.32 and Figure 5.19 show the group results for steering bias.

Table 5.32: Mean steering bias in metres

	Contralesional			Ipsilesional		
	Outside	Middle	Inside	Outside	Middle	Inside
Controls	-0.36	0.15	0.58	-0.36	0.15	0.58
HVFD	-0.26	0.18	0.41	-0.18	0.15	0.56
(AC subgroup)	-0.27	0.18	0.48	-0.36	0.05	0.45
(IC subgroup)	-0.25	0.18	0.32	0.04	0.27	0.68
USN	-0.16	0.13	0.31	-0.31	0.03	0.34

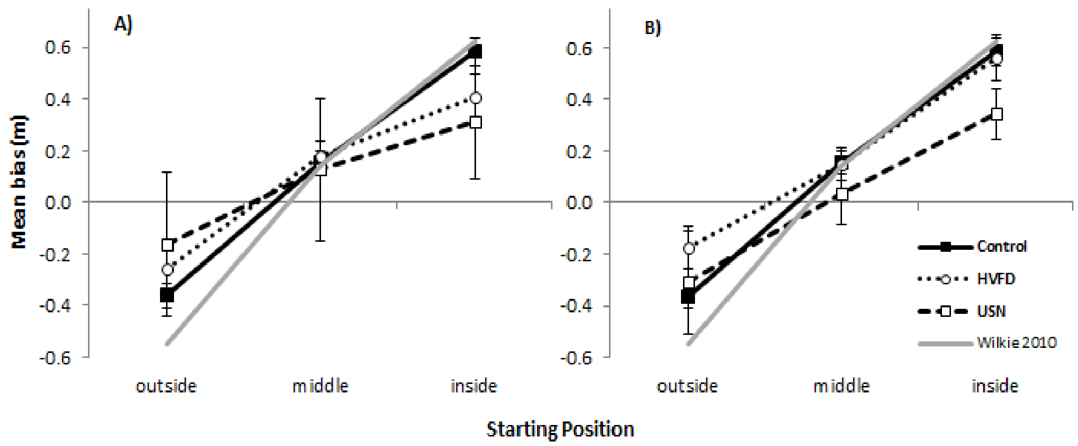

Figure 5.19: Mean steering bias for A) Contralesional side and B) Ipsilesional side. Plotted against Wilkie (2010) steering data. Bars represent SEM.

Looking for any differences in steering bias between groups using a mixed design ANOVA proved difficult as Levene's test of homogeneity of variances was violated in almost every condition. This is largely because of the extremely variable performance in the USN group. This highly variable steering performance is unsurprising given that USN is such a heterogeneous condition (Azouvi et al., 2002). We therefore decided to treat the participants with USN as case studies and to examine their performance descriptively, before running the ANOVA comparing the HVFD group (and subgroups) with the control group.

5.8.5.2 Steering Bias: USN Group

The individual bias results for the USN participants are shown below in Table 5.33. Bias scores outside of the control reference range are shown in red. Participants with at least one score outside of the control reference range are marked in red. Table 5.34 shows the gradient of mean steering bias change shown by each individual between neighbouring conditions i.e. between the outside and middle condition and between the middle and inside condition. Ideally every value of this would be 0.75 if each task condition was driven in perfect accordance with the instructions. Gradients outside of the control reference range are shown in red and participants with at least one gradient outside of the control reference range are shown in red.

Table 5.33: Individual steering bias for participants with USN

	Contralesional			Ipsilesional		
P	Outside	Middle	Inside	Outside	Middle	Inside
LVI1	-0.49	-0.07	0.06	0.26	0.19	0.51
LVI2	-0.09	0.36	0.43	0.00	0.25	0.31
LVI3	-1.26	-1.00	-0.56	-1.03	0.43	0.68
LVI4	0.00	0.11	0.22	-0.31	-0.17	0.39
RVI1	0.81	1.01	0.96	-0.02	-0.34	0.11
LHHVI	0.05	0.29	0.75	-0.76	-0.16	0.06
Mean	-0.16	0.13	0.31	-0.31	0.03	0.34
Control Mean	-0.36	0.15	0.58	-0.36	0.15	0.58
Control Range	-0.69 to 0.03	-0.19 to 0.52	0.11 to 0.89	-0.69 to 0.03	-0.19 to 0.52	0.11 to 0.89

Table 5.34: Between condition gradients of steering bias change for participants with USN (metres)

P	Contralesional Out-Mid gradient	Contralesional Mid-Inside gradient	Ipsilesional Out-Mid gradient	Ipsilesional Mid-Inside gradient
LVI1	0.42	0.13	-0.07	0.32
LVI2	0.45	0.07	0.25	0.06
LVI3	0.26	0.44	1.46	0.25
LVI4	0.11	0.11	0.14	0.56
RVI1	0.20	-0.05	-0.32	0.45
LHHVI	0.24	0.46	0.60	0.22
Mean	0.28	0.19	0.34	0.31
Control Mean	0.51	0.44	0.51	0.44
Control Range	0.07 to 0.88	0.20 to 0.80	0.07 to 0.88	0.20 to 0.80

LVI1 stayed mostly right of centre in all task conditions except for the inside condition for leftward bends where their mean steering bias was only 6cm left of centre. LVI2 drove very near to the centre of the road on outside trials. They also showed little change in steering bias between middle and inside conditions for bends in either direction. LVI3 stayed a long way right of centre on leftward bends – even on the inside condition their average bias was 56cm towards the outside road edge. On rightward bends their mean steering biases were closer to the control reference range. LVI4 stayed near the centre on all left bends and displayed little change in mean road position across the task conditions for leftward bends. RVI1 stayed very near the right road edge on rightward bends and near the centre on left bends. LHHVI also seemed to have a strong leftward bias.

Overall no clear pattern emerges except to say that all participants with USN had some bias scores (or at least gradient of change of steering bias between conditions) outside of the reference range, suggesting that they experienced difficulties in completed the task according to the given instructions. Some displayed a contralesional bias, some an ipsilesional bias, some showed little variation between task conditions and some (LVI1 and RVI1) even showed reverse gradients between conditions. Figure 5.20 shows the mean steering bias for each individual with USN for each task condition.

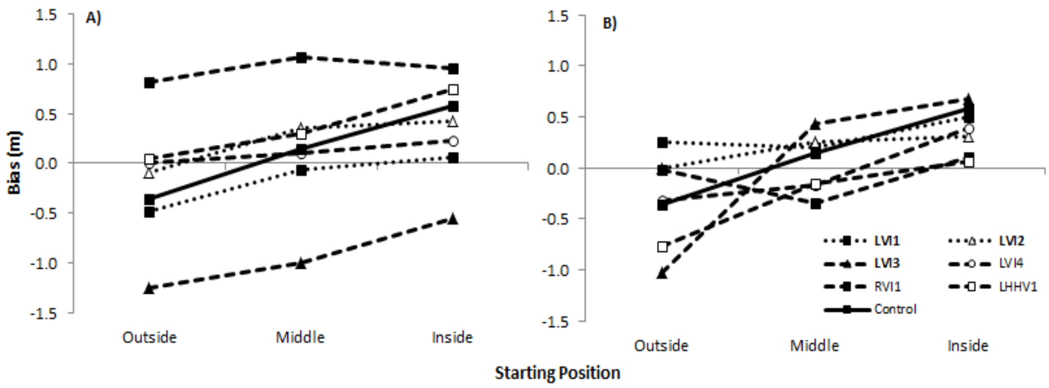

Figure 5.20: Steering bias for participants with USN driving A) Contralesional bends and B) Ipsilesional bends. Plotted against controls (black lines).

5.8.5.3 Steering Bias: HVFD group

The mean steering bias for each individual participant with a HVFD is shown in Table 5.35 below. Values marked in red lie outside of the control reference range.

Table 5.35: Mean steering bias for participants with HVFDs

		Contralesional			Ipsilesional		
	P	Outside	Middle	Inside	Outside	Middle	Inside
AC	LHH2	-0.57	0.10	0.62	-0.50	0.05	0.77
	LHH5	-0.16	0.36	0.49	-0.06	0.20	0.34
	LHH6	-0.03	-0.02	0.07	-0.45	-0.25	0.11
	RHH3	-0.42	0.12	0.47	-0.40	0.17	0.53
	RHH5	0.09	0.29	0.34	-0.15	-0.11	0.07
	RHH6	-0.51	0.21	0.87	-0.59	0.21	0.91
IC	LHH1	-0.60	-0.18	-0.10	0.25	0.29	0.75
	LHH3	-0.11	0.27	0.38	0.18	0.57	0.84
	LHH4	-0.64	0.04	0.07	-0.11	0.23	0.67
	RHH1	-0.05	0.22	0.66	-0.13	0.13	0.75
	RHH2	0.13	0.54	0.61	0.02	0.15	0.40
	Mean	-0.26	0.18	0.41	-0.18	0.15	0.56
	AC Mean	-0.27	0.18	0.48	-0.36	0.05	0.45
	IC Mean	-0.25	0.18	0.32	0.04	0.27	0.68
	Control Mean	-0.36	0.15	0.58	-0.36	0.15	0.58
	Control Range	-0.69 to 0.03	-0.19 to 0.52	0.11 to 0.89	-0.69 to 0.03	-0.19 to 0.52	0.11 to 0.89

As predicted, the largest differences in mean bias between the HVFD group and the control group were in task conditions requiring driving close to the road edge in their affected hemifield – i.e. inside position on contralesional bends and outside position on ipsilesional bends, and these differences preferentially, but not exclusively, affected the IC group.

Looking at the absolute bias may give an estimate of 'task performance'. Another potential marker of 'task performance' is the gradient between biases. i.e. someone may not be absolutely accurate at maintaining position but shifts position appropriately between conditions. This person would display large differences between biases in each task condition (though less than 0.75m due to the already known about centralisation tendency). The gradients for the participants with HVFD are shown below in Table 5.36.

Table 5.36: Between condition gradients of steering bias change for participants with HVFD. Results in red lie outside of the control reference range.

		Contralesional		Ipsilesional	
	P	Out-Mid gradient	Mid-Inside gradient	Out-Mid gradient	Mid-Inside gradient
AC	LHH2	0.67	0.52	0.55	0.72
AC	LHH5	0.52	0.13	0.26	0.14
AC	LHH6	0.01	0.09	0.20	0.36
AC	RHH3	0.54	0.36	0.57	0.35
AC	RHH5	0.21	0.04	0.04	0.18
AC	RHH6	0.72	0.65	0.80	0.70
IC	LHH1	0.42	0.08	0.05	0.46
IC	LHH3	0.39	0.11	0.39	0.27
IC	LHH4	0.68	0.03	0.35	0.44
IC	RHH1	0.27	0.43	0.26	0.62
IC	RHH2	0.41	0.08	0.13	0.25
	Mean	0.44	0.23	0.33	0.41
	AC Mean	0.44	0.30	0.40	0.41
	IC Mean	0.43	0.15	0.23	0.41
	Control Mean	0.51	0.44	0.51	0.44
	Control Range	0.07 to 0.88	0.20 to 0.80	0.07 to 0.88	0.20 to 0.80

Participants with HVFDs appear to have a small gradient of steering bias change (relative to the control gradients) between central trials and trials with a starting position close to their affected hemifield. This was more true of the IC group than the AC group.

Mixed design ANOVAs were performed to compare the steering bias in each condition (outside, middle or inside) between each group (controls, IC HVFDs and AC HVFDs). Because the controls have no ipsilesional and contralesional side, 2 separate ANOVAs were run comparing ipsilesional and contralesional bends for the HVFD groups separately with the entire dataset of steering biases for the controls (left and right bends were combined in control subjects for each ANOVA as we did not expect the controls to behave significantly differently between left and right bends).

For contralesional bends (see figure 5.21, panel A), there was, unsurprisingly, a highly significant difference in steering bias between conditions: $F(1.29,23.79) = 93.01$, $p < 0.001$, partial eta squared = 0.71. There was no significant difference in steering bias between groups: $F(2,38) = 0.18$, $p = 0.84$. The interaction between group and condition approached, but did not reach, significance: $F(2.57,48.85) = 2.685$, $p = 0.065$. Steering biases in the outside and middle conditions were virtually identical between groups. In the inside condition the IC group stayed further from the inside road edge than controls and the AC group stayed a little closer.

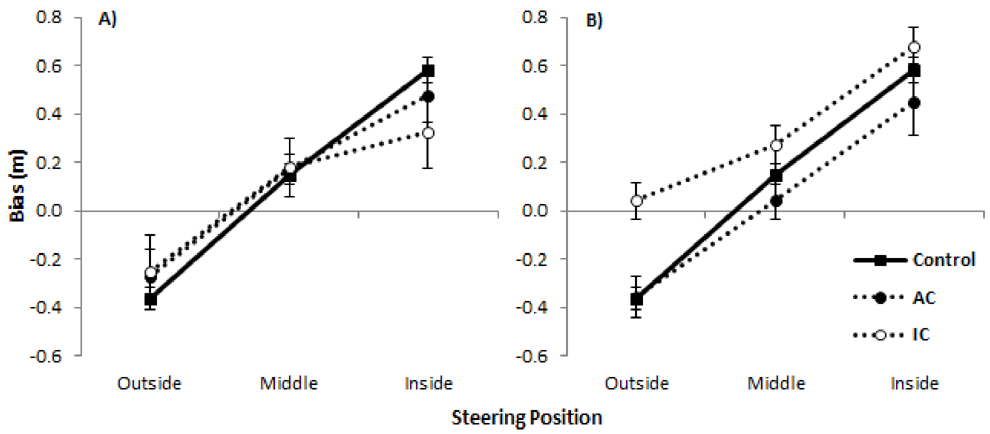

Figure 5.21: Mean bias for A) Contralesional and B) Ipsilesional bends, for AC and IC groups, plotted with controls. Bars represent SEM.

A mixed design ANOVA was also run to compare the entire control dataset with ipsilesional bends for the IC and AC, HVFD groups (see figure 5.21, Panel B). Again there was, unsurprisingly, a highly significant effect of condition on steering bias: $F(1.26,23.35) = 101.49$, $p < 0.001$, partial eta squared = 0.728. There was also a significant effect of group: $F(2,38) = 7.74$, $p = 0.002$, partial eta squared = 0.289.

There was no significant interaction between group and condition: $F(2.52,47.94) = 1.93$, $p = 0.108$

Post hoc, between group Bonferroni comparisons were made which showed no difference between the control and AC group (mean difference = 0.077m, $p = 0.534$), but a significant difference between controls and the IC group (mean difference = 0.208m, $p = 0.004$) and between the AC and IC groups (mean difference = 0.285m, $p = 0.002$).

Overall this data suggests that participants in the IC group, when instructed to drive closer to the road edge in the affected hemifield, maintained a larger distance from it than the AC or control group did.

5.8.5.4 Results: Steering Variability

The steering bias results have indicated simply that the IC group drove further from the contralesional road edge than the other groups when the instructions were to drive close to it. This finding does not give any insight into why this occurred – it is possible that the participants found such driving very difficult and chose to leave a large margin for error. It could be that as the contralesional road edge is approached, steering becomes more variable as feedback is lost from the ipsilesional road edge and the driver (voluntarily or involuntarily) tends to move away from the edge again. Furthermore, the finding of no **average** bias difference between the AC group and controls in these task conditions, does not mean that the actual steering trajectory was the same. We therefore wanted to obtain a measurement of steering variability for each individual driving each condition in order to gain insight as to whether steering variability was increased in the HVFD and USN groups – especially when instructed to drive close to the contralesional road edge.

Previously, authors have reported RMS error as a measure of steering precision measured as the mean RMS bias from actual path to ideal path (Kountouriotis et al., 2012; Robertshaw and Wilkie, 2008). In this experiment many participants drove quite some distance from the ideal path (often on the opposite side of the road from the ideal path) which gives large RMS error values simply due to the difference in bias from intended bias. This makes RMS error a less useful measure of steering variability for this experimental group. Instead we have simply measured the standard deviation of bias from mean bias for each individual – giving a measure of the variability of steering bias during each trial.

Again we were unable to formally compare our steering variability measurements between all groups as the wide variety of scores for individuals within the USN group led to Levene's Test being violated in every condition. The results for the USN group are therefore presented descriptively in Table 5.37 and Figure 5.22.

Table 5.37: Steering variability for USN group

	Contralesional			Ipsilesional		
P	Outside	Middle	Inside	Outside	Middle	Inside
LVI1	0.32	0.14	0.02	0.20	0.58	0.21
LVI2	0.25	0.61	0.05	0.12	0.15	0.18
LVI3	2.58	1.05	0.68	3.07	0.78	2.25
LVI4	0.54	0.11	0.31	0.09	0.29	0.32
RVI1	0.54	0.07	0.13	0.14	0.09	0.08
LHHVI	0.38	0.08	0.04	0.16	0.47	0.20
Control Mean	0.14	0.12	0.11	0.14	0.12	0.11
Control Upper limit	0.33	0.32	0.24	0.33	0.32	0.24

As was found in the steering bias analysis, it is hard to identify clear patterns in this data across the conditions and participants. However, every participant with USN had at least one variability score outside of the control group reference range.

Examining LVI3's steering bias results from table 5.33 and variability results from table 5.37, it is clear that they have spent significant amounts of time off the road altogether. Somewhat surprisingly, LVI1, LVI2 and LHHVI had less variable steering when driving closer to the edge on the affected side i.e. inside condition on contralesional bends and outside condition on ipsilesional bends (although LVI1 stayed mostly on the right hand side of the road irrespective of task condition, whilst LHHVI stayed mostly on the left – see table 5.33). LVI4 seemed to have more stable steering in central task conditions, but variability was high and outside of the reference range in 3 of the other task conditions. They had relatively small differences in mean bias between task conditions so it is possible that actual position on the road was not very predictive of steering variability, rather that steering was generally more variable than for controls across all trials. RVI1 showed relatively small variability in steering in comparison (only 1 condition had variability outside of the reference range).

Figure 5.22 below depicts the steering variability across conditions for the USN group.

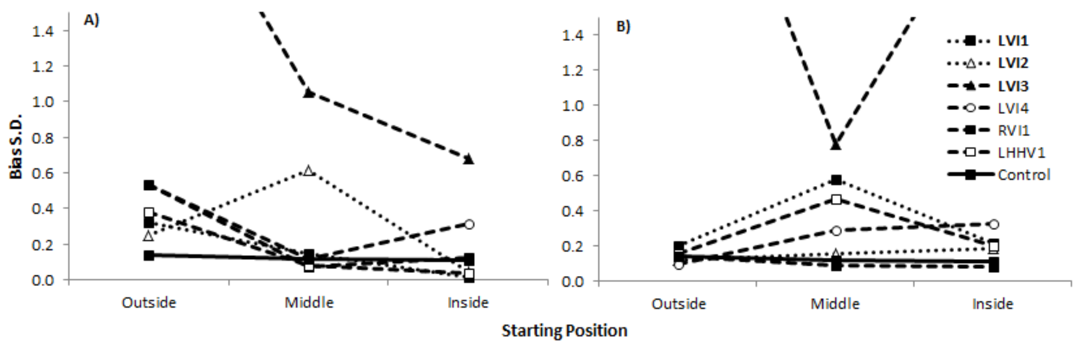

Figure 5.22: Mean standard deviation of steering bias, shown for the USN groups for A) Contralesional and B) Ipsilesional bends.

5.8.5.5 Steering Variability, HVFD group

Table 5.38 below shows the steering variability results for the HVFD group. As above, results marked in red indicate a result outside of the control reference range.

Table 5.38: Steering Variability for the HVFD group

		Contralesional			Ipsilesional		
	P	Outside	Middle	Inside	Outside	Middle	Inside
AC	LHH2	0.02	0.04	0.34	0.18	0.14	0.02
	LHH5	0.17	0.04	0.13	0.19	0.26	0.20
	LHH6	0.33	0.27	0.19	0.10	0.12	0.29
	RHH3	0.04	0.18	0.04	0.15	0.15	0.05
	RHH5	0.15	0.16	0.11	0.18	0.10	0.10
	RHH6	0.01	0.08	0.05	0.03	0.05	0.14
IC	LHH1	0.13	0.17	0.22	0.17	0.23	0.03
	LHH3	0.24	0.43	0.23	0.32	0.48	0.18
	LHH4	0.06	0.31	0.11	0.16	0.13	0.11
	RHH1	0.06	0.41	0.19	0.02	0.35	0.06
	RHH2	0.10	0.04	0.31	0.10	0.14	0.11
	Mean	0.12	0.19	0.17	0.15	0.20	0.12
	AC Mean	0.12	0.13	0.14	0.14	0.14	0.13
	IC Mean	0.12	0.27	0.21	0.15	0.27	0.10
	Control Mean	0.14	0.12	0.11	0.14	0.12	0.11
	Control Max	0.33	0.32	0.24	0.33	0.32	0.24

Mixed design ANOVAs were performed to compare across steering variability measures in each condition (outside, middle or inside) across each group (controls, IC HVFDs and AC HVFDs). Because the controls have no ipsilesional and contralesional side, 2 separate ANOVAs were run comparing ipsilesional or contralesional bends for the HVFD groups separately with the entire dataset of steering biases for the controls (left and right bends were averaged together in control subjects for each ANOVA as we did not expect the controls to behave significantly differently between left and right bends).

For contralesional bends, condition alone did not significantly affect our measure of steering variability: $F(2,37) = 2.13$, $p = 0.126$. There was, however, a significant effect for group: F(2,38) = 4.47, p = 0.018, partial eta squared = 0.191. There was also a significant interaction between group and condition: F(4,76) = 2.99, p = 0.024, partial eta squared = 0.136. Post-hoc Bonferroni contrasts revealed no significant difference between the control and AC group (p = 1) and no significant difference between the AC and IC groups (p = 0.117). But there was a significant difference found between controls and the IC group (p = 0.015).

The results are shown in Figure 5.23, Panel A. In outside trials (i.e. near to the road edge in the unaffected field), the steering variability looks very similar for each group. The IC group on average showed a far higher steering variability in the middle condition (and to a lesser extent in the inside condition) than the AC and control groups.

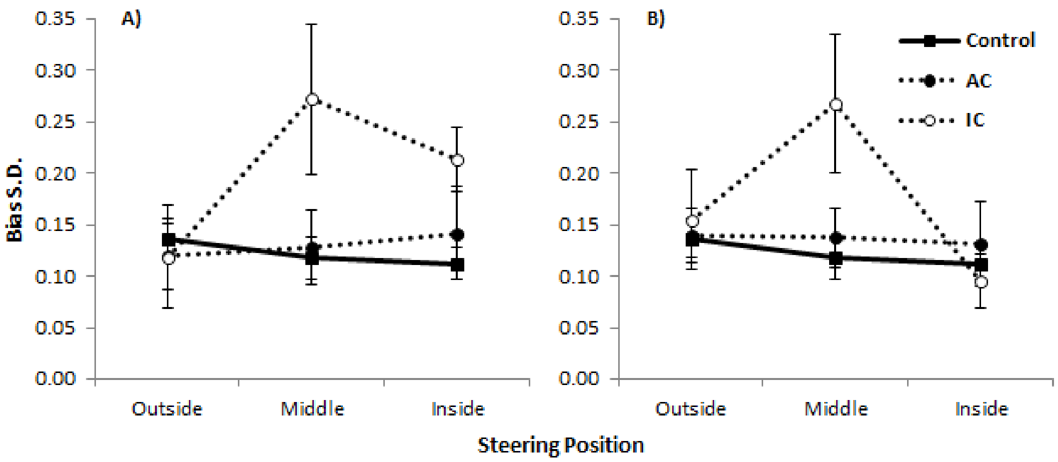

Figure 23 : Bias SD for AC and IC groups, plotted against controls, for A) Contralesional bends and B) Ipsilateral bends. Bars represent SEM.

For ipsilesional bends, there was a significant effect of condition on our measure of steering variability: F(2,37) = 3.975, p = 0.023, partial eta squared = 0.095. There was no significant effect of group: F(2,38) = 1.869, p = 0.168. There was a significant interaction between group and condition: F(4,76) = 3.475, p = 0.012, partial eta squared = 0.155.

The results are shown in figure 5.23, Panel B. The IC group show much higher steering variability in the middle condition than the AC group and controls. Variability between all groups looks similar in the other conditions.

5.8.5.6 Results: Gaze Bias

Mean gaze bias was measured to determine if the participants with stroke used gaze in a qualitatively different way to the control group. We obtained full datasets for gaze from 12 controls (CONT1, 3,4,6,7,8,9,10,12,14,15,16), 4 x IC HVFD (LHH1, LHH3, RHH1, RHH2), 4 x AC HVFD (LHH2, LHH6, RHH5, RHH6) and 4 x USN (LVI2, LVI3, LVI4 and LHHVI). We were unable to eye track the others – some could not be calibrated and for others eye tracking could not be maintained for much of the experiment (fatigue related ptosis was common in our stroke group). In total, 2 participants were excluded from each stroke group. Our key measurement was mean gaze bias, i.e. the average location of gaze fixation on the road related to the centre line and road edges. Exactly as for steering bias, the outside road edge lies at -1.5m and the inside at +1.5m. The raw mean gaze bias data for the groups are shown below in Figure 5.24

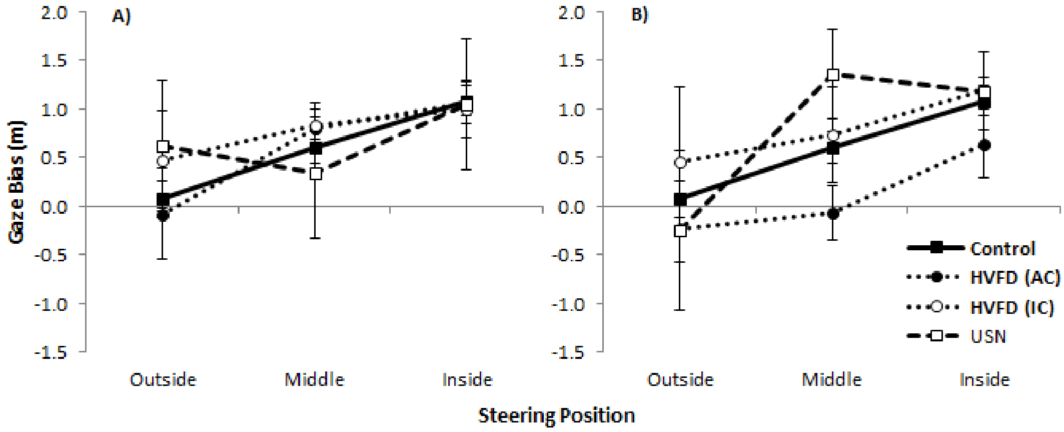

Figure 5.24: Mean Gaze bias for Control, AC, IC and USN groups, for A) Contralesional bends and B) Ipsilesional bends. Bars represent SEM

Previous iterations of this steering experiment using young, healthy participants have demonstrated evidence that people tend to 'look where they steer' (Kountouriotis et al., 2012; Robertshaw and Wilkie, 2008; Wilkie et al., 2010), meaning that there is a linear relationship between steering bias and gaze bias across the task conditions. We wished to test whether the same gaze strategy held true for our older controls and our various participant groups with stroke. In particular we wished to demonstrate whether people with unilateral visual impairments, with reduced road edge feedback from their peripheral vision, would favour an alternative gaze strategy. In order to do this we have used a primary outcome measure of (mean gaze bias – mean steering bias) across the task conditions for each participant group. If people simply 'look where they steer' then this measurement should stay constant (giving a zero gradient on the graph) for each individual and group, regardless of task condition and regardless of their actual steering bias during a bend. The mean results of this measurement are plotted below in Figure 5.25

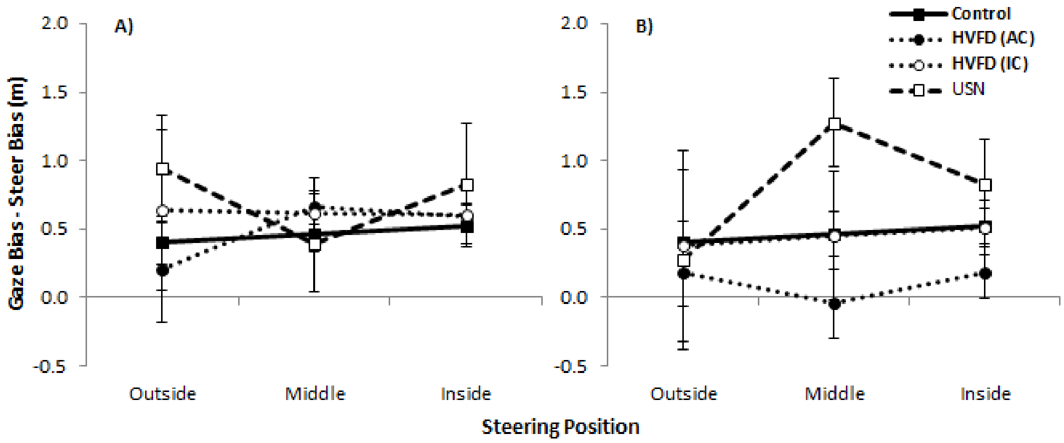

Figure 5.25: Gaze Bias minus Steer Bias for Control, AC, IC and USN groups, for A) Contralesional bends and B) Ipsilesional bends.

For contralesional bends (and the full control dataset for left and right bends), mixed design ANOVA showed no significant differences between task conditions: $F(1.32,20.46) = 0.46$, $p = 0.554$ and no significant differences between groups: $F(3,32) = 0.546$, $p=0.654$. There was no significant interaction between condition and group: $F(3.96,42.22) = 0.857$, $p = 0.496$.

For ipsilesional bends, the mixed design ANOVA showed no difference between task conditions: $F(1.288,19.96) = 1.32$, $p = 0.267$ and no difference between groups: $F(3,32) = 1.45$, $p = 0.246$. There was no significant interaction between group and task condition: $F(3.864,41.22) = 1.31$, $p = 0.282$.

An alternative way to visualise this is to plot the gaze gradient (i.e. gaze bias for middle condition – gaze bias for outside condition and gaze bias for inside condition – gaze bias for middle condition) minus bias gradient (i.e. steering bias for middle condition – steering bias for outside condition and steering bias for inside condition – steering bias for middle condition). If people are following an active gaze strategy and ‘looking where they are going’, then one would expect this measurement to always roughly equal 0. (i.e. as the car changes position on the road, the eye fixations move at the same rate. Measure shown in Figure 5.26

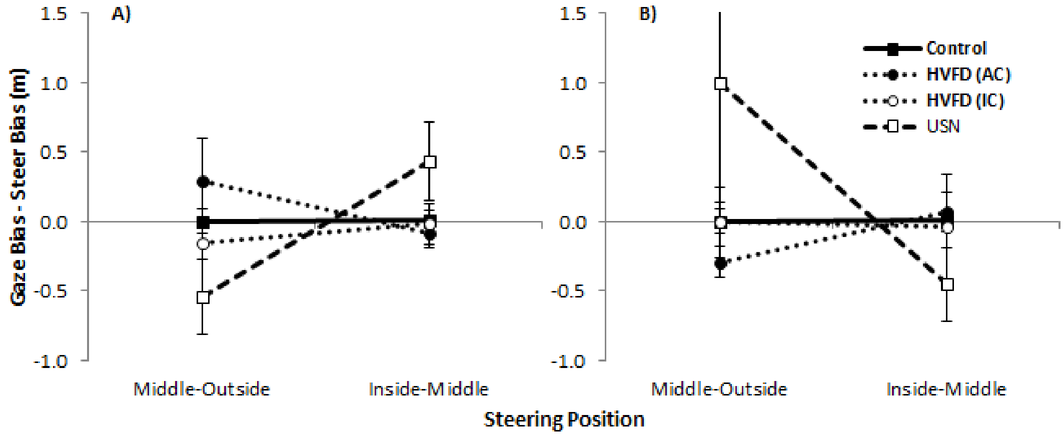

Figure 5.26: Average "Gaze Bias minus Steering Bias" for the Control, AC, IC and USN groups, for A) Contralesional bends and B) Ipsilesional bends. Bars represent SEM.

The first striking feature of Figure 5.26 is that the USN group appear to be behaving very differently to the other groups. Gaze bias is changing at a very different rate to steering bias between task conditions, giving evidence that this group are doing something other than 'looking where they are going'. However, as for the steering data, there was a large variation in gaze between individuals. Figure 5.27 plots mean steering and gaze bias for the USN participants in order to show where mean gaze was relative to both the driver and the inside road edge.

5.8.5.7 Gaze Bias: USN Group

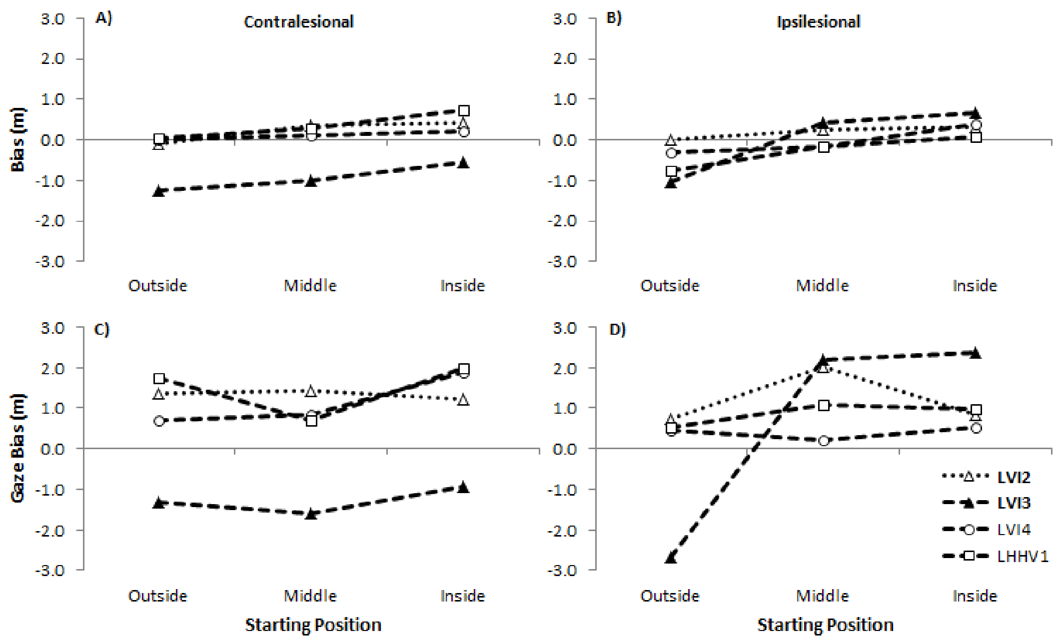

Figure 5.27: USN individual data for A) Contralesional steering bias, B) Ipsilesional steering bias, C) Contralesional Gaze Bias and D) Ipsilesional Gaze Bias.

Figure 5.27 displays results only for those USN participants with full gaze and steering datasets (LVI2, LVI4 and LHHVI) and excluding LVI3 who spent considerable time off road altogether. It is striking that the participants with USN are able to hold their gaze on or near the left road edge whilst driving on a leftward bend – just as they were able to search left of centre in the visual search tasks. In fact their gaze fell nearer the inside road edge on left bends than right bends, perhaps indicating that their gaze strategy involved deliberately fixating the road edge during some conditions, rather than simply fixating the road ahead (This would also fit with our finding that gaze and steering did not co-vary between conditions in the same way as the control and HVFD groups). All 3 were also able to drive left of midline. LVI2 seemed to be fixating on or near the left road edge on all 3 contralesional task conditions and all 3 participants fixated on or near the left road edge on the inside condition. LHHVI seemed to fixate the left edge on the inside and outside conditions, but not the middle condition. If steering bias is averaged across directions all 3 participants favoured staying left of centre which is quite a surprising result (i.e. all 3 had higher steering biases for the central condition on left bends than right bends). Gaze bias also was higher on left bends than right bends which is also quite surprising. Punt et al. (Punt et al., 2008) described wheelchair users staying the same distance from the ipsilesional side of a doorway regardless of doorway width. It would be interesting to explore this task with wider roadways to see whether our findings are simply an example of crossover effect as described above. This is still a possible explanation despite the fact that our USN participants often appear to be fixating the left road edge – people with USN may fixate objects on the contralesional side, but not process the information (Forti et al., 2005).

5.8.5.8 Gaze Bias: HVFD Group and Controls

Whilst it is not clear at all that our USN participants are following a 'looking where you are going' strategy (it is not really clear what strategy they are using!), the mean data seem to strongly suggest that the control and HVFD groups are doing exactly this – i.e. steering bias and gaze bias change roughly in line with each other across task conditions. However data at the individual level tells a more nuanced story. Firstly 9 out of 12 controls seem to follow the expected pattern but 3 showed slightly odd results (See Table 5.39).

Table 5.39: Gaze Bias for Three Example Control Subjects

	Left			Right		
P	Outside	Middle	Inside	Outside	Middle	Inside
CONT9	0.22	-0.09	-0.46	0.57	1.70	1.70
CONT12	1.09	1.04	0.94	0.19	-0.08	0.04
CONT16	1.08	0.92	1.38	1.20	1.15	1.25

CONT16 appears to mostly look at a point near to the inside edge, regardless of task condition. Despite this their steering biases indicate that the task was undertaken successfully and with no striking increase in steering variability. CONT12 appears to fixate near the left edge on left bends and near the centre on right bends, again with little change in gaze position to match steering bias. CONT9 has strange gaze bias results which defy explanation (on left bends the gaze moved outward as steering bias moved inward. On right bends they fixated near the right road edge on middle and inside conditions), despite also successfully completing the task with low steering variability.

Whilst several of the HVFD participants did seem to use a ‘looking where you want to go’ strategy, the individual level data shows some variation in this. We have examined each of the HVFD group with full datasets in turn:

Table 5.40: Steering and Gaze Results for LHH1

	Contralesional			Ipsilesional		
LHH1	Outside	Middle	Inside	Outside	Middle	Inside
Steering Bias	-0.60	-0.18	-0.10	0.25	0.29	0.75
Gaze Bias	1.16	0.51	0.38	1.61	1.13	1.16
Steering Variability	0.13	0.17	0.22	0.17	0.23	0.03

LHH1 (Table 5.40) had a complete left hemianopia with abnormal saccades, smooth pursuit and visual search. They stayed right of centre on average across each condition, although position did move as the task condition changed (only a little between middle and left sided driving conditions). On contralesional bends they looked further left on the road, the further right their position was (i.e. gaze was very eccentric when turning left on the right side of the road). Yet the very eccentric gaze position was associated with relatively low steering variability. One possible

explanation would be that, with a left hemianopia, looking straight ahead whilst on the right hand side of the road leads to a very restricted view of the bend – so perhaps the participant was trying to keep more of the road in view. However on right hand bends they looked very near the right road edge across all trials – but again gaze was more oblique on the outside road position which would lead to a more restricted view of the road. An explanation linking this participant's steering and gaze behaviour is not immediately apparent. Overall steering variability was not high but LHH1 stayed away from the road edge on the affected side of their vision

Table 5.41: Steering and Gaze Results for LHH2

	Contralesional			Ipsilesional		
LHH2	Outside	Middle	Inside	Outside	Middle	Inside
Steering Bias	-0.57	0.10	0.62	-0.50	0.05	0.77
Gaze Bias	-0.35	0.48	1.18	-0.34	0.30	1.36
Steering Variability	0.02	0.04	0.34	0.18	0.14	0.02

LHH2 (Table 5.41) had a Left Inferior Quadrantanopia with normal saccades, pursuit and visual search. They used a 'look where you are going' strategy. Steering variability was high on the contralesional, inside condition suggesting they had problems maintaining their line whilst driving leftwards near the left road edge – exactly as we predicted at the start of the chapter.

Table 5.42: Steering and Gaze Results for LHH3

	Contralesional			Ipsilesional		
LHH3	Outside	Middle	Inside	Outside	Middle	Inside
Steering Bias	-0.11	0.27	0.38	0.18	0.57	0.84
Gaze Bias	1.30	1.44	1.13	0.80	0.95	0.86
Steering Variability	0.24	0.43	0.23	0.32	0.48	0.18

LHH3 (Table 5.42) had a left hemianopia with some sparing in the inferior quadrant. Saccades, pursuit and visual search were all abnormal. They did manage to move inside of the centre of the road for the inside position driving conditions – although, on average they adopted a more rightward position across all conditions (i.e. bias was higher for the ipsilesional bends than on the same condition on a contralesional bend). Gaze position changed little across conditions - in a similar manner to LHH1 gaze was always directed towards the inside road edge regardless of task condition. On left bends gaze was very eccentric and near the inside road edge on all conditions, though steering bias did not get far left of centre. On right bends, steering bias was right of centre even on outside road conditions, though became more rightward on the other 2 conditions. Gaze stayed in a similar rightward position throughout the condition, although steering bias matched this on the inside condition. Again, just as in LHH1, there is not an obvious explanation for this pattern of gaze. Steering variability was high, especially in central conditions (though LHH3 actually drove closer to the centre on outside trials).

Table 5.43: Steering and Gaze Results for LHH6

	Contralesional			Ipsilesional		
LHH6	Outside	Middle	Inside	Outside	Middle	Inside
Steering Bias	-0.03	-0.02	0.07	-0.45	-0.25	0.27
Gaze Bias	0.93	0.99	0.49	-0.52	-0.86	-0.20
Steering Variability	0.33	0.27	0.19	0.10	0.12	0.29

LHH6 (Table 5.43) had a left sided large scotoma. They had normal saccades, pursuit and visual search scores. They stayed near the centre on leftward bends for all task conditions, looking inwards into the bend. They also stayed left on the outside and middle conditions on the right bends. Gaze was directed leftwards across all conditions – perhaps as an effort to bring more of the road into view. Steering variability was on the high side especially in task conditions where the participant was asked to stay nearer to the right road edge. (Perhaps due to the higher gaze eccentricity).

Table 5.44: Steering and Gaze Results for RHH1

	Contralesional			Ipsilesional		
RHH1	Outside	Middle	Inside	Outside	Middle	Inside
Steering Bias	-0.05	0.22	0.66	-0.13	0.13	0.75
Gaze Bias	-0.85	0.89	1.75	-1.78	-0.69	1.41
Steering Variability	0.06	0.41	0.19	0.02	0.35	0.06

RHH1 (Table 5.44) had an incomplete right hemianopia with some central and RIQ sparing. Saccades, pursuit and visual search ability were abnormal in comparison to the controls. They do seem to be using a 'look where you want to steer strategy' at least to some extent – there were large differences between steering and gaze bias on the inside and outside conditions. Just as in LHH3 central road

conditions caused a larger steering variability, despite them actually driving closer to the centre in ‘outside’ road conditions.

Table 5.45: Steering and Gaze Results for RHH2

	Contralesional			Ipsilesional		
RHH2	Outside	Middle	Inside	Outside	Middle	Inside
Steering Bias	0.13	0.54	0.61	0.02	0.15	0.40
Gaze Bias	0.31	0.49	0.72	1.20	1.56	1.36
Steering Variability	0.10	0.04	0.31	0.10	0.14	0.11

RHH2 (Table 5.45) had a complete right hemianopia with abnormal saccades and visual search scores, although smooth pursuit movements were normal. He is also an ex rally car racer. On rightward bends he stayed right of centre on all conditions but seemed very much to ‘look where he was going’. On leftward bends he looked very much towards the left road edge throughout. Steering variability was high for the inside condition on rightward bends, but normal in the other conditions.

Table 5.46: Steering and Gaze Results for RHH5

	Contralesional			Ipsilesional		
RHH5	Outside	Middle	Inside	Outside	Middle	Inside
Steering Bias	0.09	0.29	0.34	-0.15	-0.11	0.07
Gaze Bias	0.76	0.90	1.02	0.73	0.38	0.37
Steering Variability	0.15	0.16	0.11	0.18	0.10	0.10

RHH5 (Table 5.46) had a right inferior quadrantanopia with central sparing, with normal saccades, pursuit and visual search. The car position and eye position changed little across each task. For contralesional bends, gaze position seems to change along with car position again suggesting a ‘look where you are going’

strategy. For ipsilesional bends, they looked further inside on the outside condition than the central and inside road conditions, but it does seem that they were fixating the road rather than a road edge. Steering variability was similar to controls.

Table 5.47: Steering and Gaze Results for RHH6

	Contralesional			Ipsilesional		
RHH6	Outside	Middle	Inside	Outside	Middle	Inside
Steering Bias	-0.51	0.21	0.87	-0.59	0.21	0.91
Gaze Bias	-0.06	1.06	1.78	-0.84	-0.11	0.84
Steering Variability	0.01	0.08	0.05	0.03	0.05	0.14

RHH6 (Table 5.47) had a right superior quadrantanopia with no central sparing. They had normal saccades, pursuit and visual search. They completed the steering tasks successfully with good changes in bias between conditions and low steering variability. Gaze bias did change in line with changing task condition and steering bias, although they looked quite a long way right of their position on right bends and slightly right of their position on left bends (in comparison to controls who tended to look inside of their position on average).

In summary the majority of participants with hemianopia did seem to use a ‘look where you are going’ type gaze strategy, at least some of the time. There are differences across individuals. Some participants certainly seemed to direct gaze more into the hemianopic side - a strategy which would bring more of the road into view (RHH6, LHH6 and LHH3 appear to do this). RHH1 on average looked right of centre, but when driving closer to the left road edge they fixated left of the car position – perhaps simply using only the left road edge to navigate. RHH2 and LHH1 appear to fixate near the inside edge on ipsilesional bends – a strategy which would obscure more of the road. Perhaps they also are simply navigating using only the inside road edge for feedback - interestingly this strategy appears not to be associated with increased steering variability. LHH1 also displayed a puzzling behaviour on contralesional bends of looking more towards the inside edge when driving nearer the outside edge than they did when driving near the inside edge. To a lesser extent RHH5 shows a similar behaviour on ipsilesional bends. Perhaps surprisingly, steering variability was actually lower when gaze was highly eccentric.

5.9 Conclusions

The control group on average displayed steering and gaze behaviour similar to that reported in previous studies – i.e. completing the task well, with little steering variability a small oversteer bias and a small bias towards the centre of the road. Gaze position changed roughly in line with steering position across the task conditions supporting a ‘looking where you steer’ model (rather than a tangent or fixed point steering model). Two participants (CONT12 and CONT16) appeared to be using more of a fixed point steering mechanism as gaze position changed little between conditions – although interestingly CONT16 had high steering variability. CONT9 showed no clear relationship between gaze and steering, whilst still completing the task with low steering variability.

Some participants with HVFDs were unwilling or unable to drive as near to the road edge in their hemianopic field – there were statistically reliable differences in steering bias scores between the IC group and the AC and control groups, with the IC group members on average staying further from the contralesional road edge when instructed to drive close to it. Steering variability was also higher on average for the IC group than for the AC and control groups – especially in the central road condition on both contralesional and ipsilesional bends. LHH1, LHH3, LHH4, LHH5, LHH6, RHH2 and RHH5 (7/11 from the HVFD group) showed only a very small difference in steering bias between the middle and inside trials for contralesional bends suggesting that driving near to the inside edge on contralesional bends is problematic for them. LHH2 (AC) and RHH2 (IC) drove well over to the hemianopic side on contralesional bends/inside position trials, but seemed to pay with high steering variability scores.

In terms of eye movements, the HVFD group on average used gaze strategies similarly to the control group – i.e. used a ‘look where you want to go’ type approach. 4/8 (2 IC and 2 AC) participants looked more toward the hemianopic side on average – a strategy which would bring more road into view. RHH2 looked ahead on contralesional bends but mostly at the inside road edge on ipsilesional bends. The others displayed no bias. In total 3/8 (all IC group) fixated the inside road edge on ipsilesional bends when given the inside starting position – perhaps navigating simply using feedback information from this fixed point.

Overall the AC group were closer to the controls in performance on this task than the IC group but there were some differences – many were reluctant or unable to drive closer to the contralesional road edge or suffered an increase in steering variability if they did. This may have ramifications for more complex, real world driving.

For the USN group, performance varied widely between individuals. LVI3 was unable to perform the task at all, frequently leaving the road altogether. Strikingly, whilst LVI1 stayed mostly on the right side of the road, RVI1 and LHHVI all favoured staying on the contralesional side of the road – often quite far into the contralesional side. LVI2 and LVI4 appeared to be able to complete the task according to instructions although the change in road position between task conditions was quite small. All of the USN group had very high steering variability scores in at least one task condition.

A fascinating result from the USN group is that all 3 participants for which full gaze and steering data was collected (excluding LVI3 who was unable to stay on the road for many tasks) is that all favoured driving and looking into the contralesional side during contralesional bends. It may be that in complex tasks with lots of stimuli they are able to draw their attention this way and even use the contralesional road edge to help guide steering. Steering remained quite variable however, suggesting that despite their ability to look contralesionally whilst driving, steering stability problems remained.

Chapter 6: Hazard Perception Performance

The previous Chapter demonstrated the capabilities of stroke patients steering trajectories around computer simulated bending roads. This task was used because it maps onto the core perception action requirements of driving, namely directing gaze toward an appropriate location to sample the requisite visual information in order to generate an appropriate motor response via the steering wheel. Driving on real roads, however, involves additional components that aren't represented in the tests used in Chapter 5. One critical aspect that is missing is the consideration of other road users that often behave in erratic or unpredictable ways (e.g. vehicle suddenly stopping or pedestrians walking into the road). It is quite possible that compensatory gaze strategies employed to ensure successful steering may actually be detrimental to the detection of hazards that appear in road regions away from the point of gaze. This next chapter examines the extent to which stroke affects the ability to perform the basic perceptual motor components of driving, whilst also successfully detecting potential hazards.

6.1 Hazard Perception with Unilateral Spatial Neglect

Clinically detectable unilateral spatial neglect is usually felt to be incompatible with safe driving (Tant et al., 2002a). The cardinal feature of USN – namely that objects on the ipsilesional side preferentially win the race for attentional selection (Mark et al., 1988), would lead most clinicians to reasonably surmise that hazard perception would be impaired, and therefore individuals with USN would always be a risk on the road. It is possible that some people who have clinically apparent USN in the early days after stroke, but who improve to a very large extent, may become safe enough to return to driving (Jehkonen et al., 2012), but this would be considered unusual by clinicians. One study of people with USN piloting electric wheelchairs around an obstacle course found that collisions were common, especially on the contralesional side, although there was a very wide variety of ability (Punt et al., 2008).

The hypothesis being tested in this chapter is that hazard detection performance will be impaired for the participant group with USN, even in tightly controlled experimental scenarios where hazards will appear on a more regular basis than in unconstrained real world conditions. This chapter develops the driving simulator based method in order to test hazard perception within a safe and controlled experimental environment.

6.2 Hazard Perception with Homonymous Visual Field Defects

Whilst it may seem surprising, it is actually unknown whether driving with visual field loss after stroke increases crash risk – crashes are rare events and one would need a large sample size (and accurate records) to assess this reliably. Various attempts have been made to associate crash risk with peripheral visual field loss, but only one study has so far shown an increase in crash risk associated with reduced visual field (Johnson and Keltner, 1983). This study examined the visual fields of 10,000 drivers and found that those with binocular visual field loss were twice as likely to have had driving collisions or convictions as those with normal vision. Unilateral visual field loss did not predict crash or conviction risk. Others have shown no clear relationship (Ball et al., 1993; Decina and Staplin, 1993; Danielson, 1957; Owsley et al., 1998). Three of these studies only used small samples – Ball et al. reported results for 294 drivers, Danielson for 680 drivers (in 1957 when traffic density was far lower) and Owsley et al. for the same 294 drivers as Ball et al. Decina and Staplin reported crash incidence for 12,400 drivers renewing their licenses in Pennsylvania – all of whom received an unexpected eye test. They found that binocular field loss alone did not increase crash risk, but in combination with reduced acuity and reduced contrast sensitivity, crash risk was increased. Of course the visual fields of these individuals could have been affected by a myriad of disorders and homonymous visual field loss due to stroke may not be well represented in these studies – Johnson and Keltner reported cataracts, glaucoma and retinal disorders as being the most frequent causes of visual field loss in their study. Both on-road and driving simulator studies have shown evidence that at least some people with a HFVD can drive relatively safely, although some problems with maintaining lane position, gap judgement and stopping times have all been noted (Elgin et al., 2010; Wood et al., 2009; Wood et al., 2011; Racette and Casson, 2005; Schulte et al., 1999; Szlyk et al., 1993).

These studies have predominantly examined the effect of a HFVD on the ability to directly control the vehicle (i.e. steering behaviours). Driving performance can also be evaluated from the perspective of hazard detection (i.e. reacting in a timely fashion to a potential hazard on or near the road ahead), but in stroke populations this has been less frequently examined. One research group examining people with HVFDs has repeatedly demonstrated slower reaction times and increased rates of failure to detect pedestrians appearing in the affected hemifield during a lengthy simulated driving course, although performance varied widely between individuals (Alberti et al., 2014; Bowers et al., 2014; Bowers et al., 2009). Another study has assessed patients with homonymous visual field loss and controls negotiating a simulated busy intersection at a fixed speed, using number of collisions as the primary outcome measure (Papageorgiou et al., 2012a). Again a very wide spread of ability was observed in people with hemianopia, but on average the number of collisions was increased against controls, particularly at a higher difficulty level. Whilst the extent of visual field loss and participant age was somewhat associated with performance, on their own these factors were inadequate to predict performance. Further analysis suggests that there may be a link between behaviours such as exploratory head and eye movements and performance on the task, i.e. longer saccadic amplitudes, longer scanpaths, more gaze shifts and more fixations on vehicles seemed to be associated with better task performance (Papageorgiou et al., 2012b).

Current research indicates that a HFVD can impair hazard detection, but some individuals compensate to some degree. What remains unclear is the extent to which a relatively simple 'static' visual search task could provide a useful metric of compensation that also relates to hazard detection when driving. Some authors have found a relationship between visual search performance and some aspects of driving (Coeckelbergh et al., 2002a; Tant et al., 2002a). The present chapter set out to test the findings of Bowers et al. (2009) – namely that a group of individuals with a HVFD will exhibit impaired hazard detection when driving (relative to controls), but with wide variation between individuals and at least some individuals detecting hazards within a timescale consistent with safe driving (Bowers et al., 2009). We hypothesised that the people whom we categorised as being Adequately Compensated (AC) at the end of our visual search task (Chapter 4), would have a superior detection performance to our Inadequately Compensated (IC) group and perhaps perform as well as our control group of older adults. Our visual search task was essentially a size discrimination task - optical size could be important for detecting approaching objects. Human sensitivity to optic expansion information (the change in optical size) is limited, so detecting the movement of small fast vehicles (e.g. motorbikes) that are far away can be difficult (Gould et al., 2012). In some cases detecting size differences could be crucial to identifying the vehicle that is approaching or receding. It was in order to capture this property that we elected to use size difference as the primary feature of our search task described in Chapter 4. Pilot work with older adults showed that large size differences between the target and distracters caused target 'pop out' and so were detected quickly, whilst small size differences were difficult to detect, and active serial search seemed to be required. Both types of visual search are relevant to driving since sometimes hazards are strongly visually salient (e.g. a large hazard suddenly emerging in front of your vehicle) and sometimes hazards are subtle, peripheral, and embedded amongst similar distracter objects (e.g. one pedestrian moving out from a stationary crowd).

6.3 Experiment: Hazard Perception whilst Driving with a Homonymous Visual Field Defect or Unilateral Spatial Neglect

The following experiment used a series of hazard detection tasks of increasing complexity to measure reaction times and errors detecting pedestrians, either when there was no other task, or whilst simultaneously steering and changing lanes within a simulated driving environment. We expected that hemianopia and spatial neglect would make hazard detection difficult, and require extremely efficient scanning behaviours to compensate sufficiently. It should be noted that although the primary deficit for the HVFD group was visual, in line with previous research, task performance was expected to degrade only once cognitive demand increased and/or when hazards appeared in the affected part of the visual field. For the individuals with USN, despite the striking clinical manifestations immediately post-stroke, the most obvious deficits often appear to resolve with time. More detailed testing, however, using more complex arrays of stimuli usually still reveals some deficits (Mattingley et al., 1994) and so we would expect those in the USN group to exhibit hazard perception difficulties that manifest only with increased cognitive demand or when hazards appeared in contralesional space.

6.3.1 Participants

A total of 13 control participants completed the hazard perception tasks. CONT2 and CONT3 completed an earlier version of the experiment which was subsequently altered to reduce simulator-induced nausea. CONT12 and CONT17 were unable to complete testing because of nausea and CONT13 declined to carry on due to fatigue. RHH4 did not participate due to nausea, but all other participants with stroke completed all of the tasks. LVI3 ‘crashed’ the car on a number of occasions and so did not manage to reach the hidden locations of all of the pedestrians.

6.3.2 Apparatus

The reaction time tasks took place in the static, fixed base driving simulator (see figure 16 in Chapter 5). Graphics were rendered at 60Hz using a PC (Intel i7 950 3.07 GHz) running WorldViz Vizard 3.0.

Responses to pedestrians were registered by the participant pressing either the left or right wheel pad (participant choice). The wheel pads are large buttons conveniently located behind the steering wheel which can easily be depressed without interfering with steering.

6.3.3 Procedure

Each participant took part in two experiments: 6.1) the reaction time tasks, and 6.2) the driving task with concurrent hazard detection task.

Experiment 6.1 (Simple Reaction Time Tasks): The stimuli consisted of a pedestrian appearing on a black background with a randomised delay of 1.5s, 1.75s or 2s between each trial. The observer responded as fast as possible by clicking the wheel pads behind the steering wheel. The pedestrian was 1.8 metres tall and appeared 15 metres in the distance, walking on the spot, centrally or 14.1 degrees offset into the periphery. Pedestrians could be orientated towards or orthogonal to the observer, remaining on the screen until the participant responded (see Figure 6.28). For the simple reaction tasks, the participant simply clicked the wheel pad as soon as the pedestrian appeared. For the choice decision tasks the participant responded to the orientation of the pedestrian by simply clicking to indicate that the pedestrian was orientated towards them, or holding the button for 2 seconds if the pedestrian was orientated 90 degrees from them (i.e. facing sideways). Thus, there were four conditions with 20 repetitions in each, which were blocked and performed in the same order for everyone: the central reaction task (CRT), peripheral reaction task (PRT), central decision task (CRT-D), and peripheral decision task (PRT-D).

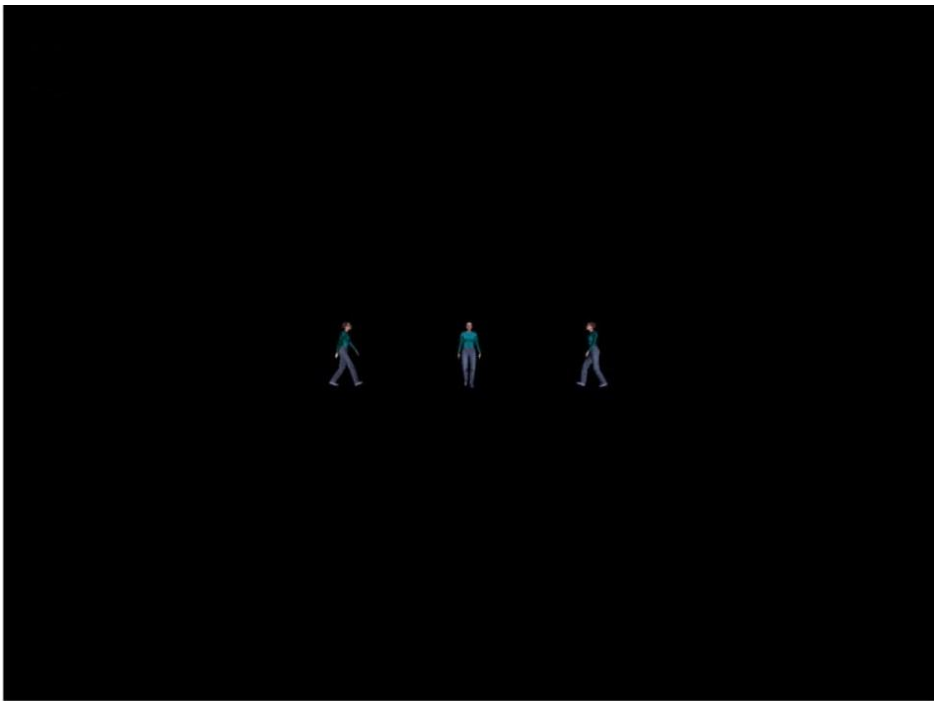

Figure 6.28: The 3 possible positions at which pedestrians appear during the simple reaction time tasks.

Experiment 6.2 (Driving Task): Participants were asked to drive normally down a straight 3 lane highway (free from traffic), maintaining the initial starting point in the middle lane. A grass verge separated the 3 lanes on the opposite side of the carriageway. Halfway down the highway a break appeared in the grass verge. Participants were asked to steer through the break and continue down the 3 lane carriageway on the opposite side of the road (see Figure 6.29). The vehicle moved at a constant speed of 12m/s (26.8 mph). The accelerator, brake, gears and clutch were not used.

Figure 6.29: The hazard perception whilst driving task showing an emerging pedestrian and the break in the central grass verge

Pedestrians (again, 1.8 metres tall) appeared on the pavement or the grass verge, 40 metres in the distance. With no steering adjustment the initial angular offset would be approximately 12.9 degrees, but this depended on the position of the driver in lane and the heading angle of the vehicle, and changed over time as the driver approached the pedestrian. The pedestrians walked and moved in space travelling at 1m/s (as opposed to Experiment 6.1 where they walked on the spot). Pedestrians appeared orientated as per Experiment 6.1, facing the observer (and walking along the pavement) or oriented orthogonally to the observer (walking into the road). As per Experiment 6.1, the participants were required to click a wheel pad for a pedestrian walking along the pavement and to hold for a pedestrian walking out into the road. Once a wheel pad was pressed, the pedestrian disappeared from view. In each trial two pedestrians appeared before the break in the grass verge and two after, with a maximum of 16 pedestrians across the experiment. Each pedestrian had a 50/50 chance of appearing on the left or right of the road, and a 50/50 chance of walking orthogonally to the driver or towards or away from them.

Participants were given practice to ensure that they could differentiate the pedestrians, use the steering controls and complete the steering task halfway through the experiment. Trials were repeated four times, crossing left to right two times and right to left two times. Each trial lasted around 30 seconds.

Originally a more complex hazard perception task was piloted. The steering task was then adjusted because older adults experienced a degree of nausea when turning tight 90 degree corners due to the large on-screen motion associated with such turns. The task was therefore redesigned to contain no large turns.

6.3.4 Analysis

The primary measure of interest was the speed of target detection since performance on this measure will determine the earliest a driver can initiate an action (e.g. braking or swerving) to avoid collision with an obstacle. The time elapsed from presentation of the pedestrian to the participants' press of the wheel pads (reaction time in seconds) was analysed for Experiments 6.1 and 6.2. In Experiment 6.1, there were 3 controls and 2 participants with stroke who each exhibited a single instance across the 4 tasks, of not detecting a pedestrian for over 5 seconds. Each instance of such an outlier trial occurred on the very first iteration of an experiment so were likely due to the participant not being fully prepared in some way. Including these extreme values in a simple average could disproportionately inflate RT estimates for these individuals and therefore the decision was taken to use medians for each individual participant's RTs. In experiment 6.2, a miss was recorded if no button was pressed 3.3 seconds after the pedestrian appeared (the time at which the pedestrian was passed by the driver). Missed pedestrians were not counted in reaction time calculations.

A secondary measure of interest was whether participants correctly identified the direction of pedestrian walking when performing the decision task (Experiment 6.1: CRT-D, PRT-D and Experiment 6.2: Driving PRT-D). The orientation of a pedestrian indicated whether they were a potential hazard, for example in Experiment 6.2 the sidewalk pedestrians were not a risk, but the pedestrians walking into the road were a potential hazard. A measure of decision error allows a fuller interpretation of reaction time behaviour (e.g. a guessing strategy could lead to quicker RTs). Accuracy rates are presented as the percentage of pedestrians correctly identified. Instances of complete failure to detect pedestrians in Experiment 6.2 are reported separately.

The USN group were extremely variable in performance and have been treated as case studies. The controls and HVFD groups (split into AC and IC groups) were more homogenous and so were compared as groups. A One-way ANOVA was conducted when comparing reaction time data and a Kruskal-Wallis test was used when comparing accuracy rates in decision tasks (the underlying distribution was heavily skewed towards high percentage accuracy scores so a parametric test was inappropriate). If the ANOVA was significant, planned contrasts were used to compare the Control group to the AC group, and the Control group to IC group. As there was no expectation of significant differences in accuracy rate or reaction time between the locations of targets for the control group (because they did not have visual field impairments), data was averaged across left and right fields.

Throughout the results, the Left homonymous visual field defect group (LHHs) and Right homonymous visual field defect group (RHHs) were treated as one group (HVFDs) with performance divided based on whether the stimuli were presented in the affected (contralesional) field or the unaffected (ipsilesional) field where possible.

6.4 Results: Reaction Time Task

The first set of tests (Experiment 6.1) measured simple reaction times and decision reaction times to a variety of targets that appeared in the affected or unaffected fields.

6.4.1 Simple Reaction Task with Central Target

Mean reaction times were: Controls: 0.30 secs, AC group: 0.37 secs and IC group: 0.32 secs (See Figure 6.30). Levene's test showed that variance was not homogenous ($p = 0.028$), therefore the means were contrasted using Welch's test with no significant differences found: $F(2,7.947) = 3.39$, $p = 0.086$

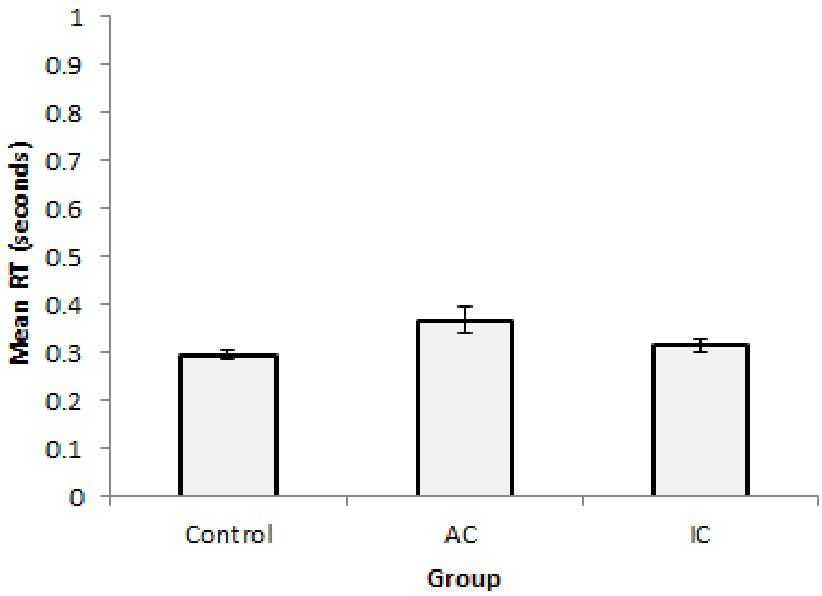

Figure 6.30: Mean simple reaction times (no decisions) for centrally presented hazards. Bars = SEM.

The results for the USN individuals (Table 6.48) show that all were slower than the slowest control participant, though LVI4 was similar to the mean of the AC HVFD group.

Table 6.48: USN group results for simple reaction time task with central target

Participant	LVI1	LVI2	LVI3	LVI4	RVI1	LHHVI	Control
Reaction Time (secs)	0.53	1.41	1.28	0.37	0.61	0.67	0.24-0.35

6.4.2 Simple Reaction Task with Peripheral Target

For targets appearing in the affected hemifield, mean reaction times were: Controls: 0.32 secs, AC group: 0.47 secs and IC group: 0.48 secs (see Figure 6.31, Panel A). Levene's test was again positive (p = 0.023) so the means were contrasted using Welch's test with no significant difference found: F(2,6.229) = 2.3, p = 0.179.

For targets appearing in the unaffected hemifield, mean reaction times were: Controls: 0.32 secs, AC group: 0.39 secs, IC group: 0.35 secs (see Figure 6.31, Panel B). A one way ANOVA showed no differences between the groups: F(2,23) = 3.108, p = 0.066.

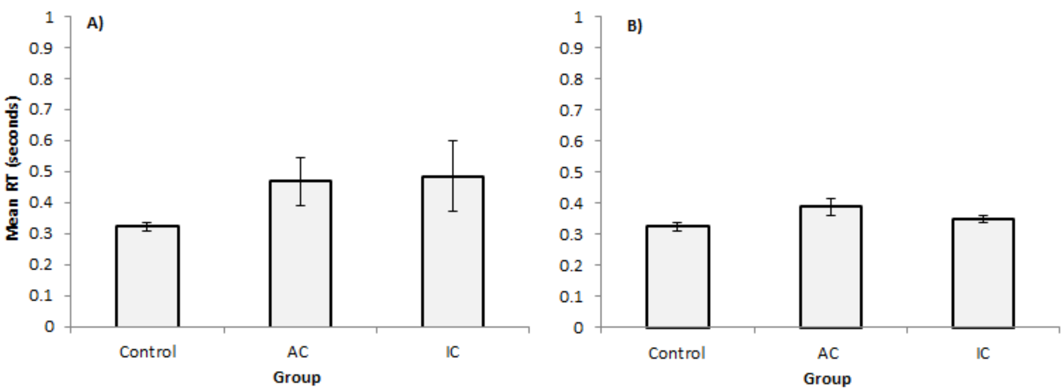

Figure 6.31: Mean simple reactions times (no decisions) for stimuli presented in the A) affected field and B) unaffected field. Bars represent SEM.

The USN results (Table 6.49) show that all individuals were slower than the slowest control participant, except for LVI4.

Table 6.49: USN group results for simple reaction time task with peripheral target

Participant	LVI1	LVI2	LVI3	LVI4	RVI1	LHHVI	Controls
Contralesional RT (secs)	0.57	1.15	1.64	0.42	0.67	0.68	0.25-0.46
Ipsilesional RT (secs)	0.57	1.05	0.84	0.35	0.52	0.50	0.25-0.46

6.4.3 Decision Reaction Task with Central Target

Mean reaction times were: Controls: 0.48 secs, AC group: 0.57 secs, IC group: 0.60 secs (see Figure 6.32, Panel A). Levene's test showed that variance was not homogenous ($p < 0.001$). Welch's test detected a significant between group difference: ($F(2,8.904) = 4.816$), $p = 0.038$. Planned contrasts (with no assumption of homogeneity of variance) showed a significant difference between the control and AC groups: ($t(16.941) = 3.14$, $p = 0.006$, $d = 1.02$), but no significant difference between the control and IC groups: ($t(4.792) = 1.48$, $p= 0.203$, $d = 1.31$). It is likely that the small sample size and large variance for the IC group made it difficult to detect group differences (whilst the difference in means between controls and the IC group is larger than for the AC group, the IC group is more variable). Alternatively the significant group difference may be a false positive (interestingly if the planned contrasts are run with homogenous variance assumed, the difference between controls and AC group is not significant, but the difference between controls and the IC group is significant).

Accuracy rates (see Figure 6.32, Panel B) were not different between the 3 groups as shown by Kruskall Wallis test: (controls = 86%, AC = 92%, IC = 94%, $X^2 = 3.46$, $p = 0.178$).

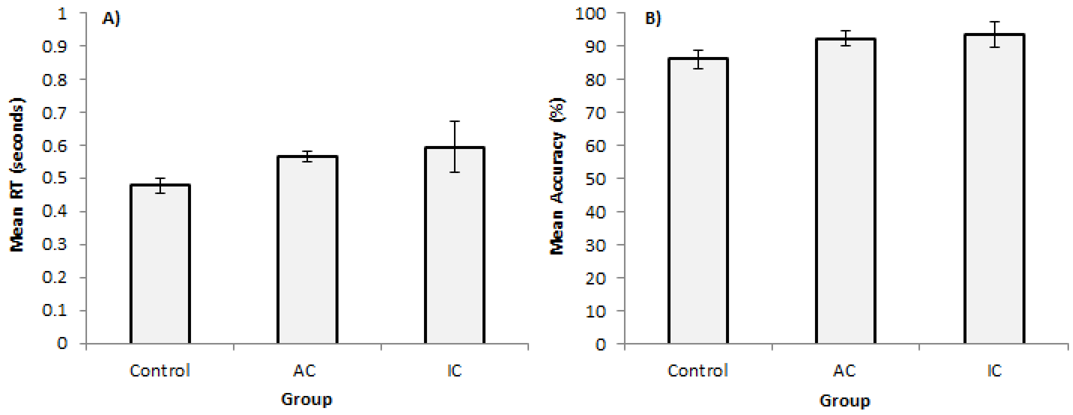

Figure 6.32: A) Mean RT for decision task with central target, and B) Mean accuracy for decision reaction task with central target. Bars = SEM

The pattern of results for the individuals with USN (Table 6.50) were similar to the SRT, with LVI4 being the only participant in the range of control performance.

Table 6.50: USN individual performance on the decision reaction time task with central target

Participant	LVI1	LVI2	LVI3	LVI4	RVI1	LHHVI	Controls
Reaction Time (secs)	0.93	0.84	1.37	0.55	1.30	0.70	0.39-0.67
% Accuracy Rate	100%	60%	70%	90%	83.3%	94.7%	60%-100%

6.4.4 Decision Reaction Task with Peripheral Target

When the target was presented in the affected hemifield, mean reaction times were: Controls: 0.55 secs, AC group: 0.75 secs, IC group: 0.75 secs (see Figure 6.33, Panel A). A one way ANOVA showed significant differences between the groups: $F(2,23) = 13.676$, $p < 0.001$. Planned contrasts showed a significant difference between the control and AC groups: ($t(21) = 4.42$, $p < 0.001$, $d = 2.26$) and between the control and IC groups: ($t(21) = 3.98$, $p = 0.001$, $d = 2.17$). No difference was found between the AC and IC groups: ($t(21) = 0.143$, $p = 0.893$).

The raw mean reaction times were identical for the AC and IC groups (0.75 secs) which was slower than the mean reaction time for controls (0.55 secs).

Accuracy rates (see Figure 6.33, Panel C) for targets in the affected hemifield were significantly different between the 3 groups as shown by Kruskall Wallis test: (controls = 92%, AC = 98%, IC = 85%, $X^2 = 6.88$, $p = 0.032$). A Games-Howell test showed a significant difference between the control and AC group ($p = 0.045$) but no difference between the control group and IC group ($p = 0.499$) or between the AC group and IC group ($p = 0.136$). Surprisingly this meant that the AC group were significantly more accurate than the controls (98% Vs 92%). This may be because the AC group on average took longer to respond giving more time to select the correct answer. However, given the large number of contrasts performed in this chapter, this may also represent a false positive effect. The lack of significant difference between the IC group and the other groups despite a larger absolute difference probably reflects a greater variability in performance for the IC group and a small group size.

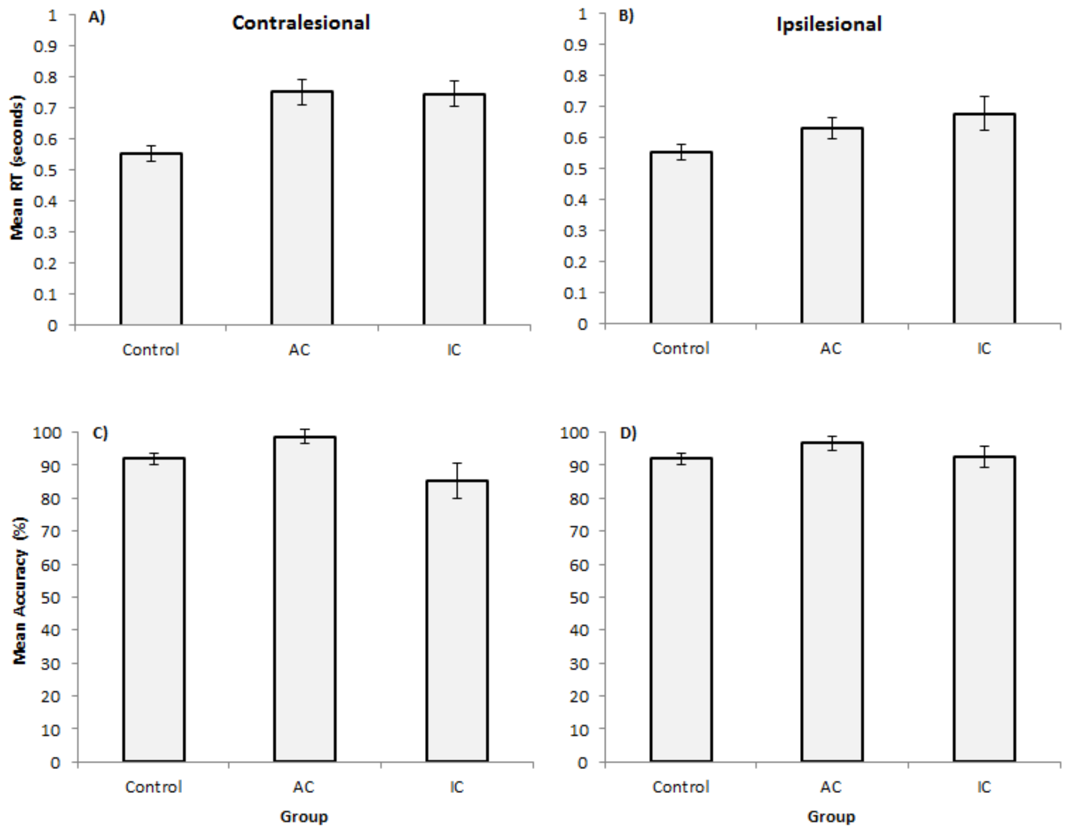

Figure 6.33: Above: mean reaction times for decision task presented in A) Contralesional and B) Ipsilesional side. Below: mean accuracy for A) Contralesional and B) Ipsilesional side. Bars = SEM.

For targets in the unaffected hemifield, mean reaction times were: Controls: 0.55 secs, AC group: 0.63 secs, IC group: 0.68 secs (See Figure 6.33, Panel B). A one way ANOVA showed significant differences between the groups: $F(2,23) = 3.65$, $p = 0.044$. Planned contrasts showed a significant difference between the control and IC groups: ($t(21) = 2.53$, $p = 0.019$, $d = 1.40$). No difference was found between the control and AC groups: ($t(21) = 1.66$, $p = 0.112$) and no difference was found between the AC and IC groups ($t(21) = 0.847$, $p = 0.407$).

Accuracy rates (see Figure 6.33, Panel D) for targets in the unaffected hemifield were not significantly different between the 3 groups as shown by Kruskall Wallis test: (controls = 92%, AC = 97%, IC = 93%, $X^2 = 2.91$, $p = 0.234$).

The results for the individuals with USN (Tables 6.51 and 6.52) suggest that all individuals fell outside of the range of Control performance, though LVI4 continued to be the best performer in the affected hemifield. Interestingly LVI4 was actually worse when the target was in the unaffected field (contrast LVI4 and LVI2 in Table 6.51 and 6.52).

Table 6.51: USN individual performance on the decision reaction time task with peripheral target.: Target in affected hemifield

Participant	LVI1	LVI2	LVI3	LVI4	RVI1	LHHVI	Controls
Reaction Time (secs)	1.11	0.93	1.77	0.76	1.01	0.89	0.44-0.71
% Accuracy Rate	100%	90%	50%	90%	100%	100%	80%-100%

Table 6.52: USN individual performance on the decision reaction time task with peripheral target.: Target in unaffected hemifield

Participant	LVI1	LVI2	LVI3	LVI4	RVI1	LHHVI	Controls
Reaction Time (secs)	0.97	0.74	1.63	0.82	1.25	0.88	0.44-0.71
% Accuracy Rate	100%	70%	70%	100%	100%	70%	80%-100%

6.5 Results for Experiment 6.2: Decision Reaction Time Task whilst Driving

In this Chapter the first experiment presented targets across various parts of scene, which required a simple response, or a decision response. These reaction times provide a good measure of whether the perceptual-motor processes required to respond rapidly to a sudden obstacle/hazard were intact for the various participant groups of interest. One issue with these measures is that the participants had only one task to perform (detect the target as quickly as possible, or identify the orientation of target as quickly as possible). When driving, however, hazard detection is actually embedded in the broader task of successfully steering a course through the world without colliding with objects. In these circumstances hazard detection could be considered secondary to the primary steering task and so it may be expected that there are task switching costs associated with responding to sudden hazards. A second experiment was run, therefore, to test the same groups detecting the appearance of pedestrians in a more realistic virtual scene, when performing a lane change driving task.

When the target was presented in the affected hemifield, mean reaction times were: Controls: 0.71 secs, AC group: 0.79 secs, IC group: 1.27 secs (see Figure 6.34, Panel A). Levene's test was significant ($p < 0.001$) so the means were contrasted using Welch's test and no significant difference was found: ($F(2,6.984) = 1.862$, $p = 0.225$).

Accuracy rates for targets in the affected hemifield (see Figure 6.34, Panel C) were not significantly different between the 3 groups as shown by Kruskall Wallis test: (controls = 91%, AC = 86%, IC = 70%, $X^2 = 3.34$, $p = 0.188$). The lack of statistical significance despite a large difference in mean reaction times and accuracy rates between groups is likely due to a lower number of hazards in this task (compared to the reaction time tasks) and the lack of homogeneity of variance.

It is somewhat surprising that the apparently considerably slower reaction time and lower accuracy rate for the IC group compared to the other groups did not reach statistical significance. However table 6.53 shows that the 5 members of the group were extremely variable in performance producing extremely wide confidence intervals

When the target was presented in the unaffected hemifield, mean reaction times were: Controls: 0.71 secs, AC group: 0.86 secs, IC group: 0.89 secs (see

Figure 6.34, Panel B). A one way ANOVA showed no significant differences between the groups: ($F(2,23) = 3.152$, $p = 0.064$).

Accuracy rates for targets in the unaffected hemifield (see Figure 6.34, Panel D) were not significantly different between the 3 groups as shown by Kruskall Wallis test: (controls = 91%, AC = 97%, IC = 76%, $X^2 = 3.90$, $p = 0.142$).

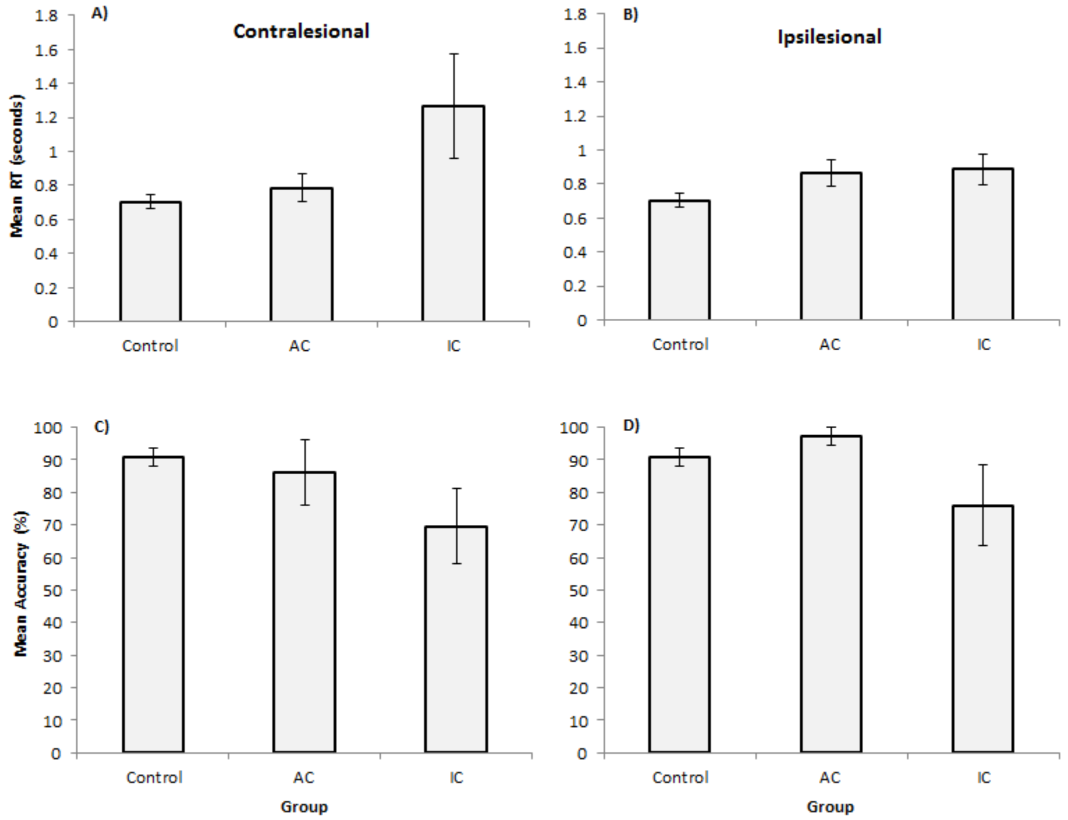

Figure 6.34: Above: mean reaction times for the driving decision task for pedestrians presented in the A) Contralesional and B) Ipsilesional Side. Below: mean accuracy for the driving decision task for pedestrians presented in the C) Contralesional and D) Ipsilesional side. Bars = SEM

During experiment 6.2, no control subject made any predictive clicks (i.e. pressed the gear pad when no pedestrian was on screen) or failed to detect any pedestrians (i.e. made no response to a pedestrian on screen).

In the AC group, RHH5 made 1 predictive click and failed to detect 1 pedestrian on their unaffected side. RHH3 failed to detect 2 pedestrians on the affected side. The other 4 members of this group made no predictive clicks and detected every pedestrian.

In the IC group, LHH4 and RHH1 made no predictive clicks and detected every pedestrian. LHH1 made 1 predictive click and failed to detect 2 pedestrians on the affected side. LHH3 failed to detect 5 pedestrians on the affected side. RHH2 made 5 predictive clicks and failed to detect 6 pedestrians – 4 on the affected side and 2 on the unaffected side.

The reaction time and accuracy performance scores are displayed in Figure 6.34. What is immediately noticeable is the wide confidence interval for the IC group's reaction times suggesting that performance within this group was highly variable. To better understand the pattern of results the median reaction times and accuracy rates for each individual with HVFD has been tabulated (Table 6.53). The mean control reaction time was 0.71 secs, standard deviation was 0.13 secs and range was 0.5-0.95 secs. For accuracy the mean control result was 90.7%, standard deviation was 9.8% and range was 66.7%-100%. Median reaction times are given for each individual with HVFD. Results that are more than 1 standard deviation from control mean are labelled blue and those outside the control range are labelled red.

Table 6.53: Reaction times and accuracy scores for the HVFD individuals performing experiment 6.2: Decision reaction time task whilst driving.

		Contralesional		Ipsilesional	
	P	RT (secs)	Accuracy (%)	RT (secs)	Accuracy (%)
AC	LHH2	.78	100	.84	100
	LHH5	1.05	89	1.17	100
	LHH6	.48	90	.76	83
	RHH3	.68	38	.65	100
	RHH5	.90	100	1.02	100
	RHH6	.83	100	.74	100
IC	LHH1	.55	60	.86	50
	LHH3	1.85	67	.93	100
	LHH4	.80	100	.62	88
	RHH1	1.02	88	.85	100
	RHH2	2.12	33	1.18	42
	Control Mean	.71	90.7	.71	90.7
	Control Range	.50 -.95	66.7-100	.50 -.95	66.7-100

Results for the USN individuals are shown in Tables 6.54 and 6.55. Results that are more than 1 standard deviation from control mean are labelled blue and those outside the control range are labelled red.

LVI1 and LVI4 detected every pedestrian and made no predictive clicks. LVI2 and RVI1 detected every pedestrian and made a single predictive click each. LHHVI made 1 predictive click and failed to detect 2 pedestrians on the affected side. LVI3 made 1 predictive click and failed to detect 5 pedestrians – 3 on the affected and 2 on the unaffected side.

Table 6.54: USN group performance for the decision reaction time task whilst driving for targets in the affected hemifield

Participant	LVI1	LVI2	LVI3	LVI4	RVI1	LHHVI	Controls
Reaction Time (secs)	**1.29**	**1.28**	**1.47**	0.68	**1.48**	**1.45**	0.50-0.95
% Accuracy Rate	**75%**	**44.4%**	**66.7%**	87.5%	100%	**71.4%**	75%-100%

Table 6.55: USN group performance for the decision reaction time task whilst driving for targets in the unaffected hemifield

Participant	LVI1	LVI2	LVI3	LVI4	RVI1	LHHVI	Controls
Reaction Time (secs)	**1.12**	**1.26**	**1.43**	0.72	**1.23**	**0.97**	0.50-0.95
% Accuracy Rate	100%	**50%**	100%	87.5%	85.7%	100%	75%-100%

6.6 Discussion

The general pattern of findings shows that the controls were quicker detecting hazards than the HVFD groups in every experimental condition. Accuracy figures were less consistent with no compelling pattern of differences between groups emerging across the experiments.

In Chapter 4 the participants with HVFD were classified as either Adequately compensated (AC) or Inadequately compensated (IC) according to performance on the visual search task. In the non-driving reaction time experiments, there was little difference in mean reaction time between the AC and IC groups, both of whom look slower on average than the control group in the more complex tasks (although statistical significance was not always reached). The largest absolute difference in reaction times is seen in presumably the most difficult of these tasks – the decision reaction time task with peripheral targets in the affected hemifield. On this task both the IC and AC group were significantly slower than controls, though they were no different to each other. It seems that the presence of a HVFD slows responses on this kind of task, but previous performance on a visual search task (the basis of the AC/IC grouping) was not predictive of performance.

When participants were asked to perform hazard detection whilst also driving (in a simulator), reaction times and accuracy of responses were adversely affected for most of the participants. Interestingly 4 participants with HVFD (LHH2, LHH4, LHH6 and RHH6) showed reaction times and accuracy rates within 1 standard deviation of the mean for the control group. In addition these 4 individuals detected every pedestrian and made no erroneous predictive clicks. Three of these participants (LHH2, LHH6 and RHH6) were included in the AC group, but LHH4 had been slow and inaccurate at the visual search task and had therefore been placed in the IC group. It should be noted that there were still some problems observed in the responses of these participants - there were markedly slower reaction times observed on at least one of the non driving reaction time tasks. LHH4, LHH6 and RHH6 all had reaction times outside of the range of the controls for the PRT-D task. LHH2's reaction times were all inside the control range, but for the decision reaction time tasks were more than 1 standard deviation slower than the mean control time. It is also very noticeable that LHH2 (LIQ with central sparing), LHH6 (L paracentral scotoma) and RHH6 (RSQ, no sparing) all had limited visual field loss, whereas LHH4 had a complete hemianopia to the midline and yet outperformed AC group members such as RHH5 (RIQ with central sparing).

As expected the USN group showed highly variable performance: 5 of the 6 individuals produced reaction times during the driving task that lay well outside of the control range, suggesting performance at this task was impaired. The only exception was LVI4 who performed well within the control range (although some of the simple reaction times were slower than controls).

The two key questions that this chapter aimed to address was whether any within the stroke population are able to complete the hazard perception tasks and reaction time tasks as well as a control group, and whether performance on a static visual search task could be used to predict performance on the "hazard detection whilst driving” task. We observed 5 participants that showed performance on the driving task that was indistinguishable from the controls (LHH2, LHH4, LHH6, RHH6 and LVI4). However, each of these individuals had shown slower reaction times in at least one of the simple or decision reaction time tasks. The driving task was designed to replicate at least some key elements of real world driving (steering, lane-changing and sudden emerging hazards), although other key elements were not replicated (speed control, gear changes, merging with traffic, reading and responding to road signs). For the majority of participants who showed impaired performance even on this relatively straightforward task, it would be reasonable to presume that real world driving would also be significantly impaired. Even in the five individuals who showed ‘normal’ performance on the driving task, there could be concerns based on the reaction times and decision making speeds for the simpler non-driving reaction time tasks. It may simply be sufficient to use such a test as a screening tool that indicates those individuals that could possibly be considered for inclusion in a real world, on road driving assessment if they desired to return to driving, but with the awareness that the on road performance may still be significantly impaired.

The visual search task in Chapter 4 seemingly has limited predictive utility. For most of the non-driving, reaction time tasks, performance of the AC and IC groups was similar and both groups were slower on average than controls in the more complex tasks. There does look to be slower reaction times and reduced accuracy rates for targets in the affected hemifield for the IC group in the driving task – with the mean scores for the AC group seemingly closer to the controls than they were to the IC group (but these differences were not statistically reliable). Within group performance was highly variable with RHH3 and RHH5 (AC group) failing to detect at least one pedestrian, whilst LHH4 (IC group) performed as well as the controls during the driving task. It seems, therefore, that a visual search task (such as the one in chapter 4) may not be the most diagnostic component of a driving assessment battery.

These findings do support to some degree the theory that individuals who scan across into the affected side are able to compensate to some degree for their visual field loss: LHH4 and LVI4 both spent far more time searching the contralesional side of the screen during the visual search task (Chapter 4), and performed unexpectedly well at the hazard perception task. This pattern was not universally successful, however, since RHH2 also spent far more time searching the contralesional side of the screen on the visual search task (and showed better visual search performance than LHH4 and LVI4), but their performance on the hazard perception task was poor. Differences between LHH4/LVI4 and RHH2 were evident in two other tests – in Chapter 3 RHH2 exhibited grossly hypometric saccades and in Chapter 2 they performed less well performance on pen and paper cognitive measures. It is possible, therefore, that RHH2 is unable to utilise the requisite compensatory strategies due to poorer overall cognitive control and/or impaired eye movement control.

The discussion so far has considered the relationship between visual search, hazard detection and driving. One possible issue, however, is whether the simulated driving task used in the present Chapter was sufficiently representative of real world driving. The problem with attempting to simulate ‘real’ driving conditions is that the visual, motor and cognitive demands vary greatly depending upon the environment being driven through - consider the differences between city driving at rush hour, motorway driving at high speeds in the rain, or driving along narrow, winding country lanes at night. It is, therefore, non-trivial to precisely determine whether the task used in the present study was less demanding or more demanding than real driving. Computer simulations have been used for many years to provide well controlled visual conditions with reliable and reproducible measures of performance (Kountouriotis et al., 2012; Raw et al., 2012; Wilkie and Wann, 2002) and in this Chapter the lane change driving task was used to reproduce some of the core visual-motor demands of city driving, whilst also testing the ability to detect and respond to pedestrians. The task lacked some other driving demands, such as using the pedals or dealing with traffic. Perhaps more problematic is the fact that the driver knew that hazards would emerge at fairly regular intervals and could (to some degree) predict when they could appear. It is important perhaps to clarify that success in this task should not be used to suggest that any single or group of participants would be safe to drive – it would be necessary to carry out a longer, less constrained simulated study to examine this question further. It is likely, however, that failure to perform this task would usefully predict possible failures in the real world. While it could also be argued that the binary button pressing motor response that we asked participants to generate is different from the usual braking or avoidance actions performed when driving, it should be noted that the control group were capable of responding rapidly (~0.71s) and detecting 100% of pedestrians (although occasionally with the wrong response as to their orientation). The stroke group contained 2 AC participants and 3 IC participants who missed detecting at least one pedestrian altogether. We would classify such misses as a major error (with huge real world implications for such failures to detect) and such misses reinforce somewhat the apparent poor predictive ability of the demanding visual search task (Chapter 4) on the ability to successfully detect hazards when driving.

Chapter 7: Conclusions and Suggestions for Future Research

This concluding chapter will pull together the main themes that emerge from the experimental results of the previous chapters. It will also set the findings in a broader context and suggest avenues for future research.

7.1 Driving with Homonymous Visual Field Defects

7.1.1 Fitness to Drive

In this project, data has been gathered from a small number of people with HVFDs. A reductionist approach was taken, using a set of controlled tasks that independently tested eye-movement function, visual search performance, and simulated driving tasks with and without potential collision targets to try and gain insight to what aspects of driving may be impaired by a HVFD. The hope was that that this approach would aid the design of future, perhaps less constrained experiments in this field that more closely map onto the complete demands made during on-road driving. While it is beyond the scope of this project to determine which participants would be safe or unsafe to drive a car in the real world, it is possible to evaluate which measures could potentially inform the decision to carry out further on-road tests, and also to discuss which measures may have a bearing on fitness to drive.

In Chapter 6, Experiment 6.1, the participants with HVFDs were on average slower than the control group to respond to a target appearing on a blank screen in their affected hemifield. Whilst the absolute difference was small (~0.15 secs and failed to reach statistical significance), it is striking that an extremely simple reaction time task could potentially be a useful test of intact function. When a decision regarding how to respond to a target was added (Also Chapter 6, Experiment 6.1), reaction times for the HVFD group were slowed compared to controls, even when the target appeared in the central field – a difference of around 0.1 secs. When examining individuals, seven people with HVFD were more than 1 standard deviation slower than the control group mean and five of these individuals had been classified as Adequately Compensated (AC). When the target was presented in the affected hemifield, the average reaction time was around 0.2 seconds slower for the HVFD groups than controls, and 10/11 of the HVFD group were more than 1 standard deviation slower than controls. For the decision task whilst driving experiment (Chapter 6, Experiment 2), 5/11 participants with HVFD were more than 1 standard deviation slower than controls (there were less data points for this experiment so the confidence intervals are wider).

Taken together these results indicate that reaction times and decision making times may be slowed for people with HVFD after stroke, even if they are otherwise highly functioning – with normal cognitive assessments and relatively intact abilities at visual search. Whilst the absolute difference in reaction times may be small (0.1-0.2s), the relative difference in reaction time is quite large: ~20 – 35% in the simple reaction time tasks, ~10% for AC's versus controls in the driving task and ~80% for ICs versus controls in the driving task. Small increases in reaction time are potentially highly significant at speed as the extra distance travelled will be at maximum speed before braking is initiated, making crashes more likely and crash severity potentially greater. For comparison, alcohol consumption to above the legal limits may only increase decision reaction times by around 5% (Leung et al., 2012; Zwahlen, 1976; Maylor and Rabbitt, 1987).

In terms of fitness to drive, a major concern about this group is that, even on a relatively simple hazard perception task (Chapter 6), 5/11 participants with HVFD failed to respond to at least one pedestrian. One of these individuals (RHH5), had normal cognitive assessments, relatively normal visual search abilities and otherwise performed well in the task – making correct decision responses to every other hazard (although somewhat slower than controls). For this individual the hazard that was missed was on the ipsilesional (unaffected) side – and reaction times on this side were slower than on the affected side. An example perhaps of overcompensation leading to impaired performance on the 'good' side.

In line with the published literature on hazard detection, no guidance was given to participants about whether they should prioritise accuracy or speed of responses. The control participants managed this trade-off without problems, but it seems that some individuals in the HVFD group adopted extreme strategies. LHH2 for instance had an accuracy score of 100%, but reaction times were fairly slow, approximately average for the HVFD group. In contrast LHH1 had faster reaction times similar to the control mean, but they exhibited poor accuracy (55% which is around chance). These findings may well reflect the different individual strategies in use by participants based on their interpretation of the task requirements. Future research could examine this issue by simplifying the task to examine solely speed or accuracy of performance to determine whether one aspect is particularly problematic, or whether it is the strategic decision making component that is being affected in this group.

The steering data (Chapter 5) is harder to interpret in terms of what information our results would add to knowledge about fitness to drive and HVFDs. It is striking that 7/11 participants showed very little difference in mean road position between ‘central’ and ‘inside’ conditions for the contralesional bends (13cm or less for an intended position change of 75cm). The absolute mean steering bias was highly variable for these conditions between participants (in the control and HVFD groups), making this data more difficult to interpret – although 3 participants with HVFD were on average within 10cm of the midline for the ‘inside’ condition – whilst another showed a similar inability or unwillingness to drive near the outside road edge on ipsilesional bends. Of the 4 who showed wider differences in road position between the ‘central’ and ‘inside’ conditions for contralesional bends, 2 had an increase in steering variability in either the middle or inside task condition. These findings are indicative that road positioning will be a problem for many people with a HFVD, a conclusion that is supported by Bowers et al. (2010) who described that some people with HVFDs exhibit a reluctance to drive near a road boundary in their affected visual field – and more importantly a reluctance to move towards this boundary when traffic was approaching (Bowers et al., 2010).

Overall our experimental data from Chapters 5-6 provide evidence that a significant proportion of people with HVFDs experience difficulties maintaining certain road positions near to a boundary present in the affected hemifield as well as problems detecting hazards in both visual fields. We would suggest that these are the key measures which any future driving assessments should be focussing on in this patient group. More work needs to be done to clarify at an operational level, exactly how steering and hazard perception are affected by visual field loss, for what proportion of people and to what extent performance is impaired. Carefully constructed highly constrained experiments may help to clarify this. A key difficulty in data interpretation in our experiments has been the unforeseen trade off between outcome measures i.e. between reaction time and choosing the correct response. It would be useful to design future experiments in order to limit the trade off – i.e. by running a driving simulator based simple reaction time hazard perception test and a decision reaction time hazard perception test in the same participants. It would also be enlightening to run simple steering tasks on roads of different widths, with different types of road edges and experiments in which the participant is asked to fixate particular parts of the bend in order to try to clarify exactly how visual feedback is used by the driver with HVFDs.

The findings of highly constrained testing could then inform the methodological design of less constrained, more realistic driving experiments in order to determine whether performance in more constrained testing is predictive of behaviour in more realistic driving tasks. These experiments could be designed in order to specifically examine driving parameters found to be impaired in more constrained testing.

7.1.2 Predicting Driving Ability with Off Road Tests

There are a total of 17 driving assessment centres covering England, Scotland, Wales and Northern Ireland, who are able to provide information and advice to people driving with disabilities and who provide detailed on road assessments to aid the DVLA in decisions regarding returning to driving for people with medical problems. With at least 300,000 people in the UK living with disability from stroke alone (Adamson et al., 2004) (and the myriad of others living with disability from other neurological, musculoskeletal, cardiovascular or ophthalmological conditions), without careful selection criteria the numbers of possible referrals could quickly overwhelm the limited specialist assessment resources available. Currently there are strict guidelines as to whether people with HVFDs may drive or not based on the extent of visual field loss alone – very few of those who are beyond this permitted threshold in terms of the extent of field loss access an on road assessment. However it is questionable as to whether the extent of visual field loss is the best predictor of driving safety – for instance in the field of hazard perception, some studies have questioned how good a predictor the extent of field loss is and suggested that the use of dynamic eye and head movement strategies may be a key factor (Papageorgiou et al., 2012a; Papageorgiou et al., 2012b) – dynamic gaze is not something which can be measured with a static field test. It is possible that an alternative measure would be better or that the predictive ability of visual field measurement would be improved by incorporating other measurements such as cognitive or visuospatial ability (see Chapter 2), Eye movements (see Chapter 3) or performance in easy to administer perception/action tests (such as visual search in Chapter 4).

The experiments in this thesis were not designed to meet the final goal of assessing fitness to drive, rather the aim was to use controlled tasks in order to better understand the perception and action deficits exhibited by groups who had experienced a stroke. This approach has made available a large number of measures across a small number of participants – which makes correlational techniques such as multiple linear regression problematic in terms of statistical validity. Nevertheless it may be useful to investigate whether some of the simple perceptual measures are predictive for the more complex steering and hazard perception tasks – if only to help with methodological design of future research which could investigate this issue more formally.

Much of the data gathered was skewed (i.e. the saccade, error and pursuit error scores were skewed towards 0 degrees, whilst the ACE-R score were skewed towards 100). Spearman's rank coefficient analysis was used, therefore, to investigate whether any of the non driving measures taken were correlated with the “driving” outcome measures (Steering and Hazard detection). 11 Participants with HVFD completed all of the testing.

The independent variables were:

- Age in years (Age)
- Extent of HVFD – ranked 1-11 in terms of amount of field missing (HVFD)
- ACE-R total score (ACE-R)
- Trail B test (Trail A test ranks identically for the HVFD group) (Trail B)
- Saccade Error for Predictable Target in Contralesional Field (Saccade-Pr)
- Saccade Error for Unpredictable Target 15 Degrees into Contralesional Field (Saccade-Un)
- Pursuit Error for Slow Target (Pur-Slow)
- Pursuit Error for Fast Target (Pur-Fast)
- Visual Search Reaction Time for Easy Targets (Accuracy for hard targets in some cases was extremely low making reaction time measures very unreliable) (SearchRT)
- Visual Search Accuracy in % for all targets combined (SearchAcc)

The Dependent Variables were:

- Steering Accuracy – measured as mean distance from intended line (i.e. -0.75, 0 or +0.75 metres) in any direction across all task conditions (SteerAcc)
- Steering Variability – measured as average standard deviation of bias from mean bias across all task conditions (Var)
- Hazard Perception Mean Reaction Time (HazRT)
- Hazard Perception Accuracy of Correct Response to Pedestrian (HazAcc)

The correlation matrix using Spearman's ranked correlation test is shown below in Table 7.56 (values given are Spearman's rho correlation coefficients. Coefficients significant at the $p<0.05$ level are marked *, coefficients significant at the $p<0.01$ level are marked ** and coefficients significant at the $p<0.001$ level are marked ***).

Table 7.56: Spearman's rho correlation coefficients for 11 participants with HVFD

Factors	SteerAcc	Var	HazRT	HazAcc
Age	.491	.178	.155	.194
HVFD	.424	.062	.241	-.666*
ACE-R	-.592	-.527	-.150	.696
Trail-B	.500	.310	.264	-.763**
Saccade-Pr	.355	.351	.245	-.910***
Saccade-Un	.273	.428	.118	-.768**
Pur-Slow	.418	.428	.064	-.671*
Pur-Fast	.227	.287	-.082	-.529
SearchRT	.291	.478	.100	-.543
SearchAcc	-.636*	-.415	.027	.768**

No single factor was found to correlate with steering variability or hazard perception reaction time in this group. SearchAcc (accuracy in visual search) showed an association with SteerAcc (Steering Accuracy) ($r = -0.636$ $p=0.035$) whereby increased search accuracy was associated with increased steering accuracy (lower values). SearchAcc was also correlated with hazard perception error ($r = -0.768$ $p=0.006$), however, the strongest correlation was with Saccade-Pr (accuracy of a saccade to a target which appeared predictably 15 degrees into the affected hemifield; $r = -0.91$ $p<0.001$). Consistent with this relationship, there was also a correlation between Sacc-Un (saccade accuracy to an unpredictable target 15 degrees into the affected hemifield; $r = -0.768$ $p=0.006$). There was also a correlation with Trail-B (time to perform the trail making task; $r = -0.763$ $p=0.006$).

With a group size of only 11, these correlational analyses need to be interpreted cautiously. However, there seems to be some indication that saccadic accuracy and visual search ability seem to be candidate functions to examine in future research designed to search for simple surrogate measures which could aid the identification of those people with HVFD who would be suitable for on-road fitness to drive assessments.

7.1.3 Evidence for Compensatory Gaze Behaviour

Frequent eye movements to look into the affected hemifield have been proposed as a possible effective compensatory strategy used by some people with a HVFD to improve performance in perceptual motor tasks such as visual search (Zihl, 1995b; Zihl, 2000; Zihl, 1999; Zangemeister et al., 1982; Kerkhoff, 1999; Pambakian et al., 2000; Tant et al., 2002b), steering a car (Coeckelbergh et al., 2002a; Wood et al., 2011) and hazard perception (Papageorgiou et al., 2012b). In the visual search task in Chapter 4, many participants with HVFD had slower search times than controls and impaired identification of targets during the harder trials, but one of the most striking findings was that that there was little difference in search times between the left and right hemifields for these individuals. There was also little bias in the search times, with most participants spending a similar amount of time searching each side of the screen. LHH5, LHH6, RHH1, RHH5 and RHH6 all searched fairly equally across both the halves of the screen and reaction time and accuracy scores were roughly equivalent across all task conditions – all 5 had partial HVFDs with considerable sparing. RHH3 and RHH4 were perhaps slightly faster at finding hard targets on the affected side than the unaffected side (RHH3: 4.0 Vs 5.2 secs, RHH4 5.6 Vs 6.6 secs), although accuracy was slightly lower (RHH3: 41.7% Vs 50%, RHH4: 37.5 Vs 50%). Targets on the affected side which were not found at all, were not included in the search time averages, so a lower accuracy at finding targets which were more difficult to locate could have brought the average search times down. LHH2 also showed a balanced searching strategy: they were quicker at finding easy targets on the unaffected side (2.1 Vs 1.3 secs) but surprisingly seemed slightly slower and less accurate at finding hard targets on the unaffected side (4.3 Vs 5.1 secs and 95.8 Vs 79.2%). This may well simply reflect noise in the data, or could reflect an attentional preference for the affected hemifield as a compensation mechanism. LHH1 showed a balanced searching strategy with 52.4% of fixations on the affected side. They did however make a first fixation left of centre 85.6% of the time and their mean time was faster for easy targets on the left (2.2 Vs 3.0 secs). Accuracy rates were similar for easy targets and extremely poor for hard targets on both sides (4.2% Vs 12.5%).

In contrast LHH3 preferentially searched the unaffected side of the screen and was quicker and more accurate at finding targets there. They had developed hemianopia relatively recently and may not yet have adapted eye movements etc. (Or may have a visual neglect not picked up by our screening).

Only 2 participants, LHH4 and RHH2, seemed to exhibit compensatory behaviours, by making a greater number of fixations within the affected side of the screen. LHH4 made 65.5% of fixations left of centre and RHH2 made 67.8% of fixations right of centre. Despite this behaviour, LHH4s time to find easy targets and accuracy for easy targets was still better on the unaffected side (2.7 Vs 3.8 secs and 100% Vs 79.2%). However for hard targets, the reverse was true (5.9 Vs 4.4 secs and 12.5 Vs 29.2%). Accuracy was poor for both sides but it may be that the extra search time in the affected hemifield allowed them to identify a few more hard targets. RHH2 performed similarly for easy targets on either side (3.1 Vs 2.8 secs and 83.3% both sides). For hard targets, accuracy was better and time was slightly quicker on the affected side (6.9 Vs 7.6 secs and 58.3 Vs 33.3%) again possibly reflecting a greater likelihood of finding a target on the side where you look the most.

Overall in the visual search task (Chapter 4), many participants showed balanced search strategies and comparable performance for both sides. Those who preferentially searched one side of the screen often improved performance on that side but at the expense of performance on the other side.

Whilst these measures were useful to determine whether there were compensatory strategies being used during visual search, it was not clear whether these patterns would be indicative of changes in gaze patterns when actively steering a course. In Chapter 5 we collected full gaze and steering data for 7 participants with HVFD for the steering task and many did seem to show gaze patterns which differed from controls (i.e. they adopted the ‘look where you are going’ strategy (Robertshaw and Wilkie, 2008; Wilkie et al., 2010; Wilkie and Wann, 2003b)). LHH2 and RHH5 showed this gaze pattern as most controls did – on average looking a little towards the inside road edge, but gaze position moved with car position. LHH5, LHH6 and RHH6 showed a gaze strategy with a strong contralesional bias – i.e. on contralesional bends they looked towards the inside road edge and on ipsilesional bends they looked more towards the outside road edge. This strategy would bring more of the road into view, perhaps allowing both road edges to be visible for feedback purposes.

LHH1 on contralesional bends kept the car mostly on the right side of the road regardless of task condition. They showed a strong leftward gaze bias which would bring more of the road into view. Behaviour on ipsilesional bends is slightly harder to interpret – again they favoured keeping the car right of centre (towards the inside edge on right bends). They then looked predominantly at or very near the right road edge. The strategy of driving near the right road edge is easy to understand if they were simply using the ipsilesional road edge for feedback purposes (and on rightward bend this appears to be the case). On leftward bends however they looked towards the left road edge so may have been using both edges to hold road position. The strategy appears to be quite successful as steering variability was quite low.

Gaze data for RHH2 is a little puzzling – on contralesional bends they looked in the direction of travel (Gaze bias – steering bias was close to 0, a strategy which would seem to obscure a substantial amount of the road) – others favoured a more contralesional gaze strategy. On ipsilesional bends they favoured looking ipsilesionally. It is possible that this participant was simply using the left road edge for feedback regardless of direction of bend.

RHH1 showed the most variable gaze strategy of all. On contralesional bends, when driving nearer the outer road edge they fixated at or near the outside road edge – a strategy which would obscure most of the road, but would allow for road position feedback from this road edge. When nearer the inside road edge they fixated at or near it. When nearer the middle they looked slightly towards the inside as per the control group. For ipsilesional bends, for the outside and middle road position conditions they fixated towards the outside road edge – this would now bring more of the road into view. On the inner task condition, they fixated near the inner road edge, presumably using this for feedback.

Overall the majority of the HVFD participants appeared to be using eye movement strategies that differed from controls to complete this simple steering task. Only LHH2 and RHH5 appeared to use the same strategies as controls (and LHH2 still exhibited high steering variability on the contralesional, inner road position task condition). The others appeared to use a mix of strategies to either look more into the hemianopic field (presumably in order to bring more of the road into view), or else to fixate a road edge (presumably to maintain a trajectory a certain distance from that road edge in order to complete the task). It would be interesting to see whether this kind of strategy would be used in a more realistic driving environment with potential hazards, since looking away from the hemianopic field would obscure much of the road with a potentially adverse effect on hazard detection.

In the hazard perception whilst driving task (Chapter 6), not unexpectedly, several participants with HVFD were either slower or less accurate in responding to targets in the affected hemifield – LHH3 was slower and less accurate as was RHH1 to a lesser degree, LHH1 missed 2 pedestrians altogether on the affected side, although accuracy was poor on both sides and RHH3 was considerably less accurate on the affected side (37.5% Vs 100%). RHH2 was slower on the affected side although reaction times were slow on the unaffected side too and accuracy was poor on both sides. LHH2, LHH4, LHH5 and RHH6 showed roughly equivalent performance between sides. LHH5 was somewhat faster at responding to targets on the affected side (0.48 secs Vs 0.76 secs) which could potentially reflect a strategy of more actively scanning to look for pedestrians on this side. RHH5 was slightly faster at responding to targets on the affected side (0.9 secs Vs 1.02 secs) again possibly reflecting a strategy of actively scanning for pedestrians on this side. RHH5 did, however, fail to respond altogether to a pedestrian on the unaffected side. Whilst a single instance of this occurrence does not prove anything, it is just about possible that, just as the participants who searched more on the affected side in the visual search task showed relatively reduced performance on the unaffected side, a strategy of actively scanning for pedestrians in the non seeing hemifield caused this participant to fail to see a pedestrian altogether on the unaffected side. It is also possible, of course, that they thought that they had clicked the response button when they had not, or that for some reason something on the screen obscured the view of the pedestrian.

Overall our experiments to give evidence that at least some, if not the majority (in the steering task particularly) of participants with HVFD showed adapted eye movements at least in an attempt to compensate for their visual field loss. These strategies may well improve perception/action performance in the affected visual hemifield, but we have also uncovered at least some evidence that performance may then be degraded on the unaffected side as a side effect of these strategies.

7.2 Driving with Unilateral Spatial Neglect

7.2.1 Gaze behaviour in Perception/Action Tasks

Chapter 4 tested the ability of the individuals with USN to search for a target amongst a set of distracters. LVI3 who had the most pronounced neglect syndrome, followed the classic pattern of directing visual search predominantly into the unaffected hemifield (36.8% Vs 63.2%). Visual search performance was generally poor, but was worse for targets in the affected hemifield. Surprisingly LVI1 (46.4% Vs 53.6%) and LHHVI (47.9% Vs 52.1%) searched almost as much of the time in the affected hemifield as they did in the unaffected. LVI1 showed slower reaction times for contralesional targets but accuracy scores were roughly equal. LHHVI showed quicker reaction times and better accuracy for easy targets on the ipsilesional side – accuracy for hard targets was only 12.5% bilaterally.

RVI1 made 57.1% of fixations in contralesional space and LVI4 made 76.9% of fixations on the contralesional side. This finding is in stark contrast to the reports of previous authors who concluded that people with USN would search more on the ipsilesional side (Husain et al., 2001; Karnath, 1997; Kinsbourne, 1993; Behrmann et al., 1997). It seems that at least these 2 participants are able to overcome their spatial processing deficit at least within this task – both still clinically manifested evidence of neglect according to their rehabilitation teams. Despite (or perhaps because of) this preference for searching the contralesional hemifield, LVI4 showed roughly equal performance for left and right sided targets. RVI1 was quicker at spotting ipsilesional easy targets (2.3 secs Vs 3.9 secs) and more accurate (100% Vs 75%). Accuracy was only 12.5% for hard targets on both sides.

Chapter 5 shows that all 6 members of the USN group exhibited high steering variability in at least some task conditions – even the best performing members of this group (LVI4 and RVI1). LVI4 showed steering variability outside of the control range on 3 task conditions – contralesional outside and inside and ipsilesional inside conditions. RVI1 showed high steering variability only on the contralesional outside task. LVI4 stayed roughly in the centre of the road in all conditions for contralesional bends whilst RVI1 stayed close to the right sided inside road edge for all task conditions on contralesional bends, and close to the middle on ipsilesional bends. This suggests that all members of this group were unable to steer the task in line with instructions with the same ability as the control group. Unfortunately we were unable to collect gaze data for LVI1 and RVI1 and LVI3's data is very difficult to interpret as they spent a significant amount of time off the road altogether.

LVI2 fixated at or near the left (inside) road edge on leftward (contralesional) bends. On ipsilesional bends they fixated the right (inside) road edge on the middle condition, but behaved like controls on the other 2 conditions. LVI4 showed a gaze strategy similar to controls – looking ahead and slightly inward towards the inside road edge in all conditions except for the contralesional inside road edge condition where they seemed to fixate a long way inside of their road position. LHHVI fixated further towards the inside road edge than most controls on both left and right bends.

The striking feature of the results from Chapter 5 is that all 3 participants for whom full datasets were collected appeared to have no problem in bringing their attention into contralesional space on contralesional bends, in order to fixate at or near the road edge in the affected hemifield. Again it seems that in this task, people with USN can overcome their ipsilesional attentional bias. Road position and steering variability are not normal, so even though they are able to do this, it seems that this behaviour is insufficient to allow the task to be completed as well as controls, but it is surprising that this behaviour is exhibited at all.

In the hazard perception task (Chapter 6), LVI4 showed performance similar to controls and with no difference between left and right sided pedestrians (reaction time 0.68 secs and 0.72 secs, accuracy 87.5% both sides). RVI1 was also roughly equivalent between sides, although reaction times were very slow on both sides (1.48secs for contralesional targets, 1.23secs for ipsilesional. Accuracy - 100% contralesional and 85.7% ipsilesional). LVI2 was very slow to spot and had reduced accuracy of response to targets on either side roughly equally (1.28secs Vs 1.26secs, 44.4% Vs 50%) LVI3 was slow on both sides (1.47secs Vs 1.43secs) and accuracy was worse on the affected side (66.6% with 3 total misses on affected side, 100% but with 2 total misses on the unaffected side). LVI1 seemed slower and less accurate for contralesional pedestrians (1.29 secs Vs 1.12 secs and 75% Vs 100%). LHHVI was also slower and less accurate for left sided targets (1.45secs Vs 0.97

secs and 71.4% with 2 total misses Vs 100%). Overall performance was poor bilaterally with either no difference between sides or the affected side being slower and/or less accurate. The exception to this is LVI4 who was shown to have adapted eye movements in the visual search task and possibly the steering task and who performed equivocally between left and right sides on this task with performance well inside the control range.

Overall, and somewhat surprisingly, Chapters 4-6 show that several of the people with USN were able to bring their attention over to look into the affected hemifield. However, despite these capabilities, performance in visual search, steering and hazard perception performance was generally poor for the participants with USN, with the exception of LVI4 who performed the hazard perception task fairly well, although performance in steering and visual search was reduced.

7.2.2 Fitness to Drive and Unilateral Spatial Neglect

As stated previously in this chapter, whilst the experiments were not designed to judge whether participants were fit to drive, there was an expectation that we would be testing some processes which are essential to successful driving. The current practice amongst clinicians would be to advise anyone with ongoing clinical manifestations of USN that continuing to drive would be unsafe. If there was a genuine consideration that someone may have recovered sufficiently to return to driving, they would usually be referred for an on road assessment. No consistent way of evaluating the manifestations of USN in the context of driving exists (Galski et al., 2000) but deficits would be expected in hazard perception causing collisions (Webster et al., 1989; Webster et al., 1994; Webster et al., 1995; Punt et al., 2008), gap judgement (Punt et al., 2008) and maintaining a consistent heading (Turton et al., 2009).

In the steering task reported in Chapter 5 LVI3 was unable to consistently stay on the road which would cast serious doubts about any return to driving. RVI1 and LVI1 seemed to have problems judging road position relative to the road edges and often failed to adopt the appropriate lane position, and/or exhibited variable steering. LVI2, LVI4 and LHHVI fared somewhat better, and whilst their issues were not as pronounced as they were for LVI1, the results did seem to indicate some problems with judging road positions in some cases (and increased variability for some conditions). Overall no participant with USN managed to maintain all steering parameters within the range of that demonstrated by any control participant.

In the hazard detection task (Chapter 6), the slowest average reaction time for any control was 0.95 secs. Every participant with USN except for LVI4, showed average reaction times for contralesional and ipsilesional targets slower than this. LVI3 and LHHVI missed some pedestrians on the contralesional side altogether. LVI2 correctly identified less than 50% of the pedestrians. LVI1 and RVI1 showed reasonable accuracy at making the correct response, but reaction times averaged well over a second for both of them.

LVI4's average reaction time matched the mean control reaction time and they made the correct response 14/16 times. Slower reaction times were, however, apparent on the non driving reaction time task with peripheral targets requiring a decision response.

Overall these findings would be in line with most clinician's judgement that most people with USN would have significant problems driving safely. The possible exception to this would be LVI4 who performed well in the hazard perception task. This participant is considered in more detail in the next section.

7.2.3 LVI4 – a Case Study

Throughout testing LVI4 seemed to show better performance than the other participants with USN and to exhibit some eye movement behaviours that were not anticipated. This participant was recruited through specialist rehabilitation services and was referred to the project as someone with left spatial neglect causing significant impairment of function. At the time of testing LVI4 was 52 years old and was tested 12 months after their stroke. Modified Barthel score was 68/100 suggesting significant disability. LVI4 scored down on several tests of visuospatial function including being unable to successfully complete the interlocking pentagons task or clock face drawing task (see Chapter 2). Chapter 3 showed that their saccades were somewhat hypometric (averaging around 3 degrees of error for both predictable and unpredictable targets) but smooth pursuit performance was normal.

Surprisingly in the visual search task (Chapter 4), LVI4 made 76.9% of their fixations on the affected side of the screen. Reaction times were slow, but not worse than the slowest control subject and not different for left or right targets. Accuracy for easy targets was 100% on both sides but only 12.5% for difficult targets on both sides. Gaze positions on the steering task were similar to controls, and the gaze patterns generally suggested no problem in directing attention leftwards during this task. The main metric where we observed difficulties for LVI4 was steering variability which was higher in some conditions than controls. During the hazard perception task whilst driving, the reaction times of LVI4 were as fast as the control mean on both sides and accuracy was high on both sides.

During clinical examination and therapy sessions, LVI4 exhibits clinical features of left neglect, with problems noticing visual stimuli on the left and problems with proprioception and movement of the left arm and leg. Yet in some of these tasks, LVI4 appears to be able to override this visuospatial impairment and utilise compensatory gaze strategies, looking into the affected hemifield – and seemingly with a good functional outcome. During therapy sessions LVI4 has been practicing trying to shift attention leftwards and it would seem that LVI4 is able to incorporate these techniques into novel tasks. This is a reassuring finding for those involved in the rehabilitation of people with unilateral spatial neglect, since the expected rehabilitation outcomes for those with USN are fairly limited.

7.3 Conclusions

Overall our experimental findings are broadly in keeping with previous researchers, in that our participants with HVFDs and USN showed a wide variation in performance from individual to individual. Whilst extent of HVFD is important, it does not seem to be the only or even the best predictor of performance in skilled perceptual – motor tasks. The findings in this thesis indicate that accuracy of saccadic eye movements and visual search performance may be useful for predicting driving performance for people with HVFDs though further research would be needed to confirm this. The majority of participants with HVFD exhibited impaired hazard perception compared to controls and the majority of HVFD participants did not complete the simple steering task in the same way as controls – seemingly finding it more difficult to drive close to a road edge in the affected hemifield. It seems, therefore, that problems in perception-action function are common (if not ubiquitous) to people with HVFDs and any formal decision to restore a driving license would need to be taken very carefully. Problems may not be immediately apparent as in the participant who had normal hazard perception reaction times and accuracy of decision response, but failed to detect one pedestrian altogether on the unaffected side.

The thesis contains evidence that compensatory gaze patterns can be observed in people with HVFDs. For example, in Chapter 5 many participants in the steering task adopted different gaze positions to the control group, and some of these individuals also showed a reasonable ability to complete the task according to instructions. In Chapter 4 changes in gaze patterns during visual search were less common, but in 2 participants there was a preference to search for longer in the affected hemifield (though this seemingly improved performance for one participant but not the other).

As predicted the USN group were less able than controls to complete the hazard perception task and steering task. The exception was LVI4 who seemed to be able to voluntarily override their perceptual processing deficit to attend to the affected side, at least for the duration of some of the tasks. It was noticeable that, for this individual, performance on each side was roughly equal, but that performance in steering and visual search was still generally poorer than the control group.

7.4 Suggestions for Future Research

There were a number of methodological problems with this project that have impacted on the interpretation of the data. Firstly we did not use a robust, validated measure, such as the Rivermead Behavioural Inattention Test, to categorise our participants as to whether they had USN or not – although as detailed in Section 2.3, this test was not calibrated for use on people with HVFDs and possible co-existent USN. Instead we relied on a range of slightly ad hoc tests and clinical judgement. We can therefore not be completely sure that our individuals with stroke are categorised correctly – it is possible that some of our HVFD group in fact did have co-existent USN. Secondly our driving tasks were designed that at least 2 outcome measures needed to be used to interpret how the task was being performed – for instance one could trade off speed of reaction for accuracy of correct response in the hazard perception task, or choose not to try to follow the task instructions in the simple bends task and stay away from the road edge on the affected side, in order to improve steering variability. Therefore one of these measures does not give a reliable indication of task performance, and it is difficult to judge one person's performance against another, as the strategy that they used needs to be taken into account. Future projects should be designed to explicitly let the participant know which measure is being collected and allow them to direct their efforts to optimise task performance in this area. In more realistic tasks for instance, numbers of lane marking crossings may work. Finally we opted for a novel visual search task where participants were required to perform size discrimination with harder task conditions generated by having the target closer in size to the distracters. The idea behind the task was to emulate in a static visual field some of the perceptual properties of an approaching obstacle that would loom optically during an approach. The task was successfully piloted on an older adult in the age range of those in the HVFD group, but unfortunately for some participants (i.e. LVI4) the easy targets were found with 100% accuracy whilst performance on the hard task condition was too poor to produce usable data (i.e. accuracy 12.5%). In many cases a parametrically varying measure would be a more useful outcome measure such as the dot counting task used by Zihl et al. (Zihl, 1995b).

There is much still to be learned about steering behaviours for people with HVFDs and USN. Some of the gaze behaviours that we found (i.e. fixating the road edge in the unaffected, ipsilesional, field) may be a limited strategy that works only for this particular task. It may aid visual feedback about road position in this particular steering task, but in the real world, a driver fixating a road edge on the ipsilesional side would not be able to see much of the road ahead as this would be in the hemianopic field. This could potentially create very significant problems with hazard perception or navigating bends and junctions. As detailed in Section 7.1.1, we feel that further detail regarding the steering and hazard perception abilities of people with HVFDs and USN at an operational level could be gained from carefully constructed, highly constrained, simulator based experiments. Designing experiments that test one parameter at a time (i.e. a simple hazard perception whilst driving task as well as a decision response hazard perception whilst driving task) may clarify the exact cognitive processes affected by stroke related visual impairments. Careful experimental manipulations of parameters such as road width or road edge features, or forced gaze fixation on particular parts of a bend may also help to tease apart the mixture of impairment driven steering errors, compensatory processes and steering strategy. Once these issues are a little clearer there would also be a need to discover whether the findings are generalisable to real world driving using less constrained driving tasks designed measuring specific key outcomes identified in the more constrained research.

What is clear is that there is a growing need for useful surrogate markers of driving performance, to identify people who would most benefit from an on road driving assessment (i.e. those who would have the best chance of passing it). There is a growing body of evidence that suggests simply measuring the extent of the visual field defect is inadequate. These tests could also usefully inform the driving assessor of possible potential difficulties faced by individuals in order to help driving assessors to look specifically for the problems which are likely to occur. We would recommend that the search for surrogate markers continue with measurements of saccadic accuracy and some parameters of visual search performance in order to compare these with robust markers of driving performance.

Finally the findings of compensatory eye movement behaviours for some participants in the visual search and driving tasks, raises the possibility of using eye movement training as a rehabilitation tool. Oculomotor training has been shown by several authors to improve visual search times but it is currently unknown whether such improvements would generalise to other tasks such as driving. Demonstrating improvement from visual compensation training in a task such as hazard perception, in a controlled trial, would go a long way to bringing this promising rehabilitation technique into the mainstream.

Appendix 1: The Oxford Community Stroke Project Classification of Stroke

TACS = Total Anterior Circulation Stroke – large cortical stroke in middle or anterior or middle cerebral artery territories. Symptoms are a triad of 1. Unilateral weakness (and/or sensory deficit) of face, arm and leg. 2. Homonymous hemianopia and 3. Higher cerebral dysfunction i.e. dysphasia or unilateral spatial neglect

PACS = Partial Anterior Circulation Stroke – Cortical stroke in middle or anterior cerebral artery territories. Symptoms are of 2 out of 3 of the TACS syndrome or isolated dysphasia or parietal lobe signs.

POCS = Posterior Circulation Syndrome. Symptoms would be one of: 1. Cerebellar or brainstem syndrome, 2. Loss of consciousness or 3. Isolated homonymous hemianopia

LACS = Lacunar syndrome – Subcortical stroke due to small vessel disease. Symptoms are one of: 1. Unilateral weakness (and/or sensory deficit) of at least 2 of face, arm and leg, 2. Pure sensory stroke or 3. Ataxic hemiparesis, all without evidence of higher cerebral dysfunction

Appendix 2: The Modified Barthel Score

Items	Unable to perform	Attempts task but unsafe	Moderate help required	Minimal help required	Fully independent
Personal Hygiene	0	1	3	4	5
Bathing Self	0	1	3	4	5
Feeding	0	2	5	8	10
Toilet	0	2	5	8	10
Stair Climbing	0	2	5	8	10
Dressing	0	2	5	8	10
Bowel Control	0	2	5	8	10
Bladder Control	0	2	5	8	10
Ambulation	0	3	8	12	15
Wheelchair*	0	1	3	4	5
Chair/Bed Transfers	0	3	8	12	15
Range	0				100

* Score only if patient scores 0 for ambulation but patient trained in wheelchair management

Appendix 3: Visual Saccade Performance of Participants with Stroke to Targets on Ipsilesional Side

The following 3 tables show the results of the participants with stroke making a first saccade to a target appearing at a predictable location 15 degrees into their unaffected hemifield (Experiment 3.1), to an unpredictable target appearing 15 degrees into the unaffected hemifield and finally an unpredictable target appearing 7.5 degrees into the unaffected hemifield (Experiment 3.2).

Table 3.57: Performance of participants with stroke on the predictable target simple saccade task for targets appearing in the unaffected hemifield. Lat **= median latency to first saccade (in milliseconds);** Error **= median error of first fixation (in degrees);** Bias **= median distance of first fixation from target with negative numbers showing an Undershoot (U) and positive numbers an Overshoot (O). DH = Direct Hit; M = Miss; NS = No Saccade; NA = Not Counted.**

	Participant	Lat(ms)	Error(deg)	Bias(deg)	DH	U	O	M	NS	NA
HVFD	LHH1	143	2.26	-2.26	3	5	0	0	0	0
HVFD	LHH2	198	0.30	+0.12	8	0	0	0	0	0
HVFD	LHH3	253	1.51	1.51	6	0	2	0	0	0
HVFD	LHH4	188	0.44	-0.44	8	0	0	0	0	0
HVFD	LHH5	315	0.45	-0.45	7	0	0	0	1	0
HVFD	LHH6	239	0.71	-0.71	6	2	0	0	0	0
HVFD	RHH1	129	1.96	-1.14	3	2	1	1	0	1
HVFD	RHH2	247	2.26	-2.26	3	4	0	0	1	0
HVFD	RHH3	224	1.04	-1.04	5	2	0	0	0	1
HVFD	RHH4	277	1.07	-1.07	8	0	0	0	0	0
HVFD	RHH5	238	0.91	-0.91	7	0	0	0	0	1
HVFD	RHH6	201	0.64	-0.38	6	0	0	0	0	2
USN	LHHVI	284	0.98	-0.98	8	0	0	0	0	0
USN	LV1	298	0.68	-0.68	6	1	0	0	0	1
USN	LVI3	148	1.89	-1.89	3	4	0	0	1	0
USN	LVI4	228	0.42	-0.42	7	1	0	0	0	0
USN	RVI1	190	0.53	+0.53	8	0	0	0	0	0

Table 3.58: Results for the unpredictable saccade experiment where targets appeared 15 degrees into the unaffected hemifield. DH = Direct Hit; U = Undershoot; O = Overshoot; M = Miss; NS = No Saccade; NA = Not Counted

	Participant	Lat(ms)	Error(deg)	Bias(deg)	DH	U	O	M	NS	NA
HVFD	LHH1	145	1.68	-1.68	4	4	0	0	0	0
	LHH2	204	0.56	+0.43	8	0	0	0	0	0
	LHH3	264	error							
	LHH4	262	0.87	-0.87	6	2	0	0	0	0
	LHH5	302	0.78	+0.22	7	0	0	1	0	0
	LHH6	359	0.54	-0.21	7	1	0	0	0	0
	RHH1	225	1.22	+0.71	5	2	0	1	0	0
	RHH2	281	1.76	-0.84	3	3	1	0	1	0
	RHH3	211	1.19	-1.19	5	3	0	0	0	0
	RHH4	261	0.81	-0.81	8	0	0	0	0	0
	RHH5	339	1.75	-1.75	3	5	0	0	0	0
	RHH6	207	1.19	-1.19	6	2	0	0	0	0
USN	LHHVI	253	1.42	-1.42	5	3	0	0	0	0
	LV1	356	1.58	-1.58	0	2	0	0	0	6
	LVI3	300	2.12	-2.12	2	4	0	0	0	2
	LVI4	231	0.50	-0.41	8	0	0	0	0	0
	RVI1	194	0.24	+0.03	5	0	0	1	0	1

The calibration for right sided targets for LHH3 failed, giving unusable readings. Light scatter from moisture on the eye during rightward gaze caused the eye tracker to confuse this moisture with true eye tracking.

Table 3.59: Results for the unpredictable saccade experiment where targets appeared 7.5 degrees into the unaffected hemifield. DH = Direct Hit; U = Undershoot; O = Overshoot; M = Miss; NS = No Saccade; NA = Not Counted

	Participant	Lat(ms)	Error(deg)	Bias(deg)	DH	U	O	M	NS	NA
HVFD	LHH1	158	0.86	+0.72	6	0	2	0	0	0
	LHH2	168	0.62	+0.62	8	0	0	0	0	0
	LHH3	244	0.67	+0.40	6	1	1	0	0	0
	LHH4	174	0.49	+0.42	8	0	0	0	0	0
	LHH5	249	0.66	+0.18	8	0	0	0	0	0
	LHH6	237	0.84	-0.74	6	2	0	0	0	0
	RHH1	212	1.34	+1.34	6	0	2	0	0	0
	RHH2	223	0.67	-0.67	6	2	0	0	0	0
	RHH3	202	0.48	+0.34	8	0	0	0	0	0
	RHH4	248	0.43	+0.32	8	0	0	0	0	0
	RHH5	316	0.84	-0.84	7	1	0	0	0	0
	RHH6	199	0.39	-0.39	8	0	0	0	0	0
USN	LHHVI	271	0.82	-0.82	8	0	0	0	0	0
	LV1	161	0.6	-0.6	2	0	0	0	0	6
	LVI3	174	0.82	-0.82	5	2	0	0	0	1
	LVI4	184	0.25	+0.10	8	0	0	0	0	0
	RVI1	178	0.55	+0.31	6	1	0	0	0	1

Lat – median latency to first saccade (in milliseconds)

Error – median error of first fixation (in degrees)

Bias – median distance of first fixation from target – with negative numbers being undershoots and positive numbers being overshoots

Direct Hit (**DH**): First saccade landed within 1.5 degrees of target

Overshoot (**O)** or Undershoot (**U**): First saccade missed target but corrective saccade or saccades then successfully made to fixate target within the 2 seconds allotted for each task

Miss (**M**): Saccade(s) made towards target, but target never fixated (all were undershoots)

No Saccade (**NS**): No saccade of at least 1.5 degrees amplitude made toward target

Not Counted (**NA**): Predictive saccade made, eye tracking failed, saccade made in wrong direction or eye not on central fixation point at start of task

Appendix 4: Control Performance in Visual Search Trials (Experiment 4.1)

Table 4.60: Full visual search results for control participants. Results in blue lie more than 1 standard deviation from the mean

	Reaction Time		% Correct		
Participant	Easy	Hard	Easy	Hard	Total
CONT1	1992	5206	100	66.7	83.3
CONT2	2476	5933	89.6	60.4	75
CONT3	3018	5788	95.8	75	85.4
CONT4	1672	3780	97.9	85.4	91.7
CONT5	2538	4330	87.5	72.9	80.2
CONT6	1902	4472	97.9	85.4	91.7
CONT7	1898	4466	100	66.7	83.3
CONT8	2335	4325	97.9	58.3	78.1
CONT9	1514	3696	77.1	68.8	72.9
CONT10	1522	3977	93.8	75	84.4
CONT11	1580	4863	91.7	66.7	79.2
CONT12	2280	5562	95.8	64.6	80.2
CONT13	2850	4533	79.2	41.7	60.4
CONT14	1766	4200	97.9	87.5	92.7
CONT15	1822	4588	97.9	87.5	92.7
CONT16	1835	3717	100	83.3	91.7
CONT17	2086	4765	100	77.1	88.5
MEAN	2064	4600	94.1	71.9	83.0
MEDIAN	1902	4472	97.9	72.9	83.3
S.D.	439.6	667.8	6.9	11.9	8.3
RANGE	1514-3018	3696-5933	77.1-100	41.7-87.5	60.4-92.7

Table 4.61: Asymmetry of gaze for control group during visual search task.

	Number of Fixations		Total Time Searching	
Participant	Left	Right	Left	Right
CONT1	46.56%	53.44%	44.18%	55.82%
CONT2	52.02%	47.98%	49.87%	50.13%
CONT3	45.56%	54.44%	45.58%	54.42%
CONT4	46.91%	53.09%	47.14%	52.86%
CONT5	47.39%	52.61%	49.61%	50.39%
CONT6	43.59%	56.41%	45.59%	54.41%
CONT7	50.3%	49.7%	50.59%	49.41%
CONT8	45.66%	54.34%	46.5%	53.5%
CONT9	56.01%	43.99%	57.08%	42.92%
CONT10	50.19%	49.81%	48.87%	51.13%
CONT11	49.02%	50.98%	45.88%	54.12%
CONT12	48.06%	51.94%	49.89%	50.11%
CONT13	53.18%	46.82%	53.03%	46.97%
CONT14	50.38%	49.62%	48.83%	51.17%
CONT15	55.76%	44.24%	54.77%	45.23%
CONT16	61.76%	38.24%	60.44%	39.56%
CONT17	53.01%	46.99%	52.81%	47.19%
MAX	61.76%		60.44%	

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