Change blindness as a tool for investigating compensation in hemianopia

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Summary

Hemianopic visual field loss is blindness or reduction in one half of the visual field caused by damage to the visual cortex or visual pathways. Despite these significant impairments, there is evidence that individuals with hemianopia appear to compensate to varying degrees in everyday functional activities such as driving. Using a driving-related task based on the change blindness paradigm, this research investigated compensation in hemianopic field loss. Thirty-one cases with hemianopic and quadrantanopic visual field loss and thirty-one matched controls participated in the study. Of interest was whether individuals with hemianopia could accurately respond to targets across the blind and seeing regions of visual space. The focus here was to describe the characteristics of scanpaths used by individuals with hemianopic field loss, and it was expected that successful performance on the change blindness task would be associated with altered scanpaths, suggesting compensation. In addition, the study investigated the relationship between performance on the change blindness task and cognitive and vision tests commonly used in driving research and assessment. The general approach was to compare the characteristics of individuals with hemianopia who performed well with those who did not; and ultimately to identify the variables that best predicted performance on the change blindness task.

Three key findings emerged. Firstly, it was found that although the cases as a group performed more poorly than controls overall, a subset of the hemianopic group were able to accurately identify changing targets in both their blind and seeing regions. Thus, the capacity to respond to targets in areas with no visual function suggests that this subset of cases were able to compensate well for their visual field defect on this task.

Consistent with previous research, the study found that as a group, the hemianopic cases searched the scenes differently to controls. In general, the search patterns of hemianopic cases was characterised by an increased number of fixations with smaller saccade amplitudes. However, further analysis revealed different patterns of scanpaths amongst the hemianopic cases, not previously reported in the literature. Those who compensated for their field loss (fewer errors) searched the scenes differently to those who did not. Specifically, those who compensated made fewer fixations and had longer saccade amplitudes, closely matching those of the controls; however the spatial scanpaths used to reach the target were markedly different to the controls. In contrast, the cases who performed poorly on the task made more fixations with smaller saccades relative to controls, but searched the scenes using similar spatial paths, suggesting that spatial scanpath is a key mechanism underpinning compensation on this task.

Performance on the change blindness task was best explained by age and selected cognitive assessments, including Trails B and the Motor Free Visual Perception Test (Visual Closure Subtest), whereas measures of visual function, including the extent of field loss, did not predict performance well. These results suggest that age and cognitive function were more predictive of the ability to compensate for visual field loss on the change blindness task than measures of visual function.

This research represents the first attempt to link attentional processing with eye movements and compensation for hemianopic field loss in naturalistic driving scenes. Outcomes of this research provide new evidence describing the characteristics of scanpaths associated with successful compensatory performance in hemianopia. The findings highlight the usefulness of the change blindness task for discriminating those individuals who were able to successfully compensate. Further research is recommended to explore the utility of the driving-related change blindness task as a suitable screening assessment for visual fitness to drive with hemianopic field loss.

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This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other institution.

To the best of my knowledge, the thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Carlyn Muir

Date

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Acronyms

ACRONYM	DEFINITION
CB	Change Blindness
CI	Confidence Interval
CS	Contrast Sensitivity
D2	Concentration Endurance Test (D2 Test of Sustained Attention)
dB	Decibel
FIT	Feature Integration Theory
HFA	Humphrey Field Analyzer
ISI	Inter-Stimulus Interval
LCL	Lower Confidence Limit (interval)
LL	Lower Left
LR	Lower Right
MD	Mean Deviation
MEG	Magnetoencephalography
MMSE	Mini-Mental State Examination
MUARC	Monash University Accident Research Centre
MVPT	Motor-Free Visual Perception Test
MVPT-VCS	Motor-Free Visual Perception Test Visual Closure Subtest
TBI	Traumatic Brain Injury
Trails A	Trail-Making Test Part A
Trails B	Trail-Making Test Part B
UCL	Upper Confidence Limit (interval)
UL	Upper Left
UR	Upper Right
UFOV	Useful Field of View Test
VA	Visual Acuity
VF	Visual Fields
VFL	Visual Field Loss

Glossary of key terms

TERM	DEFINITION
Chiasm	See ‘optic chiasm’
Congruous field loss	Both hemi-fields are symmetrical in all characteristics
Contralateral	On the opposite side of the body
Contralesional	On the opposite side of the lesion
Diplopia	Double vision
Field extent	Angle of visual field available to both eyes while fixating
Fixation	Fixed direction of gaze so an object is held within the fovea
Fovea	Area in the macula that provides the clearest vision
Hemianopia	Loss of one half of the visual fields in each eye
Hemi-neglect	See ‘neglect’
Heteronymous	Affecting both nasal or temporal sides of vision
Homonymous	In the same relative position in each eye
Incongruous field loss	Field loss is asymmetric in one or more characteristics
Lux	Unit of illuminance
Macular sparing	Retained macular function despite adjacent field loss
Macular splitting	No spared area in the macula, the scotoma bisects the fovea
Neglect	Syndrome where contralesional stimuli are ignored
Optic chiasm	Location in the brain where the optic nerves cross
Quadrantanopia	Loss of one quarter of the visual fields in each eye
Post-chiasmal pathway	Pathways in the brain behind the optic chiasm
Saccade	Small rapid movement of the eyes
Scanpath	Pattern of eye-movements
Spatial neglect	See ‘neglect’
Suprathreshold	Stimulus that produces a perceptible physiological effect
Visual field	Total binocular perceptual space available while fixating centrally
Visuo-spatial neglect	See ‘neglect’

Structure of thesis

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Chapter 1 Hemianopia and driving review

1.1 Overview

Road crashes are a serious public health concern world-wide, each year resulting in approximately 1.3 million deaths and injuring between 20 and 50 million individuals (World Health Organization, 2009). A crucial responsibility for licensing authorities is to manage road safety within their own jurisdiction, and a fundamental aspect of this responsibility is to accurately identify drivers with impairments that place them at significant risk of crashes. Older drivers pose a particular challenge; they are the fastest growing sector of the driving population and a high risk age group for serious injury crashes per distance travelled (Langford & Koppel, 2006). The high prevalence of age-related vision impairments contributes to these high crash rates, and thus there is a need for accurate assessments, policies and guidelines regarding the level of vision required for safe driving (Ball & Owsley, 1991).

Although road safety is of primary importance to the community, it is also imperative that the independence and mobility of individuals is maintained. Research has shown that increased levels of depression may be one of the many consequences associated with driving reduction or cessation among older adults (Ragland, Satariano & MacLeod, 2005). Social integration, particularly involving networks of friends, is also negatively affected by driving cessation amongst older adults competent in using alternative forms of transport (Mezuk & Rebok, 2008). Therefore, it is beneficial for a number of reasons to ensure that driver licences are not revoked unnecessarily.

Driving is a complex physical and cognitive task which is carried out in a continually changing environment. It involves a number of components such as perceptual processing, information processing, attention, decision-making, motor programming and execution, and engagement in concurrent tasks (Groeger, 2000). According to the Michon model of driving, skills are required both at the strategic level (e.g. route planning), tactical level (e.g. adjusting speed to driving conditions) and operational level (e.g. maintaining lane position, keeping a safe distance to the car in front, avoiding hazards) (Michon, 1985). Brouwer and colleagues suggest that these processes are linked by a mental schema in a co-ordinated manner and presumably stored in procedural memory. It is assumed that the application of the schemata is triggered by the visual context of the driving situation and is therefore dependent on visual information processing (Brouwer & Withaar, 1997; VanWinsum & Brouwer, 1997).

Furthermore, safe driving is considered to be dependent on the ability to use effective visual strategies to identify critical cues and hazards in the driving environment (Wilkinson, 1999). Thus, it has been suggested that although other sensory modalities are important, visual information provides the most substantial information during the driving task (Brouwer & Withaar, 1997; VanWinsum & Brouwer, 1997). Some researchers have estimated that visual cues provide up to 95% of all sensory input in the driving environment (Shinar & Scheiber, 1991).

Given the importance of visual information, there are several aspects of visual function that are thought to be important for safe driving: *visual acuity*, which refers to the sharpness of vision (Snowden, Thompson & Troscianko, 2006); *contrast sensitivity*, which is the capacity to discriminate between the contrast of an object against its background (Faye, 2005); and the *visual fields,* which can be defined as that portion in space in which objects are visible at the same moment during steady fixation of the gaze in one direction, with the binocular visual field being the sum total of perceptual spaces available to both eyes when open and fixating centrally (Eyesight Working Group, 2005).

Hemianopia and quadrantanopia are visual field defects that occur as a result of damage to the visual areas of the brain at the optic chiasm (the junction in the brain where half the fibres from each eye cross to the other side) or along the post-chiasmal pathways. Thus, hemianopic visual field loss is neurological rather than ocular in nature and occurs in both eyes simultaneously (Luu, Lee, Daly & Chen, 2010). When the lesion is at the chiasm, the resulting field loss is heteronymous, where the location of field loss is in the opposite side of the field in each eye. Lesions more commonly affect the post-chiasmal pathways, and the resulting field loss is homonymous, being in the same relative position in visual space for each eye. The extent of visual impairment resulting from lesions along the visual pathways can range from loss of vision in one quadrant of each eye (quadrantanopia) to loss of vision in one half, or hemi-field, of each eye (hemianopia) (Luu et al., 2010).

Hemianopic field loss can result from a range of neurological diseases or injuries. The most common presentation occurs following a cerebrovascular accident (CVA; stroke), with other causes including traumatic brain injuries, tumours and neurosurgery (Zhang, Kedar, Lynn, Newman & Biousse, 2006). Field Loss ranging in severity/extent has been reported in up to fifty percent of cases with trauma or stroke (Henriksson, Raninen, Nasanen, Hyvarinen & Vanni, 2007; Jones & Shinton, 2006; MacDiarmid, Rowe & Parsons, 2007; MacIntosh, 2003; Mueller, Mast & Sabel, 2007; Pambakian & Kennard, 1997; Pelat, Dubin & Whitney, 2007; Rowe et al., 2009; Sahrie et al., 2003; Zhang et al., 2006). Although spontaneous recovery occurs in some cases, this is less likely if the underlying deficit is vascular in origin, with less than ten percent of individuals recovering full field. Where recovery does occur, it is typically seen within the first three to six months post-injury (Pambakian & Kennard, 1997). When hemianopic loss is the result of trauma, some recovery of the visual fields is much more likely (Pambakian & Kennard, 1997).

The prevalence of hemianopic field loss has not been clearly established, although it is known to increase with advancing age, possibly because of the higher frequency of stroke in older age groups. A population based study of all ages reported a 0.5

percent prevalence rate of hemianopia (Taylor, Livingston, Stanislavsky & McCarty, 1997), and similarly a prevalence of 0.8 percent has been reported in community-dwelling adults aged 49 years and over (Gilhotra, Mitchell, Healey, Cumming & Currie, 2002). In the community-dwelling older adults, prevalence rose with increasing age from 0.4% in those aged less than 60 years to 1.1% in those aged over 70 years (Gilhotra et al., 2002). Furthermore, in this sample just over 8% of those with a history of stroke reported homonymous field loss, and 52% of those with homonymous field defects reported a history of stroke.

Currently, persons with hemianopic visual field loss are precluded from holding a driving licence in many jurisdictions around the world, regardless of the cause or prognosis (International Council of Ophthalmology, 2007). It is not clear how many individuals with hemianopia are active drivers, however, evidence from Gilhotra and colleagues suggests that as many as 48 percent of those who reported hemianopia continued to drive (although these were primarily incomplete homonymous quadrantanopias), and only 28 percent stopped driving as a result of their field loss (Gilhotra et al., 2002). These findings suggest that guidelines for visual field loss and driving may not be applied or interpreted in a uniform way by driver licensing authorities. It is crucial therefore, that evidence-based policies and clear guidelines regarding driving with hemianopic field loss are in place to ensure the safety of those with hemianopia and that of others on the roads. While vision is clearly fundamental to driving, the impact of hemianopic visual field loss on driving is less clear and is likely to be subject to a wide range of complex interacting factors.

1.2 Visual fields and fitness-to-drive

A review of international licensing guidelines shows a lack of consistency in the specific visual field criteria for safe driving (Charlton et al., 2009). Peripheral vision is likely to be important during certain common driving manoeuvres, such as merging, changing lanes and detecting roadside hazards (Austroads, 2006), however, the research is inconclusive regarding what constitutes a 'safe' minimum visual field extent.

There have been few studies that have considered the relationship between visual fields and road crashes, and none could be found that specifically considered hemianopic field loss and crashes. One review of visual fields and driving suggested that visual field restriction slightly increased the relative risk of crashes (VanRijn, 2005); however, Ball and colleagues failed to find a significant association between visual field defects and crash rates (Ball, Owsley, Sloane, Roenker & Bruni, 1993). Apart from the contradictory nature of the results, interpretation of these studies in the context of hemianopia is difficult given the wide range of aetiologies investigated: only a very limited number of the participants included in these studies had hemianopic field loss. Moreover, the neurological nature of the field defects in hemianopia adds complexity to the issue. When visual field loss is ocular in origin, it is less likely that there will be compounding cognitive, attentional or physical impairments to consider when determining fitness to drive.

1.3 Current licensing guidelines

Currently, international licensing guidelines vary widely regarding recommendations for minimum acceptable visual fields for safe driving. Many jurisdictions around the world categorically preclude individuals with hemianopic field defects from holding a licence, and others allow restricted licensing and/or the use of medical review process to determine eligibility on an individual basis. A summary of selected international guidelines are presented in Table 1.

The European Commission states that visual fields should be a minimum of 120° horizontally with no diplopia, however, in practice there is wide variation across European countries (DeLaey & Colenbrander, 2006). Some jurisdictions require visual field testing to be binocular, whereas others define field extent monocularly (for example, Sweden), and the European guidelines do not stipulate the method of measuring the visual fields (DeLaey & Colenbrander, 2006).

Legislation in the US varies widely across states, with only 31 jurisdictions defining a minimum binocular horizontal field extent, ranging from 90° to 140° where specified, and some states opting for monocular criteria and others binocular. Vertical ranges of visual field extent are stipulated in addition to horizontal ranges in some jurisdictions. Not all states require vision testing at the time of licence renewal, and the validation periods range from two to twelve years, which raises the possibility that a driver could retain a licence for 12 years before reassessment is required (DeLaey & Colenbrander, 2006). Furthermore, there are varied processes for medical and vision assessment and review across jurisdictions.

In Australia, the visual standards for granting an unconditional licence require a binocular visual field with a horizontal extent of at least 120° within 10° above and below the horizontal midline. The presence of hemianopia or quadrantanopia precludes an unconditional driver's licence, and all individuals who report these conditions are referred for ophthalmological assessment (Austroads, 2006). At the discretion of the specialist and licensing authority, a conditional licence may be granted subject to periodic review. Although certain medical and vision health care providers may report a case to the licensing authorities for investigation, the onus generally remains on the individual to report the condition (Austroads, 2006).

Table 1 Selected international licensing guidelines for hemianopia

JURISDICTION	GUIDELINES	ADDITIONAL CRITERIA
Australia (Austroads, 2006)	At least 120° within 10° above and below the midline (binocular).	No unconditional licenses, however unconditional licenses permitted with wide variation across states.
Canada (CCMTA, 2009)	120° along the horizontal meridian and 15° above and below fixation continuously (binocular).	Visual field defects must be fully assessed by optometrist or ophthalmologist.
European Commission (Colenbrander & DeLaey, 2006)	Horizontal field spanning 120° with no diplopia.	Wide variation across countries, with restricted licensing in some countries.
New Zealand (NZ Transport Agency, 2009)	Binocular horizontal field of 140° with no significant pathological defect encroaching within 20° of the point of fixation.	No licenses granted if minimum field extent is not met.
Sweden (SNRA, 1998)	Visual field defects that occur in both eyes are acceptable if the defect is in the periphery of the eye and has limited extent and depth.	The minimum binocular field of vision should be equal to that of one good eye, and licensing authority to be consulted where doubt exists.
United Kingdom (DVLA, 2010)	At least 120° extent using a target equivalent to the white Goldman III4e setting. There should be no significant defect within 20° of fixation above or below the horizontal meridian.	No licenses granted if minimum field extent is not met.
United States (Colenbrander & DeLaey, 2006)	Varies by state - 31 jurisdictions define a minimum binocular horizontal field extent with the minimum extent ranging from 90° to 140°.	In some states, a restricted licence may be issued (speed, area and time of day restrictions) with approval from the Medical Advisory Board.

Few would argue that severe visual field loss, for example those with tunnel vision with a field extent spanning only 20°, would be acceptable for safe driving. However, on the broader question of what constitutes an acceptable minimum standard for safety, there is less agreement. A recent review of vision requirements for driving suggested that the minimum acceptable standard for an unconditional licence should be an unrestricted visual field of 120° in the horizontal meridian and 40° vertically (DeLaey & Colenbrander, 2006). This is conditional upon the field being approximately evenly distributed around fixation and no attentional problems being identified. This report encouraged the use of restricted or conditional licences, for example only driving during daylight hours or within a certain distance from home (DeLaey & Colenbrander, 2006). These standards would, in effect, result in a large number of people with hemianopic field loss being precluded from driving. In addition, these guidelines do not consider the role of individual compensation or adaptation for visual field loss.

1.4 Visual assessments for driving

Although there is wide disparity in the guidelines for determining fitness to drive, the main visual factor involved in determining licensure is visual acuity. The Snellen static visual acuity test, while useful as a clinical tool, has been criticised for not adequately reflecting the vision requirements for driving in complex traffic: it does not evaluate visual function under varying luminance conditions or evaluate the capacity to respond to dynamic objects (DeLaey & Colenbrander, 2006).

Early research examining visual functions, including static visual acuity, demonstrated a weak correlation with crashes, but only for older drivers and thus the authors argued that more explanatory power may be attributable to age-related declines in higher level processing (Burg, 1967). More recent research also reported a weak relationship between static visual acuity and crash risk (Charman, 1997; Owsley & McGwin, 1999; Owsley, Stalvey, Wells & Sloane, 1999). Despite this evidence, there is continued widespread use of visual acuity tests for initial licence assessment, as well as for re-assessment for older drivers.

Where visual field impairment is suspected or identified, visual field extent is usually assessed in addition to visual acuity (Austroads, 2006). Traditionally, visual fields were assessed using kinetic perimetry (such as a Goldmann instrument) where a light stimulus is moved manually by the examiner from the periphery to the central region of the visual field. Generally, these tests have been superseded by automated static perimetry methods, for example, a Humphrey Field Analyzer (HFA). The location, severity and size of the defect in the visual field of each eye can be mapped using these techniques, and the monocular fields can be merged using the highest point of sensitivity for each location to calculate the extent of the binocular field (Esterman, 1982; Eyesight Working Group, 2005; Nelson-Quigg, Cello & Johnson, 2000).

A fundamental issue with the vision tests used to determine eligibility for driving is whether the test actually measures those visual functions that are relevant to the task. *Visual function* describes how the eye and the visual system functions, and involves measures of functional changes at the organ level: it is usually assessed quantitatively, such as in the case of visual acuity or visual fields (Colenbrander, 2003). In contrast, *functional vision* describes how the *person* functions, and involves measures of a person's visual skills and abilities when applied to activities of daily living. Functional vision is usually measured binocularly, and is concerned with suprathreshold performance (Colenbrander, 2001, 2003, 2005; Lueck, 2004; Mayer & Fulton, 2006).

The traditional visual acuity and visual field tests used for driving licensure are measures of visual function, and determine threshold performance in a controlled environment where only a single parameter is varied in any one test (International Council of Ophthalmology, 2007). However, driving is a dynamic and rapidly changing task, and therefore implies use of *functional vision.* A recent report by the

International Council of Ophthalmology noted that tests of functional vision must determine sustainable performance in a real-life environment, where multiple uncontrolled parameters may vary simultaneously and in unpredictable combinations (International Council of Ophthalmology, 2007). Instead of standard tests of visual function, the Council suggests a combination of assessments that tap into multiple domains and measure both visual (e.g. visual fields) and non-visual (e.g. cognitive) parameters in conjunction with an on-road test.

1.5 Visual fields and driving research

When considering the research on visual fields and driving performance, it is important to acknowledge differences in the types of assessment and definitions of field loss. Few studies provide information on the type of visual field impairment, or how the field loss is measured (i.e. Goldmann or HFA). Furthermore, few studies specifically include participants with hemianopic or quadrantanopic field loss, which would arguably present a unique set of challenges. Thus, it is difficult to interpret the research findings in the context of multiple field impairments with different aetiologies and clinical manifestations. It is also difficult to compare results from simulated visual field impairments (using optical devices) with those impairments resulting from true field loss.

Experimental studies on visual fields and driving performance are typically conducted in either driving simulators or on-road vehicles. Simulator studies provide a safe and controlled environment to assess performance, and the laboratory setting allows standardised and replicable conditions which are important factors in research. Further, in jurisdictions where individuals with hemianopia are not permitted to drive, simulator studies offer an ethical and legal alternative to on-road assessments. However, there have been few studies investigating the validity of simulators for on-road driving, and simulators have also been criticised for their lack of predictive validity thus making it difficult to draw conclusions regarding their efficacy and applicability to on-road driving performance (Schultheis, DeLuca & Chute, 2009).

In contrast, on-road driving assessments are arguably more valid for assessing driving performance; however, varying traffic and weather conditions can make it difficult to define a standardised and replicable driving route. Some of these issues could be circumvented with the use of a closed road track, although these too have limitations such as the lack of other vehicles and predictability. No studies were found specifically investigating hemianopia and driving on a closed road track.

1.5.1 Driving simulator studies

1.5.1.1 Simulator studies of visual field loss

Several studies have found impaired performance on aspects of simulated driving in individuals with visual field loss; specifically, difficulties with steering stability and increased lane boundary crossings. For example, Coeckelbergh and colleagues assessed 50 drivers with moderate peripheral field loss in a driving simulator, and found that drivers with a horizontal field diameter of 85° (±35°) had greater deviations in lateral position on the road and made more lane boundary crossings than drivers with paracentral or mid-peripheral visual deficits (Coeckelbergh, Brouwer, Cornelissen, Wolffelaar & Koojiman, 2002). In this same study, those with mild to moderate field loss (horizontal diameter 130° ± 21°) did not demonstrate any significant differences in driving performance compared with age-matched controls.

In contrast, Lövsund and colleagues examined the performance of 31 drivers with visual field defects of different sizes and locations compared with 20 normally sighted controls (Lovsund, Hedin & Tornros, 1991). In this study, all participants demonstrated good skills for maintaining speed and lane position during a simulated driving task. Apparent discrepancies between these findings and those of

Coeckelberg and colleagues may reflect differences in the extent of visual field impairment; the severity of impairment was not reported in Lövsund's study, and participants had a range of ocular pathologies. Lövsund also found that some drivers with field defects had large increases in reaction times to stimuli presented in areas of visual field loss. However, four participants with field defects did not display these increased reaction times, which the authors interpreted as an ability to compensate for deficiencies in the visual field. Furthermore, the best driving performances (shortest brake reaction times) were observed in participants who had an 'active' visual search pattern; characterised by scanning stimuli presented in the blind area at very short time intervals (measured by distribution of fixations in the horizontal plane) (Lovsund et al., 1991). In a small follow-up study, Lövsund found that the driver who showed the best ability to compensate for their field defect employed more frequent visual fixations on the affected side of the visual field than the non-compensating driver with similar field restriction (Lovsund et al., 1991). However, the degree to which this compensatory behaviour ameliorates crash risk is unclear, and further research is needed to elucidate the relationship between eye-scanning behaviours, compensatory strategies and driving performance.

Thus, the results from the driving simulator studies generally indicate that the most common driving errors observed in people with visual field loss (all types, including but not restricted, to hemianopic field loss) were lack of steering stability, increased lane boundary crossings, and increased reaction times to stimuli presented in blind fields.

1.5.1.2 Simulator studies of hemianopia

There have been few simulator studies that have specifically assessed driving performance in hemianopic field loss. The impact of hemianopia on simulated driving performance has generated conflicting results: some studies report more lane boundary crossings and increases in lateral deviation compared with non-impaired controls, whereas others have found no differences. In a small scale study of drivers with hemianopia (n=6), Szlyk and colleagues reported more lane boundary crossings and increased lateral deviation in the hemianopic group compared with controls (Szlyk, Brigell & Seiple, 1993). In contrast, Schulte and colleagues studied nine people with hemianopia and found no differences in lane boundary crossings or steering stability between the control and hemianopic groups (Schulte, Strasburger, Muller-Oehring, Kasten & Sabel, 1999). Similarly, Peli and colleagues tested 12 people with complete homonymous hemianopia and found no increase in time spent out of lane compared with controls (Peli, Bowers, Mandel & Goldstein, 2008). However, some evidence of increased lane deviation was found in the hemianopic group, who adopted a lane position with a bias away from the blind side. These effects differed between individuals and were more pronounced in right-sided field loss than left-sided (Peli et al., 2008). It is difficult to evaluate the role of field loss and other potential factors in explaining the more pronounced differences in steering stability and lane boundary crossings observed in Szlyk's study given that half of the drivers had co-morbid conditions affecting attention (neglect). In addition the small sample sizes and the wide variation in performance within the groups in these studies make generalisations regarding lane boundary crossings and lateral deviation difficult.

The detection of peripheral objects during simulated driving has also been studied in the context of hemianopia. In a recent study, Bowers asked twelve individuals with complete homonymous hemianopia and twelve controls to respond to pedestrian targets at small (4°) or large (14°) eccentricities in a range of traffic situations. The results suggested that hemianopic drivers had more difficulty detecting targets in the periphery, their detection rates were worse on the blind side, and they failed to scan the blind side at ten percent of intersections (Bowers, Mandel, Goldstein & Peli, 2007, 2008, 2009).

Interestingly, not all of the evidence for simulated driving performance in hemianopic field loss demonstrates impairment. For example, Schulte and colleagues studied nine individuals with cerebral visual defects, and failed to find any differences between the hemianopic and control groups on any of the parameters investigated, including speed, reaction times to hazardous and unexpected events, and driving errors (Schulte et al., 1999). The authors concluded that some individuals with visual field defects, including those with homonymous hemianopia, may perform as well as normally sighted individuals on simulated driving scenarios. This is supported Bowers and colleagues, who suggested that some individuals compensate for their field loss, and that head movements play an important role in compensation (Bowers et al., 2009). In this study, lower target detection rates at intersections were associated with lower failure-to-scan rates and greater numbers of scans to the blind side. However, it is important to note that the relationship between head movements and compensation for field loss has not been adequately described in the literature.

Some studies have also raised the possibility that driving limitations in hemianopia may be more severe with increasing age. Szlyk and colleagues compared a group of six people with hemianopia (mean age 71 years; range, 53-80 years) to a group of normally sighted older drivers (mean age 70 years) and a group of younger drivers (mean age 39 years). The hemianopic group performed at a similar level to the older adults, and *both* of these groups performed worse than the younger drivers on a range of simulator indices, but were not significantly differently from one another (Szlyk et al., 1993). This highlights the possibility that some people with hemianopia do not display impairment on simulated driving tasks beyond those seen in older drivers. Findings from Bowers' study support this contention, showing lower target detection rates associated with advancing age (Bowers et al., 2007). These studies suggest that it is not necessarily the visual field defect that results in functional impairment; rather it may be a combination of factors that leads to an individual with hemianopia being considered unsafe. However, these studies were all based on very small sample sizes, making interpretation difficult given the very heterogeneous nature of performance in hemianopia. In some instances there were cognitive and attentional impairments present (particularly neglect) that could influence task performance. Furthermore, the validity of simulated driving and its applicability to real-world driving performance remains subject to debate.

1.5.2 On-road driving assessments

1.5.2.1 On-road studies of visual field loss

The most direct way of studying driving performance with visual field loss is through an on-road driving assessment. However, few studies have employed this method due to the inherent legal and ethical issues associated with licensing in visual field impairment.

Bowers and colleagues assessed 28 drivers with restricted peripheral fields (M=123°±20°) while completing an on-road driving course. The results suggested that more restricted binocular horizontal, vertical and total field extents were associated with poorer outcomes on a range of driving measures, including speed matching, path-keeping, lane positioning and maintaining appropriate following distances during curve taking (Bowers, Peli, Elgin, McGwin & Owsley, 2005). Overall, this study suggests that mild to moderate peripheral visual field restrictions were associated with poorer driving skills during manoeuvres where wide fields of vision were likely to be important (Bowers et al., 2005). Interestingly, although reduced speed was highlighted as a negative aspect in Bowers' research, in a separate study of 50 drivers with visual field loss, official driving examiners considered reduced speed (in association with increased scanning) to be an effective compensatory strategy for central and peripheral visual field defects (Coeckelbergh, Cornelissen, Brouwer & Koojiman, 2002).

Haymes and colleagues assessed the on-road driving performance of 20 drivers with visual field loss (glaucoma) compared with controls (Haymes, LeBlanc, Nicolela, Chiasson & Chauhan, 2008). This study found no significant differences between the glaucoma and control groups for total satisfactory driving manoeuvres, driving skills, or overall driving rating. However, the drivers with glaucoma had more at-fault critical interventions (60% of the sample) compared with controls, most often related to failure to detect and yield to pedestrians. These findings suggest that despite being able to perform many driving manoeuvres safely, the glaucoma group had difficulty with the detection of peripheral objects and hazards (Haymes et al., 2008).

A slightly different approach to studying visual field loss and driving involves the use of artificial restrictions of visual fields in drivers completing an on-road driving circuit. One such set of studies investigated closed-road driving performance with severe and moderate simulations of restricted peripheral fields (Wood & Troutbeck, 1992). The results indicated that severe impairment (20° to 40° horizontally) compromised aspects of driving performance, such as identifying road signs and vehicles in the periphery, avoiding obstacles, and reversing. However, speed estimation and stopping distance (in response to an object being thrown across the road) were not affected (Wood & Troutbeck, 1992). When the simulated field loss was moderate (90° horizontally), peripheral awareness was the only measure that was affected. These studies provided some interesting observations about the extent of visual field loss and the level at which this may start to affect driving performance. However, simulating peripheral field loss does not allow for the effects of adaptation or compensation, which may develop over longer periods of time than would be available to normal sighted participants under these experimental conditions. It is also difficult to simulate field loss well because in real field loss the defect moves with eye movements, which is not necessarily the case for goggle mounted simulations.

1.5.2.2 On-road studies of hemianopia

On-road driving performance in hemianopia has been assessed in several ways. One approach used a retrospective review of clinical notes for 20 drivers with hemianopic field loss (Racette & Casson, 2005). Driving test performance was rated as safe or unsafe based on the notes taken by specialist Occupational Therapists during on-road assessment. All of the drivers with quadrantanopia and a subset of the drivers with hemianopia were rated as safe using this method. The authors also reported that localised visual field loss in the left hemi-field and diffuse loss in the right hemi-field were associated with impaired driving performance. The study provided some degree of support for the notion that some hemianopic drivers may be fit to drive. However, the authors acknowledged that the study was limited by the lack of a standardised driving route, variations in assessors and assessment methods, and no control group of drivers with normal vision for comparison (Racette & Casson, 2005).

Two studies have been reported in the literature that more directly assess the impact of hemianopic field loss on driving performance. Tant and colleagues tested the on-road performance of 28 individuals with homonymous hemianopia using a qualified driving examiner (Tant, Brouwer, Cornelissen & Koojiman, 2002). The results showed that a small proportion of the hemianopic group (14%) passed the on-road test, with poor steering stability the most frequently reported driving problem. A limitation of this study was that the driving assessor was not masked to clinical condition, creating a potential bias given that there is a strong stereotype that individuals with hemianopia are not safe to drive (Wood et al., 2009).

Wood and colleagues (2009) investigated the on-road driving performance of 30 individuals with hemianopic field loss (22 with hemianopia and 8 with quadrantanopia) compared with 30 age-matched controls. This study used assessors that were masked to clinical condition, and found that a proportion of the hemianopic drivers passed the on-road evaluation (Wood et al., 2009). In fact, in this study 73% of the hemianopic group and 88% of the quadrantanopic group were rated as safe, and where driving performance was considered unsafe, difficulties were seen in maintaining lane position, steering stability and gap judgement relative to controls (Wood et al., 2009).

It is important to note that both of these studies represent (different) subsets of the hemianopic population as a whole: Tant specifically recruited individuals whose driving was suspected to be unsafe; Wood recruited people who were currently driving; and both studies excluded people with additional neglect. These factors likely explain the wide variation in the number of passed/failed driving assessments across the two studies. Nevertheless, on the basis of the collective findings from these two studies, the authors concluded some drivers with hemianopic and quadrantanopic field defects possessed driving skills that were indistinguishable from those of drivers with normal visual fields, and suggested that the presence of hemianopia should not be an absolute contra-indication for driving (Tant et al., 2002; Wood et al., 2009).

Overall, the studies investigating on-road performance in people with hemianopia have found some evidence of driving impairment compared with healthy controls. The most frequently observed problems are lack of steering stability and maintaining lane position, which interestingly are the same issues that have been observed in simulator studies. However, it is not known how these specific issues translate to crash risk, or more broadly to road safety in general. The research also suggests that although extent of field loss appears to be related to driving performance, large individual differences in performance indicate that aspects such as visual processing speed, executive function and other measures of visual function should be considered in addition to individualised on-road assessments for those with visual field defects (Racette & Casson, 2005; Wood et al., 2009). Furthermore, an important finding reported in several studies is that a proportion of people with hemianopia do not display impairment during on-road driving tasks. A summary of the key findings from the research investigating hemianopia and driving is presented in Table 2.

Table 2 Key findings from hemianopia and driving studies

AUTHORS	METHOD	KEY STUDY CHARACTERISTICS	KEY RESULTS
Bowers et al. (2008, 2009)	**Driving simulator** 12 homonymous hemianopia 12 matched controls	Simulated drive with pedestrian targets and small or large eccentricities.	Detection worse on blind side. Cases had more difficulty with peripheral targets. Higher detections at intersections associated with more scans to the blind side.
Peli et al. (2008)	**Driving simulator** 12 homonymous hemianopia 12 matched controls	Two simulated drives. City and rural scenarios, varied traffic conditions.	Cases adopted a lane position biased away from the blind side. Cases did not spend more time out of lane than controls.
Racette et al. (2005)	**On-road driving** 20 hemianopia/ quadrantanopia	Retrospective medical chart review. Occupational therapists assessed performance (recorded as safe, unsafe or unknown).	31% of the cases were rated safe. All quadrantanopia rated safe. Localised left hemi-field and diffuse right hemi-field loss associated with impaired performance.
Shulte et al. (1999)	**Driving simulator** 9 hemianopia 9 controls	One simulated drive at 100 km/h with suddenly appearing object (deer) and unexpected events.	No differences between the groups in any of the driving parameters investigated (speed, lane position, reaction times).
Szlyk et al. (1993)	**Driving simulator** 6 hemianopia 6 matched controls 6 younger drivers	One simulated drive with 6 hazards (1 passing car, 3 intersections, 1 merge and 1 unexpected hazard (cow).	More lateral deviation and lane boundary crossings in cases. Cases similar to older adults and worse than younger adults. Worse performance with neglect.
Tant et al. (2002)	**On-road driving** 28 homonymous hemianopia	Formal driving examiner assessment. Rated 55 aspects of driving behaviours.	A small proportion of hemianopes passed (14%). Most reported problem was lack of steering stability.
Wood et al. (1992)	**On-road driving** 4 simulated visual field conditions 9 controls	Driving performance assessed across nine driving domains. Repeated measures for 9 participants.	Constricted fields impaired performance: time to complete, identifying signs, avoiding obstacles and manoeuvring. No effects on speed estimation, stopping distance or time for manoeuvring or reversing.
Wood et al. (2009)	**On-road driving** 22 hemianopia 8 quadrantanopia 30 controls	Driving route with city and interstate segments. Two independent masked evaluators rated driving.	73% hemianopia rated safe. 88% quadrantanopia rated safe. Typical problems included lane position, steering stability and gap judgement.

1.6 Eye movement research

As discussed in the previous section, a consistent observation from studies of hemianopic field loss and driving are the large individual differences in performance among drivers with hemianopia. These differences have been interpreted as reflecting the magnitude of field loss, level of impairment, and the ability to compensate for the field defect. However, compensation is difficult to define and objectively investigate, primarily because it encompasses multiple processes, including visual search strategies, object recognition and visual attention. One commonly used approach to investigate compensation which may have useful applications for driving research is the study of head and eye movement patterns.

Differences in the visual scanpaths of people with hemianopia were first demonstrated in laboratory based studies where it was found that 'hemianopic scanpaths' were characterised by small-amplitude 'staircase' saccades toward the blind hemi-field, along with frequent repetitions of scanpaths during visual search and inspection (Pambakian et al., 2000; Zihl, 1995). Zihl (1995) reported that 60% of subjects with homonymous hemianopia had impaired visual scanning patterns on dot counting tasks compared to controls, characterised by search times that were almost three times longer than controls and a substantially greater number of fixations. Fixation durations and saccadic amplitudes for the two groups were not different (Zihl, 1995).

Findings relating to hemianopic scanpaths demonstrated in studies using simple patterns have also been extended to naturalistic scenes. Pambakian and colleagues found that people with hemianopia made more fixations with different spatial positions (more widely distributed) and of shorter duration than controls, and they also made more saccades of shorter latencies and amplitudes into the blind regions compared with controls (Pambakian et al., 2000).

In an investigation of the effects of eye movement strategies on driving performance, Coeckelbergh and colleagues (2002) studied people with moderate visual field loss (not hemianopia). In this study, people with peripheral field defects were more impaired than controls on a simple dot counting task; they made more fixations, had longer search times, made more errors and had shorter fixation durations than controls. The same participants were asked to complete a visual search task using a target display with distractors. On this task, it was found that field extent was related to the degree of impairment: decreases in visual field extent resulted in increases in the number of fixation and search times for the target (Coeckelbergh, Cornelissen et al., 2002). It was interesting to note that none of the eye movement parameters from the dot counting task were significantly related to viewing behaviour while performing an on-road driving test (fixations, saccades and scanning patterns). Total search time and number of errors on the dot counting task were significantly related to the on-road assessment score, although neither of these improved the ability to detect at-risk drivers. This study suggests that the use of eye movement parameters to predict viewing behaviour in a complex task such as driving may be limited (Coeckelbergh, Cornelissen et al., 2002). It also highlights the important differences in the role of vision in artificial laboratory experiments and real-world driving conditions.

Thus, although hemianopic scanpaths have been described in the literature as a measure of compensation for field loss, it remains unclear as to whether this strategy actually has functional benefits in a driving context. It appears that hemianopic scanpaths vary, and are employed to different degrees among individuals. Identifying whether these scanpaths actually correspond to higher-order aspects of vision, such as attentional processing, would provide evidence for the underlying mechanisms and indicate whether they represent an aspect of compensation.

1.7 Rehabilitation and assistive technologies

Several rehabilitative techniques designed to improve functional visual fields in low vision have emerged over the last few years. These have been comprehensively reviewed elsewhere (Schofield & Leff, 2009; Strong, Jutai, Russell-Minda & Evans, 2008). An overview of the techniques relevant to hemianopic field loss is provided here. These rehabilitative techniques fall broadly into three groups: optical solutions, in which the damaged visual field is brought into view by the use of optical devices; eye movement-based therapies, which involves training individuals to more effectively search the blind areas; and visual field restitution therapies, where attempts are made to improve vision in the damaged field (Schofield & Leff, 2009).

Optical devices have been used to bring the damaged visual field into view, with the most common example in hemianopia being prisms. In a study by Szlyk and colleagues, the use of prisms was examined for effectiveness in improving driving performance in 10 drivers with homonymous hemianopia (Szlyk, Seiple, Stelmak & McMahon, 2005). Following training in prism use, the average improvement across a range of visual skills categories after 6 months of using the prisms was twenty percent, with overall improvement in all visual skill categories observed at two years follow-up. However, the authors note that conclusions about the safety of driving with prisms cannot be drawn until there is evidence available from effective rehabilitation programs and longitudinal studies of driving performance with and without optical devices (Szlyk et al., 2005).

Eye movement based therapies aim to improve visual performance by training more effective searches in the blind areas. The therapies employ one of two eye movement strategies: either improving voluntary saccades; or training predictive saccades based on smooth pursuit of a target that disappears and then reappears in the blind region (Jacquin-Courtois, Bays, Leff & Husain, 2008). A review of rehabilitative techniques in hemianopia concluded that visual search therapy appears to have a modest effect for a relatively small amount of training time (Schofield & Leff, 2009). However, most visual field improvements from training tend to be transient and task specific for those strategies employed during training, and not all researchers agree that these benefits translate to functional tasks of daily living. Furthermore, eye movement therapies have typically been studied in the context of reading, and applicability to the driving task has not been well demonstrated.

Visual field restitution therapies aim to improve vision in the damaged field. The technique brings stimuli from the damaged visual field into the intact visual field for processing (Schofield & Leff, 2009). Some studies have demonstrated benefits in people with brain injuries, increasing the visual field by around five degrees (Mueller, Poggel, Kenkel, Kasten & Sabel, 2003). Importantly, the mechanisms underpinning the improvements in the visual field have been subject to debate in the literature. Some researchers argue that the improvements are due to therapy-dependant reorganisation at the level of the visual cortex (Schofield & Leff, 2009). Other researchers argue that if fixation is carefully controlled, the benefits of visual restitution training are not evident; this would indicate that the effects are not visual improvements, but rather they are effects from fixation in the blind region (Glisson, 2006). The clinical utility of visual restitution training has also been criticised due to the prohibitive nature of the time required for any demonstrated effects; it takes many hours of practice and exposure to derive any positive results (Schofield & Leff, 2009).

Overall, despite some promising early findings on rehabilitative techniques to improve the visual fields in hemianopia, these techniques are still largely untested with respect to driving performance.

1.8 Conclusions

Driving safety in hemianopia has been investigated through both epidemiological studies of crash risk with visual field defects, and experimental studies directly assessing aspects of driving performance. The research regarding crash risk and visual fields is inconsistent, and there has been no research to date that has specifically examined the relationship between hemianopic field loss and crash risk. The review of evidence presented here has revealed a number of gaps in knowledge the extent to which hemianopia affects driving.

Experimental studies provide evidence that some individuals with hemianopia perform as well as controls on both simulated and on-road driving tasks, although a considerable level of heterogeneity of performance has been reported. Interestingly, in both simulated and on-road driving, the most frequently observed problems in hemianopic drivers are lack of steering stability and maintaining lane position. However, it is not known how these specific issues translate to crash risk, or more broadly to road safety. Eye and head movement research provides useful information about hemianopic visual search patterns. However, it remains unclear whether altered scanpaths can be described as compensatory with functional benefits for the individual, and it is unclear whether all people with hemianopia use these scanning patterns to the same extent.

Several rehabilitative techniques designed to improve functional visual fields in low vision have emerged over the last few years: optical therapies, eye movement-based therapies, and visual field restitution therapies. All three have potential for improving the functional visual field in hemianopia, however there is insufficient evidence at this time, for their use as an effective return to driving measure. Further research is needed to elucidate the relationships between visual field loss, disease aetiology, individual compensation and driving performance.

Chapter 2 Literature review

2.1 Overview

Currently in Australia and many other jurisdictions worldwide, persons with hemianopic or quadrantanopic field loss are precluded from holding an unconditional driving licence. However, the evidence presented in Chapter 1 suggests that there may be a subset of drivers with hemianopic visual field loss who have driving skills that are indistinguishable from controls, and have the capacity to pass on-road driving tests. The heterogeneity of performance on driving tasks (and other functional tasks of everyday living) in people with hemianopia is likely to be due to complex interactions between a number of factors, including age, cognitive status, severity and extent of field loss, and aetiology. A critically important factor is also the extent to which an individual adapts or compensates for their visual field loss. However, there is a significant gap in knowledge regarding compensatory mechanisms in hemianopia, and how these mechanisms might be objectively measured.

In this chapter, the existing evidence regarding functional performance in hemianopia is reviewed in order to develop a framework for studying compensation in hemianopic field loss. Firstly, the fundamental aspects of physiological vision (*visual function*) are discussed. The literature regarding *functional vision* is then presented, including a discussion of the mental processes that transform basic visual elements into meaningful information and the perceptual processes that mediate object recognition and visual attention. Effective visual search is also discussed, both in the context of normal visual fields and hemianopic loss. Finally, the role of age, attention and aetiology in hemianopia is discussed. Based on the research that is presented in this chapter, a framework for studying visual performance and compensation in hemianopia is developed using the change blindness paradigm.

2.2 Visual function and functional vision

In Chapter 1, a brief overview was provided of the two fundamental components of vision: *visual function* and *functional vision* (Colenbrander, 2001, 2003, 2005; International Council of Ophthalmology, 2007; Lueck, 2004; Mayer & Fulton, 2006). Visual functions are quantitatively measured aspects of vision that depend on ocular, refractive and oculo-motor status, and the integrity of the primary visual pathway (Mayer & Fulton, 2006). In contrast, functional vision describes visually mediated performance on tasks required for daily living (e.g. reading, writing, cooking, walking and driving) (Mayer & Fulton, 2006). Essentially, visual functions describe how the *eye* functions, and functional vision describes how the *person* functions (Colenbrander, 2001, 2003, 2005).

The distinction between these two aspects of vision is critical for this thesis. The current standards for determining fitness to drive in Australia, and internationally, tend to focus on visual function. In Australia, for example, those with a horizontal field extent of less than 120 degrees are automatically precluded from holding an unconditional driving licence. However, visual field extent measures how well the *eye* performs, but does not consider how well the *person* functions while engaging in functional tasks such as driving, and thus does not consider the role of adaptation or compensation for visual field loss. This distinction underpins the theoretical framework described in this thesis, which argues that performance on functional tasks requires functional assessment.

2.3 Visual function in hemianopia

Visual field loss can occur from disease or disorders of the eye, optic nerve, visual pathways or cortical regions. When field loss is caused by ocular trauma or damage to the optic nerve, the pattern of visual impairment usually affects the visual field in the affected eye (Evans, 1995). However, when the damage (lesion) to the visual pathways occurs at the chiasm or along the post-chiasmal pathways, as occurs in hemianopia, the impairment characteristically affects the fields in both eyes. This is a result of the way in which visual information is transferred to the brain via the central visual pathway, which extends from the retina to the lateral geniculate nucleus to the primary visual cortex (an area susceptible to strokes and tumours) (Evans, 1995). The nerve fibres in this pathway are arranged in an orderly manner, so lesions at different levels of the pathway cause specific patterns of field loss that are characteristic of that level (Evans, 1995).

The arrangement of the neural pathways involves the nasal portion of each retina crossing over and joining the fibres from the temporal portion of the retina at the optic chiasm contralaterally. These combined fibres form the optic tracts. Synapsing at the thalamus, the fibres continue as optic radiations to terminate in the cortex of the right and left occipital lobes. The consequences of the fibres crossing at the chiasm are that damage to the visual system before the chiasm will affect the visual fields for only the affected eye, whereas damaging the pathway at or after the chiasm will damage only one hemi-field in both eyes. Lesions at a particular site of the visual pathway result in a specific visual field defect (Evans, 1995; Luu et al., 2010). A diagram of the visual fields and neural pathways is presented in Figure 1.

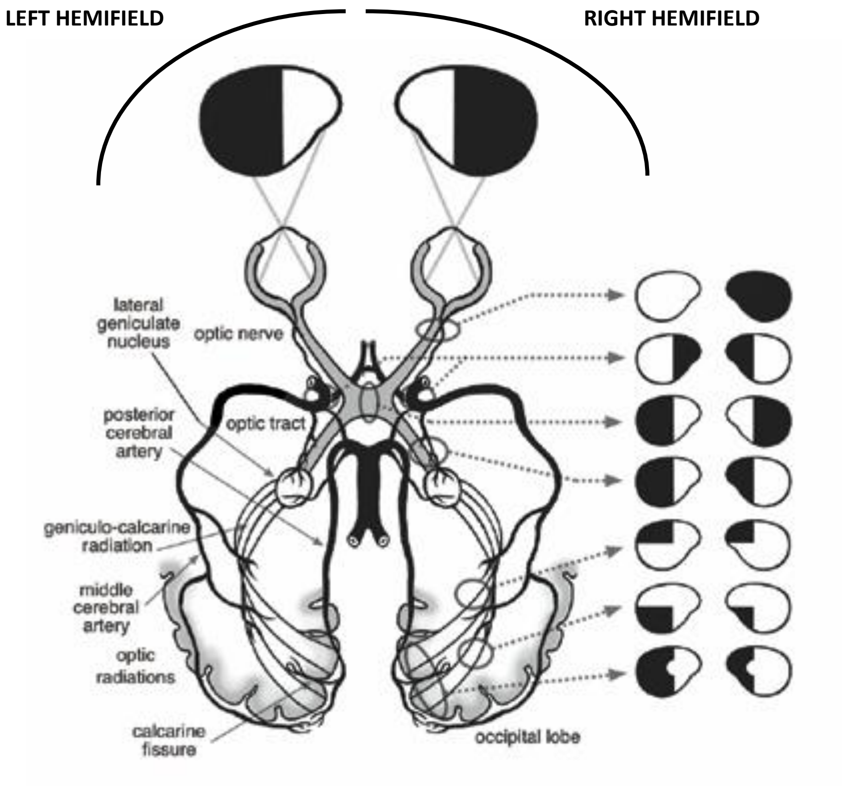


Figure 1 Diagram of the visual fields and neural pathways

Diagram depicting the basic visual fields, adapted from (Luu et al., 2010)

The normal human visual field extends approximately 60° nasally, 90° temporally, and approximately 50° above and 70° below the horizontal meridian. Visual acuity, a measure of the capacity of the visual system to discriminate fine detail, is not uniform throughout the visual field, rather it varies depending on the proximity to the visual axis, the size of the image and the luminance of the stimuli, with acuity highest near fixation and reducing with eccentricity into the periphery (Olver & Cassidy, 2005). Hemianopia results in a restriction of the extent of visual field, however the impairment can range from complete loss of vision in one hemi-field of each eye (hemianopia) to loss of a part of a quadrant with islands of preserved vision (quadrantanopia). The most common lesion sites and associated field defects are summarised in Table 3, and the most common clinical manifestations are discussed below.

Table 3 Common lesion locations and associated field defects

LESION AREA	FIELD DEFECT	DESCRIPTION
Optic chiasm	Bitemporal hemianopia	Loss of vision in temporal half of both eyes
Right optic tract	Contralateral hemianopia	Complete loss of vision in the left hemi-field
Right optic radiation just after lateral geniculate nucleus	Contralateral hemianopia	Complete loss of vision in the left hemi-field
Right visual cortex	Contralateral hemianopia	Complete loss of vision in the left hemi-field
Right optic radiation (specific to Meyer's loop)	Quadrantanopia (left superior)	Loss of vision to upper left quadrant
Lower bank of calcarine sulcus	Quadrantanopia (left superior)	Loss of vision to upper left quadrant
Parietal portion of right optic radiation	Quadrantanopia (left inferior)	Loss of vision to lower left quadrant

2.3.1 Total homonymous hemianopia

Total homonymous hemianopia is characterised by field loss in the same relative space in each eye, occurring on either the left or right side, although always bilateral. Total blindness occurs in the temporal field of one eye and the nasal field in the other. The dividing line is vertical, which may split the fixation point (macular splitting) or pass a few degrees around it (macular sparing) (Olver & Cassidy, 2005). The extent of macular sparing can vary from a very small area of one-half of a degree to a major portion of the affected hemi-field, with margins that range from perfectly semi-circular to extremely irregular (Olver & Cassidy, 2005).

2.3.2 Partial homonymous hemianopia

Partial homonymous hemianopia is by far the most common visual field defect resulting from damage to the post-chiasmal visual pathways. This type of field loss is caused by partial destruction or physiologic interruption of the nerve fibre bundles at any location between the optic tract and occipital pole. Field loss is less than one half of the visual field, and occurs bilaterally, with a dividing line that is usually vertical in either the upper or lower half of the field, and horizontal in the other. Field loss can be congruous, where both hemi-fields are symmetrical in all characteristics (for example size, shape, density), or incongruous, where the loss is asymmetric in one or more characteristics (Olver & Cassidy, 2005).

2.3.3 Binasal and bitemporal hemianopia

Binasal and bitemporal field loss occur in different relative positions in each eye, binasal in the inner portion of each eye and bitemporal in the outer portion of each eye. Bitemporal hemianopia occurs as a result of conditions which commonly damage the mid-optic chiasm, for example pituitary tumours, chiasmal gliomas, meningiomas, sarcoidosis, multiple sclerosis and abscesses (Olver & Cassidy, 2005). Binasal hemianopia is associated with more rare lesions of the eye, or central nervous system (such as congenital hydrocephalus), and both binasal and bitemporal field loss are less common that homonymous field loss (Olver & Cassidy, 2005).

2.3.4 Homonymous quadrantanopia

Homonymous quadrantanopia can be considered a partial form of homonymous hemianopia. Loss is limited to one quadrant of the visual field bilaterally, and may occur superiorly or inferiorly. Presentation of quadrantanopic loss is variable, and can occur as congruous or incongruous loss, with steep or sloping margins (Olver &

Cassidy, 2005). A diagram of the different visual field loss presentations is depicted in Figure 2.

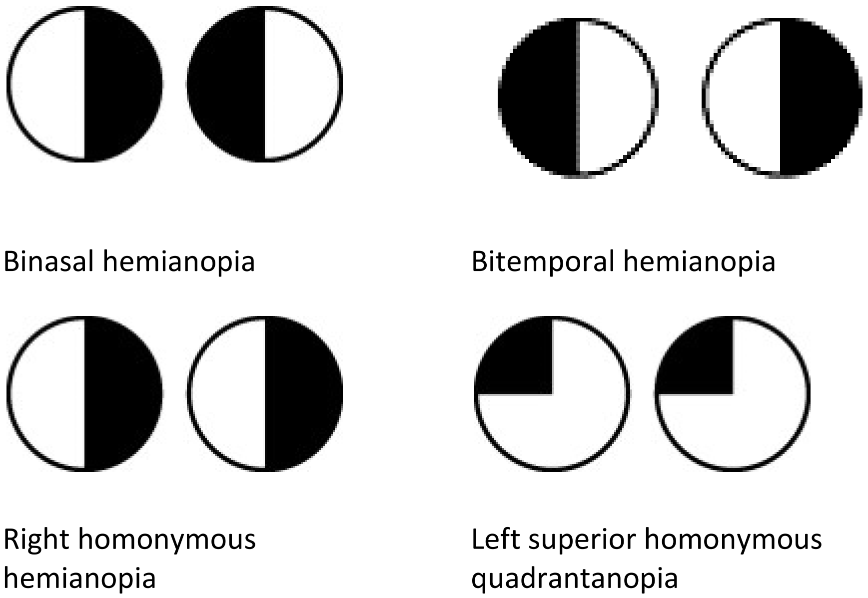


Figure 2 Diagram of visual field loss presentations in hemianopia

Black shading depicts areas of visual field loss. In binasal and bitemporal hemianopia, the field loss occurs in different relative positions in each eye. In homonymous conditions (hemianopia and quadrantanopia), the area of visual field loss is in the same relative space in both eyes (Vision Australia, 2007).

2.3.5 Co-morbidity with hemi-spatial neglect

Hemianopic field loss frequently co-exists with (hemi-spatial) neglect, which describes the phenomenon where stimuli presented on the contralesional side are ignored (Paton, Malhotra & Husain, 2004). Individuals with neglect may also demonstrate 'motor neglect', and fail to use body parts on the opposite side of the lesion (Paton et al., 2004). It is usually associated with right hemisphere lesions, particularly in the occipital, parietal or temporal regions (Zihl, 2003), or associated with focal lesions of the frontal lobe (Paton et al., 2004). Although neglect it is observed with many pathologies, it is most commonly associated with cerebral infarction or haemorrhage, affecting up to two-thirds of right hemisphere stroke survivors (Paton et al., 2004). Unlike hemianopia where spontaneous recovery of visual impairment is fairly low, spontaneous regression of neglect is reasonably common; occurring in around 66% of cases (Zihl, 2000).

There is evidence that neglect has a strong attentional component (Heinke & Humphreys, 2003; Mattingley, Bradshaw, Nettleton & Bradshaw, 1994; Mesulam, 1999). For example, studies have shown that people with neglect display extinction, which is a failure to respond to stimuli presented simultaneously in the blind and seeing fields (Deco & Zihl, 2004). Furthermore, people with neglect often display lateralised spatial defects on tests of representational neglect, such as clock drawing from memory (Paton et al., 2004). Thus, the mechanisms (particularly attentional) underpinning hemianopia and neglect are probably quite different and it is important to differentiate between the effects of visual field loss and the effects of neglect when considering the issue of compensation for a specific field defect.

2.4 Functional vision in hemianopia

Visual field loss is the classic clinical manifestation observed in hemianopia. However, impairment has also been found on a number of aspects of functional vision and activities of daily living. Specific impairments are usually found on more complex everyday tasks, such as reading and writing, shopping, financial management, meal preparation and driving, although some individuals also report significant impairment with fundamental tasks such as personal hygiene and feeding (Warren, 2009). General mobility and navigation problems are increased in this group, which probably represents difficulties with identifying objects on the side of field loss, or more generalised motor problems (Rowe, 2009). Some authors have attributed significant limitations on everyday tasks to difficulties in using environmental cues and (semantic) features to support task performance (Warren, 2009).

However, it is also clear that some individuals with hemianopia do not display impairment on functional or everyday tasks (Gassel & Williams, 1963). Studies reviewed in Chapter 1 identified that a subset of people with hemianopia appear to have relatively unimpaired driving (Racette & Casson, 2005; Schulte et al., 1999; Tant et al., 2002; Wood et al., 2009). There have been a number of explanations proposed for this variation in performance, with the most likely because of a complex interaction between the aetiology of the underlying brain injury, extent of field loss, age, cognitive status of the individual and ability to adapt for the visual field loss. These factors are reviewed in detail later in this Chapter.

Overall, it is clear that although visual function is impaired in people with hemianopia, this does not necessarily translate into impairment of functional vision (or on functional tasks such as driving). In general, the findings from functional tasks suggest that cognitive factors and the ability to use semantic features may influence overall functional ability and performance in hemianopia, rather than the more static measures of visual function.

2.5 Perception, attention and visual search

Functional vision in the psychological literature describes the mental processes that are employed in order to transform basic visual elements into meaningful information. There is an extensive body of literature regarding the processes underpinning functional vision. This review addresses those areas most relevant to the everyday task of driving and is therefore by no means exhaustive. The three elements of critical relevance for this research include visual attention, object recognition and visual search.

Visual perception is a complex activity and requires the integration of multiple processes in order to accurately identify and respond to visual information. Three of the most important factors are: visual attention, which is required to select the object of interest; effective eye movements which allow the eyes to focus on the object of interest; and memory which is required to apply stored knowledge to the stimulus (i.e. object recognition).

These elements are often studied separately, but it is important to consider the combined effects for an overall understanding of visual performance during a task. For example, when considering a driving scenario where a red traffic signal is presented, the driver's attention must be attracted to that location so that the eyes can be directed there for fine-detail visual processing to occur. The application of stored knowledge from memory is also required so that the individual places the red signal in the context of the task and responds appropriately by applying the brakes.

Given the importance of these combined effects, evidence relating to visual attention (divided and selective) will first be reviewed, followed by a discussion on object recognition. In the third section, consideration is given to the role of visual search (which is driven by attention and recognition), including evidence from normal visual search and hemianopic visual search.

2.5.1 Visual attention

In the human visual system, the amount of information transferred from the retina to the brain is estimated at between 10^8 and 10^9 bits per second, which far exceeds the amount the brain is capable of processing and assimilating into conscious experience (Deco, Pollatos & Zihl, 2002). Visual attention has been described as the requirement that the visual system attends to different events in the visual field thus filtering out irrelevant information (Harris & Jenkin, 2001).

Although there have been many theories proposed regarding the exact mechanisms underpinning visual attention, there is general agreement that attention is not singular in capacity, but is a combination of complementary components which are integrated together by multi-modular brain systems (Rosseaux, Fimm & Cantagallo, 2002). Components of visual attention include: sustained attention, referring to the ability to maintain a consistent behavioural response during continuous and repetitive activity; focused attention, referring to the ability to respond discretely to specific visual, auditory or tactile stimuli; alternating attention, or the ability to shift the focus of attention and move between tasks with different cognitive requirements; selective attention, or the capacity to maintain a cognitive set despite distracting stimuli; and divided attention, referring to the ability to respond simultaneously to multiple tasks or demands. The aspects of attention most frequently discussed in relation to visual search, and thus of primary relevance to this research, are selective attention and divided attention.

Divided attention refers to the phenomenon of attending to two stimuli simultaneously and is considered one of the key functions of the central executive system of working memory. Researchers have suggested that tasks requiring divided attention are the rule rather than the exception, with typical examples being note taking whilst on the phone, conversing with a passenger whilst driving or solving a complex problem while walking (Leclercq, 2002). One significant issue with divided attention tasks is that the degree of difficulty of the tasks when performed individually is very different to when performed simultaneously, because this introduces new demands of co-ordination and avoidance of interference (Eysenck & Keane, 2005).

Most divided attention research involves the study of performance on dual tasks. For example, Duncan (1993) found that participants were able to make two simultaneous judgements about one object (what the object was, as well as where it was located) without any deficits in accuracy. However, when asked to make two simultaneous judgements about two different objects, for example where both objects were located, the error rates were very high. This research demonstrates that the perceptual system can perform some divided attention tasks, but when the tasks become too demanding, failures of attention occur (Duncan, 1993).

Divided attention has been shown to be strongly affected by practice, or task familiarity (Matlin, 2002). For example, during two experiments, college students were trained to read stories silently at the same time that they copied down irrelevant words dictated by the experimenter (Hirst, Spelke, Reaves, Cahrack & Neisser, 1980; Spelke, Hirst & Neisser, 1976). When the task was first administered, the students had trouble combining the two tasks; their reading speed decreased substantially and their handwriting was illegible. After six weeks of training, they could read as quickly while taking dictation as when they were only reading, and their handwriting improved. After practising the task over a period of time, the participants did not appear to attend to the dictated words. In fact, they were able to recall only 35 of the several thousand words they had written down. However, with more extensive training they became so accomplished at this divided-attention task that they could even categorise the dictated word (for example by writing ‘fruit’ when they heard the word ‘apple’) without any decline in reading rate. Hirst and colleagues argue that practice apparently alters the limits of attentional capacity (Hirst et al., 1980).

Research has also considered the role of experience or task familiarity on divided attention. One study in the driving context compared novice (or inexperienced) drivers with experienced drivers (Wikman, Nieminen & Summala, 1998). Participants were instructed to drive as they would normally, while performing several routine secondary tasks: changing an audio cassette, dialling a mobile phone and changing the radio station. The experienced drivers completed each task quickly and efficiently, glancing away from the road for less than three seconds for each task. In contrast, the novices divided their attention ineffectively. Specifically, they frequently glanced away from the road for more than three seconds, and lane deviation was noted during these lapses (Wikman et al., 1998).

In an effort to explain all the factors that are thought to influence divided attention, such as task complexity and automation, Hirst proposed a theoretical model (Hirst, 1986). The model incorporates four key aspects to explain the facilitation of simultaneous execution of tasks. The first aspect is integration, which implies the co-ordination of two or more combined tasks in a task of a higher level where the task reorganisation can be at stimulus or response level. The second aspect is automation, where there is a greater impact of practice on consistent mapping than varied mapping. The third aspect is segregation, where the differences between the tasks include all the factors that contribute to their maintained separation on the cognitive and neuronal level. Finally, time-sharing refers to the capacity to conduct several tasks simultaneously by continuously and rapidly shifting attention from one task to another (Hirst, 1986).

Divided attention problems have been observed in a number of tasks in the presence of hemianopia, for example avoiding obstacles, reading, walking and driving. These difficulties have been interpreted as a result of missing parts of the scene because of an incomplete overview of the environment (Pambakian, Mannan, Hodgson & Kennard, 2004; Zihl, 2000). However, the extent to which divided attention is affected in hemianopia is less clear. It would be expected that visually guided visual attention, for example simultaneously fixating a centrally and peripherally located target, would be significantly affected given the unrealistic demands of the task in the presence of field loss. However, whether individuals with hemianopic field loss can compensate for divided attention deficits has not been reported in the literature.

In contrast to divided attention, selective attention has been described as the selective aspect of perception and action, which is limited in capacity and consists of preparation and orientation toward one or several specific perceptual channels, and one or several particular stimuli (Rosseaux et al., 2002). There are several factors that are thought to influence selection: endogenous factors such as relevance and importance to the task and intention of the observer; and exogenous factors, referred to as visual transients, which include fast changes of luminance or colour in the retinal image, arising for example through motion, which represent peripheral cues that may attract attention to their location (Styles, 2005).

Research suggests that observers are unable to ignore cues from visual transients, as attention is automatically allocated to that cue. However, endogenous shifts of orientation are voluntary, and can be overwritten by exogenous cues (Styles, 2005). As an example it is possible to choose to focus on a particular stimulus (a book or computer screen) or engage in a mental task (read the contents), however, an environmental stimuli such as a flashing light or a loud noise will capture attention automatically, overwriting the initial task. To translate this to the driving environment, the driver could choose to focus on a particular stimulus (for example the speedometer) or engage in a mental task (read a street sign), however, an external cue such as a flashing traffic signal may capture attention overwriting the task at hand.

To conceptualise selective attention, most theorists agree that the large amount of perceptual information being passed to the brain at any given time creates a bottleneck, and attention is the process used to modulate this information processing. However, the mechanism by which this processing occurs is subject to debate, and the focus of many theoretical models. The basic theory is considered here, but for a more comprehensive review refer to Harris and Jenkin (Harris & Jenkin, 2001).

Two of the most prominent theories of visual attention, which a have a strong influence on much of the current theoretical research, are the Spotlight of Attention and Feature Integration Theory (FIT). The Spotlight of Attention theory assumes that selective attention has an internal ‘spotlight’ or beam to benefit visual perception. The spotlight illuminates a portion of the field of view where stimuli are processed in more detail and transfers it to a higher level of processing, with information outside the spotlight being filtered out (Posner, Snyder & Davidson, 1980).

Other researchers have suggested that the size of the spotlight can be varied depending on task demands, the analogy being a zoom-lens (Laberge, 1983). Erikson and Yeh demonstrated that the spotlight has a fixed size of about one degree of visual angle, and can't be reduced to focus on one item within a closely packed group. Further research indicated difficulties in attending to different spatial locations at the same time, suggesting that the spotlight could not be split, but could possibly be shifted (Eriksen & Yeh, 1985). Lavie (1995) argued that the perceptual load of a task determines whether attention acts as a spotlight or a zoom-lens. By manipulating experimental task difficulty, her results demonstrated that in high load conditions attention is narrowly focused, whereas when load is reduced, attention is spread more widely with processing of other information in the display. Lavie ascribes a causal role of perceptual load in determining the efficiency of selective visual attention (Lavie, 2006).

Feature Integration Theory (FIT) postulates that different features of visual stimuli, for example colour and orientation, are extracted 'preattentively' and in parallel, without a need for serial analysis of each item in the visual field (Treisman & Kanwisher, 1998). However, serial attention to the location of each item is required to integrate the different features so that appropriate multi-dimensional percepts of objects can be created. These percepts contain objects with features (for example colour and orientation) which have been bound together (Treisman & Kanwisher, 1998). This theory has its basis in earlier work on selective attention which demonstrated that simple physical features are coded preattentively in parallel, and more elaborate coding requires a serial attentive process (Driver, 2001). FIT provides a detailed description of how attention can be used to solve a computational problem by integrating separately extracted features such as colour and orientation. Furthermore, a specific mechanism to solve this computational problem was proposed by FIT, through the selection of particular locations in space one at a time, with the features to be integrated being specified by their common position at their selected location (Driver, 2001).

There is a considerable body of evidence in support of FIT. A typical visual search paradigm involves visual search for a target among displays of varying numbers of distractors (Driver, 2001). Reaction times are measured from the time of target presentation until the participant determines whether or not the target is present. In parallel search tasks, the target subjectively ‘pops out’ of the display, and performance is not significantly affected by the number of distractors (Driver, 2001). This implies that the properties distinguishing the target can be extracted for all stimuli in the display simultaneously. However, during serial search tasks, performance tends to decline with each additional distractor, often in a linear fashion. This pattern of performance suggests that a particular process (postulated as spatial attention) is repeated for every item, which accounts for the increased reaction time required to make a decision about the presence of the target (Driver, 2001).

Research has also focused on the features of the particular targets presented in a display. The original studies by Treisman and Gelade reported that search for targets defined by a unique, salient colour, for example a red target among green distractors, or orientation, for example a vertical target in a display of horizontal distractors, could be performed in parallel (Treisman & Gelade, 1980). However, searches for specific conjunctions of the same orientations and colours (for example a red vertical target in a display of green vertical and red horizontal distractors) where the target is not unique in either colour or orientation produced a less efficient (apparently serial) search (Treisman & Gelade, 1980). This provides evidence that individual features could be extracted preattentively and in parallel, whereas feature integration required serial attention to the location of each item sequentially.

There have been many studies conducted in response to FIT, and as a result the original FIT theory has been modified several times in order to address contrasting patterns of data (Quinlan, 2003). For example, research has shown that FIT does not fit well for the integration of oriented elements which comprise a shape, and some of the sophisticated properties of shapes and surfaces can affect parallel stages of a search (Driver, 2001). Furthermore, the idea of an initial featural processing stage (preattentive operations) followed by a conjunction-processing stage (attentional operations) does not fit well with subsequent research and as a result this idea has been reassessed (Quinlan, 2003). However, the notion of feature integration remains central to current iterations of FIT, and the argument remains that feature binding is a real problem solved by the perceptual system (Quinlan, 2003). Furthermore, many alternative accounts of visual attention have similarities with the fundamental aspects of FIT, such as initially separate coding of different feature domains, and serial selection of the most salient locations during a search (Quinlan, 2003). Although there are specific elements of FIT that have been challenged, it remains a compelling explanation for visual attention.

Although there is still debate regarding the underlying mechanisms for selective attention, it is generally accepted to be an extremely important aspect of visual search and a fundamental component of visual processing. Thus, visual attention is a key aspect of interest for compensatory visual search and processing in hemianopia.

2.5.2 Object recognition

Related to attentional processes, but a fundamentally separate concept is that of object recognition. Object recognition can be described as the identification of a complex array of sensory stimuli; when object recognition occurs, sensory processes transform and organise the raw information provided by sensory receptors for comparison with information in memory storage (Matlin, 2002). Object recognition represents the realisation that a particular visual configuration has been seen previously but the object's name is unfamiliar, or alternatively a label can be applied to the stimuli. The process of matching a set of stimuli with a label stored in memory is referred to as object identification (Matlin, 2002).

Visual stimuli can be either distal (the actual object) or proximal (the information registered on sensory receptors). The identity of the distal stimulus can be discerned even when the image of the proximal stimulus is degraded (for example, when it is partially occluded) (Matlin, 2002). When a new scene is presented, objects in the scene can be recognised in approximately one tenth of a second with assistance from sensory (working) memory. Working memory has been described as a large-capacity storage system that records information from each of the senses with reasonable accuracy. For example, visual working memory allows an image of a visual stimulus to persist for around 200-400 milliseconds after the stimulus is no longer visible (Matlin, 2002). This suggests that object recognition occurs when visual information that is registered on the retina is transferred to the primary visual cortex via the visual pathway, where basic visual processing occurs. This sensory information is then organised and compared with knowledge stored in memory.

The mechanisms by which visual attention and object recognition interact with memory are subject to debate. The most widely accepted theory is centred around iconic memory, or a fleeting memory store that can retain visual information for further processing, perhaps between saccades (Neisser, 1967). The theory is based on research paradigms using rapidly changing lights to present brief visual displays (Sperling, 1960). Typically, observers can accurately report a subset of all items presented, and they report 'seeing' the display for a short time afterwards. The authors interpreted this as evidence of a rapidly fading memory for visual information, and that if this information was not transferred to a more durable store, then it would be lost (Sperling, 1960).

Therefore, visual working memory is considered a transient store of visual information on which selective attention can operate to transfer information to a more durable, reportable form, for example long term memory (Styles, 2005). This longer term storage is important for accessing knowledge about the scene being viewed, especially if responses are required. Object recognition is clearly a critical component for functional task performance, and is required in addition to attentive processes for effective visual perception.

2.5.3 Visual search

To effectively search the visual environment, the eyes must be directed to relevant areas of the visual field using two key eye movement parameters; saccades and fixations. The fovea is the most sensitive part of the retina, and the encoding of richly detailed information occurs when the eyes are still and thus the fovea fixates an object or part of the scene. Saccades represent small eye movements that allow the fovea to focus on one location after another, and when viewing a scene saccades generally occur around three times a second (Styles, 2005). Active scanning is necessary to build an accurate representation of a scene, and the resulting pattern of saccades and fixations is known as a visual scanpath. When an observer is presented with an image to search, the scanpaths tend not to be systematic, but rather concentrate foveal vision on a number of fixation points in a repetitive and idiosyncratic manner (Dempere-Marco, Xiao-Peng, Ellis, Hansell & Guang-Zhong, 2006).

There are a number of factors that are known to affect visual search, including both basic visual features and high level semantic properties of a scene or task. For example, evidence suggests that fixation duration is affected by low level visual factors including contrast and luminance (Liversedge & Findlay, 2000). However, high level semantic properties of a task, such as task complexity or the instructions provided to the observer have also been shown to affect the patterns of fixation

(Rayner, 1998). Furthermore, in driving scenes, driving experience (and thus familiarity with driving scenes) have also been shown to affect eye movements (Crundall & Underwood, 1998; Underwood, Chapman, Berger & Crundall, 2003). Therefore, when engaging in a visual search task, scanpaths depend on a wide range of additional factors, including the complexity of the scene, complexity of the task, familiarity to the observer, and the goal of the observer.

While it is recognised that there are a number of aspects that affect visual search in people with normal vision, several studies have shown that people with hemianopic field loss tend to employ *different* search strategies to those with normal vision. One of the most consistent findings regarding visual search in hemianopia is an unsystematic or stepwise pattern of saccades. For example, an early study by Chedru compared a sample with unilateral focal cerebral lesions (n=115) of which a proportion had hemianopia (n=27 right hemianopia, n=27 left hemianopia) to a group of controls without neurological impairment (n=36) on a visual search task (Chedru, Leblanc & Lhermitte, 1973). This study found that the cases made saccadic movements that were at times curved or oscillating, in contrast to the controls whose searches were more circular. They also had fixation points that were close together indicating that the gaze was progressing in a stepwise manner, longer fixation durations, and short saccadic movements compared to the controls who made long saccadic movements. The authors described these exploratory strategies as unsystematic and irregular, and suggested they were not guided by any definite or precise search strategy (Chedru et al., 1973).

Similarly, Meienberg and colleagues found that cases with hemianopia (n=3, with occipital lesions) used a staircase strategy consisting of a series of stepwise saccadic search movements in order to find targets on a search task (Meienberg, Zangemeister, Rosenberg, Hoyt & Stark, 1981). However, both Chedru and Meinberg's studies were based on search of simple patterns, and given the effects of semantic properties on scanpaths (Rayner, 1998), it is not clear whether search patterns would be different if higher-order semantic elements found in naturalistic scenes were presented.

More recent studies using naturalistic search tasks have provided support for the notion of distinctive hemianopic scanpaths. Pambakian and colleagues compared people with hemianopia (n=8) to age-matched controls and found that the hemianopic group tended to repeat saccades and fixations to the same object resulting in longer and unsystematic scanpaths during searches for targets among a display of distractors (Pambakian et al., 2000). Martin and colleagues also found that during a standardised building (functional) task, the hemianopic group (n=3) tended to fixate on apparently irrelevant locations more often than controls, and were less predictable in terms of the sequential pattern of their fixated locations (Martin, Riley, Kelly, Hayhoe & Huxlin, 2007). In this study, saccades were also found to be longer in both duration and amplitude than those described by Chedru (1973) who used simple pattern searches, highlighting the influence of higher-level semantic features on search parameters.

Differences in search parameters and task performance have also been reported in blind versus seeing regions of visual space. Chedru found that increased search times among the hemianopic participants were most pronounced when targets were presented in the blind side. Furthermore, the cases searched the intact visual field first, using a circular movement (similar to the controls' strategy) before proceeding to the hemianopic field for further search (Chedru et al., 1973).

Gassel and Williams also reported differences in search strategies between the blind and seeing hemi-fields, where the cases made abrupt eye movements to the hemianopic side which were sometimes difficult to control. Some case participants reported that they were unable to prevent these movements while others claimed they were unaware of them, which suggests the potential of reduced oculomotor control among these cases. In addition, a tendency to position the eyes toward the hemianopic side was observed in some cases, and when examined monocularly this tendency was most pronounced on the same side as the lesion (Gassel & Williams, 1963). Gassel also reported that there is a tendency for people with hemianopia (without unilateral neglect) to view the hemianopic side of an image longer, although a different pattern was observed in those who also had neglect. A similar observation was made by Ishiai and colleagues, who found that hemianopic cases (n=10, five left and five right) fixated longer on the blind than the seeing field when undertaking a simple pattern viewing task (Ishiai, Furukawa & Tsukagoshi, 1987).

Zhil also observed differences in oculomotor scanning behaviour in both hemi-fields in a larger sample of people with hemianopia (n=60, none with neglect) on a dot counting task. In this study, the hemianopic group spent considerably more time searching the affected hemi-field compared with the controls where search time was equally balanced across the left and right hemi-fields (Zihl, 1995). These search patterns were most pronounced in the right side ‘pathologic’ hemianopic group (cases who demonstrated large impairments on the task) who spent approximately 70 percent of their time in the affected field. It was proposed that the difficulties encountered during the dot counting task may reflect a more generalised cognitive decline rather than spatial disorganisation (Zihl, 1995). However, it is interesting to note that the time since onset of visual field loss significantly affected visual scanning; participants who were tested soon after the occurrence of the brain lesion were more impaired than those who were tested at a later stage. This is an important finding given that compensatory or adaptive strategies are likely to develop over time. Taken together, these studies raise the possibility that people with hemianopia use different strategies to search the blind (versus seeing) field, at least in the case of simple patterns.

Interestingly, Chedru also found that search patterns differed for participants with right and left sided lesions. In right sided lesions, longer search times in the field ipsilateral to the lesion were found compared to the contralateral field, which is consistent with perceptual impairment being more common in right sided brain damage (Chedru et al., 1973). Cases were also reported to start their search in the left hemi-field slightly more often than the right (55%) (Chedru et al., 1973). No other studies were found that have reported differences in search parameters as a function of side of lesion for comparison.

Other findings have shown differences in visual task performance in hemianopic cases. Chedru and colleagues found group differences in search times to *respond* to targets; the mean search times of those in the brain damaged group were significantly longer than those of the controls, and the participants with hemianopic field loss had the longest search times compared with both the control group and the brain damaged group without field loss (Chedru et al., 1973). Similarly, Zihl found that none of the hemianopic group neglected any targets during a dot counting task, and one-third of the cases performed as well as controls despite the finding that two-thirds of the cases in his study employed a very detailed and time consuming pattern of scanning characterised by a high number of saccades and fixations which appeared to be spatially disorganised (Zihl, 1995). These findings suggest that as a group, hemianopic cases respond more slowly to targets, and that this might be explained by unsystematic searches. However, there is also evidence that this does not necessarily impair task performance.

Not all studies have suggested that the altered scanpaths observed in hemanopia represent ineffective search strategies. For example, Meinberg's study of three hemianopic cases indicated that although saccade patterns of cases and controls differed, the cases adopted one of two search strategies: wait for the target with eyes in the mid-position, making repeated search movements to the blind field; or wait for the target on the blind side where it was expected to appear (Meienberg et al., 1981). These saccadic strategies did not appear deficient, in that saccadic amplitudes were quite accurate when the target position in the blind field could be predicted, and the velocities of saccades were the same towards the blind field as they were to the intact field (Meienberg et al., 1981). The authors interpreted these results to indicate that people with hemianopia employ a consistent set of compensatory strategies to find and fixate objects, and the staircase strategy consisting of a series of stepwise saccadic search movements preferred by the cases could be considered effective, but slow. However, it must be noted that the sample used in this study was extremely small, and the authors did not state whether the participants displayed any neglect or other co-morbidities. Furthermore, at least one of the cases showed spontaneous regression of the visual field defect during the testing period which would be likely to influence search patterns.

Similarly, there was variability in the exploratory strategies observed for the brain damaged cases described by Chedru and colleagues. Generally, the search patterns of the cases were exploratory and showed prolonged search times and a tendency to begin the search on the seeing side. However, some cases mimicked the circular search paths evident in controls (Chedru et al., 1973). Thus, although the authors interpret these exploratory strategies as imprecise and not guided by a definite search strategy, it would appear that at least some of the cases with hemianopia employed strategies that were similar to controls and clearly effective. It should also be noted that a proportion of the sample had neglect and other clinical conditions, making it difficult to tease out the true effects of hemianopia on the eye movement patterns. Another potential confound which limits the interpretation of this study is that time since onset of the condition, for some cases, was less than three months. It is possible that some spontaneous regression of field loss may have occurred during this period (Chedru et al., 1973) and compensatory strategies may not be fully developed.

A slightly different pattern found in the blind side of hemianopic cases was reported by Ishiai and colleagues (1987). The study reported evidence of repetitive eye movements between the centre and edge of patterns presented on the blind side. The authors interpreted this pattern as a compensatory strategy; fixation points of the group with homonymous hemianopia (without neglect) deviated toward the blind side, while in the seeing side of the visual field, fixations showed the same global pattern as observed in controls (Ishiai et al., 1987). Other differences in blind side search were reported by Pambakian and colleagues, who found that hemianopic cases made more saccades of shorter duration and amplitude into their blind region compared with their seeing region, they spent more time fixating in the intact hemi-field, and their saccades were less regular, accurate, and too small to allow rapid, organised scanning. This pattern was associated with omission of objects or relevant parts of a scene in the blind hemi-field (Pambakian & Kennard, 1997).

In contrast, Martin and colleagues did not find any systematic differences in search patterns on a model building task between cases and controls as a function of hemi-field. For example, fixation durations did not differ significantly between the blind and seeing hemi-fields, and there were no consistent differences in saccade amplitude, mean or peak velocity, or saccade duration between the hemi-fields (Martin et al., 2007). This is an interesting observation given that this study was based on a more functional and naturalistic task, and thus a possible explanation for the differences is that cognitive or semantic features may influence the eye movement patterns in hemianopia.

Interestingly, some authors have also found that a subset of hemianopic cases do not appear *functionally impaired* on visual tasks. For example, Gassel and colleagues reported that evidence of visual dysfunction was minimal or absent in almost one third of cases, and most participants lived entirely normal and active lives without functional impairment based on their field loss (Gassel & Williams, 1963). This is an interesting finding given it suggests that there may be individual variation in the functional impact of hemianopic field loss. Similarly, Zhil's study found that 40 percent of the hemianopic group did not have impaired search patterns relative to controls, irrespective of age or degree of macular sparing, and the author suggested that these patterns may be due to individual adaptive and compensatory strategies, in which some engage more successfully than others (Zihl, 1995). Pambakian also provides support for some cases performing as well as controls; two of the hemianopic group (25%) displayed consistently similar fixation patterns to the controls in this study (Pambakian & Kennard, 1997).

A significant challenge in interpreting studies of visual search in hemianopia is the wide range of eye movement measurement methods. Some of the studies reported above used video-based observations of eye movements, and others used oculographic methods or infrared technologies. These technologies measure different aspects of visual search, and the precision varies widely making it difficult to compare individual search parameters. Additionally, several studies included a range of pathologies other than hemianopia, and some included cases with additional neglect which makes it difficult to separate out the effects of field loss. The typically small sample sizes make interpretation challenging; however they are also not unexpected given the difficulty in recruiting such cases.

In summary, the research generally suggests that the quality and patterns of eye movements in hemianopia differ to those of controls, although this is not necessarily indicative of an ineffective search strategy. In addition, there is a suggestion that people with hemianopia may explore the left and right hemi-spaces differently, and the type and location of brain damage sustained can interfere with spatial organisation and integration of visual scanning during searches, which leads to disorganised and time consuming searches. Alternatively, these patterns could reflect individual adaptive and compensatory strategies, which some adopt more successfully than others. However, it is evident that not all hemianopic cases adopt these strategies, and it is not clear whether these altered scanpaths provide any functional benefit in terms of task performance.

2.6 Factors that influence attention

2.6.1 Attention and the visual fields

Selective attention is clearly an important factor in visual perception, and research has also shown that selective attention can have a direct effect on the visual fields. For example, several researchers have documented that visual capabilities are not uniform throughout the visual field: visual performance tends to be better when stimuli are presented in the lower visual field rather than the upper hemi-field. This is probably explained by the higher density of ganglion cells in the superior retina, therefore mediating a bias toward processing objects in the inferior hemi-field (Danckert & Goodale, 2001).

Some studies have also suggested that there are hemi-field differences present beyond the retina, with behavioural studies indicating that there could be differential representation of the visual fields in regions of the brain mediating visuomotor control and visuoperceptual abilities (Danckert & Goodale, 2001). Further, there is evidence of variation in visual field representation in the dorsal and ventral pathways (Danckert & Goodale, 2001). An experimental study engaging participants in a visually guided pointing task in both the upper and lower hemi-fields demonstrated a distinct advantage for the lower visual field. The authors interpreted these results as evidence supporting the theory that the control of skilled, visually guided motor actions are better in the lower hemi-field (Danckert & Goodale, 2001).

However, there have also been studies indicating a preference for the upper hemi-field. These studies have generally involved serial searches, where the distractors are present in both hemi-fields. When reading, visual search tends to scan from left to right and top to bottom, therefore the upper field preference could be attributed to the search strategy employed (Levine & McAnany, 2005). Imaging studies using magnetoencephalography (MEG) with humans have shown larger occipital responses to visual pattern onset presented in the lower visual field rather than the upper fields. However, MEG responses to apparent motion from the extrastriate cortex have shown a directional preference for downward versus upwards motion in the upper visual field (Sdoia, Couyoumdijan & Ferlazzo, 2004).

There is emerging evidence that lower hemi-field preferences are more pronounced when the complexity of the stimuli is increased, implying that attentional demands influence the perceptual task (Levine & McAnany, 2005). Levine and McAnany (2005) suggest that the spotlight of attention is more finely focused in the lower visual hemi-field, therefore improving performance when fine discrimination is required. Although the research is inconclusive, it does raise the possibility that the processing of stimuli in the upper and lower hemi-fields may be subject to different search strategies. This is an important consideration in the context of hemianopia and driving, given that the lower hemi-field is likely to be of greater importance on tasks such as driving where stimuli are more densely packed in the lower region. This may also have implications for location of field loss, in that those with an inferior field loss may demonstrate greater impairment than those with field loss restricted to the superior regions.

Another way in which attention has been shown to affect the visual fields is through constriction of functional fields. The functional field of view represents the area around the fixation point from which information is briefly stored and processed during a visual task (Williams, 1988). When there is too much information, the useful field constricts to prevent overloading of the visual system, thus the extent of the functional field of view varies to accommodate the amount of information in a display. Increased visual noise generally results in poorer performance, particularly for targets located more eccentrically (Williams, 1988). Williams also reported that size or shape similarity between targets and distractors decreases search performance (Williams, 1988).

Other studies have indicated that the functional visual field varies under the effect of different variables (for example age and vehicle speed), and deteriorates with the duration of a monotonous task requiring sustained attention, ultimately leading to tunnel vision (Roge, Pebayle, Hannachi & Muzet, 2003). Furthermore, research has also indicated that driving experience affects the functional field of view, which suggests that perceptual skills or strategies that affect the functional field of view may develop with driving experience (Crundall, Underwood & Chapman, 1999, 2002).

Several studies have investigated whether adding secondary tasks impacts on performance. These studies have generally found that secondary task performance, particularly when presented peripherally, is impaired when simultaneously presented with central (foveal) load, and this assumption has held whether the task combinations were visual only, or of mixed modality (Williams, 1988). Therefore, as primary (usually foveal) task complexity increases, secondary (usually peripheral) task performance deteriorates. A study by Williams (1988) varied cognitive load while maintaining the visual complexity of foveal displays, and found results which suggested a top-down interference mechanism that appeared sensitive to task complexity and attentional allocation (Williams, 1988).

Supporting evidence for this effect was provided in a study by Wood and colleagues, who investigated the effects of auditory and visual distractors on Useful Field of View (UFOV) performance in young, visually normal adults (Wood et al., 2006). Participants were presented with the UFOV (a computer-based test designed to assess selective and divided attention) in the presence of visual distractors, and auditory distraction at one of three levels: none, listening only or listening and responding. The results showed more central errors in the presence of auditory (but not visual) distractors, whereas peripheral errors increased for both auditory and visual distractors. Peripheral errors increased with eccentricity, and were greatest in the inferior region in the presence of distractors (Wood et al., 2006).

Similarly, driving studies have been conducted to assess higher level interference processes using distractors that have no foveal load (i.e. cognitive tasks). Increased cognitive workload was reflected in significant pupil size increments, indicative of additional mental effort and spatial gaze concentration, and several measures of visual search behaviour were also affected (Recarte & Nunes, 2003). General effects included lower variability in gaze direction, and reduced inspection frequency of mirrors and speedometer. These results suggest that increased workload from mental tasks affects the capacity to process visual stimuli (Recarte & Nunes, 2003).

Findings from these studies suggest that the visual fields can be affected by a range of factors. For example, there may be variations in sensitivity across the visual field (i.e. hemi-field preferences), and cognitive and attentional factors have the additional capacity to affect the extent and efficiency of the visual field. Thus, attentionally driven aspects of visual search are critically important when designing a framework to assess visual performance in hemianopia.

2.6.2 Attention and hemispheric lateralisation

Laterality of brain injury is an important factor in hemianopia as the left and right hemispheres are generally thought to have different functions. Left hemisphere activity tends to be focused on task analysis, mathematical operations, logical interpretation of information, sequencing, symbolic information, abstraction and reasoning. In contrast, right hemisphere activity is believed to focus on more holistic functioning, processing multisensory information, integrating and storing complete representations of the environment and language processing (Frackowiak, 2004).

Additionally, different areas (lobes) of the brain are thought to represent different functions (Frackowiak, 2004). Frontal lobe functions include, for example, motor function, movement, problem solving and impulse control. Parietal lobe functions include processing and discrimination of sensory input, spatial processing, localising objects and directing movement in space, visually guided movements and body orientation. The temporal lobe is concerned with auditory input, long-term storage of sensory input, processing details and visual object recognition and categorisation. The occipital lobe is considered the 'visual processing centre' and contains the primary visual cortex (V1). However, although the different lobes of the brain are focused on specific functions, the hemisphere in which they are located has a fundamental impact on the way the function is performed (Frackowiak, 2004). Attention, for example, is thought to be largely a frontal lobe and right hemisphere function (Anastasi, 1998; Farah, 2000).

Thus, the type and location of brain injury is likely to influence task performance and level of impairment. Considering hemianopia more specifically, right-hemisphere brain injuries (resulting in left-sided visual field loss) are more often associated with visual neglect and perceptual problems. In contrast, left-hemisphere injuries (resulting in right-sided visual field loss) tend to be associated with language or reading problems (Arlinghaus, Shoaib & Price, 2005; Bertelson, 1982; Farah, 2000). In addition, clinically, functional impairment is often described as more severe in those with right-hemisphere lesions (Anastasi, 1998).

This evidence highlights the importance of the underlying brain injury, and suggests that laterality may play a role in determining functional performance outcomes in hemianopic field loss.

2.6.3 Attention and brain injury

Brain injury has also been implicated in a range of aspects of attention, making it important to consider the underlying brain injury and the effects this may have on attentional processes in hemianopia. Hemianopia can result from an isolated brain injury (e.g. surgical intervention or traumatic brain injury) or more diffuse damage (e.g. stroke) which can result in very different patterns of impairment; although one of the most frequently reported problems in both stroke and traumatic brain injury is attentional impairment. The specific impairments observed include a global, non-specific slowing of information processing, and possibly impairment of higher aspects of visual attention (Bertsch et al., 2009; Deiber et al., 2010; Lavie, 2005; Leclercq, Deloche & Rosseaux, 2002; Madden, 2007; Madden & Whiting, 2004; Parkin & Walter, 1992; Parkin, Walter & Hunkin, 1995; Salthouse & Czaja, 2000; Salthouse, Hambrick & McGuthry, 1998).

It has also been observed that the presence of specific attentional impairments may depend on the nature and complexity of the task. For example, complex resource-demanding tasks performed under time pressure generally result in poor performance in people with traumatic brain injury (Albert & Kaplan, 1980; Andres & VanDerLinden, 2001; Bryan, Luszcz & Pointer, 1999; Crawford, Bryan, Luszcz, Obonsawin & Stewart, 2000; Leclercq & Azouvi, 2002; Leclercq et al., 2002; Luchies et al., 2002; Parkin & Walter, 1992; Perfect, 1997; Reitan & Wolfson, 1994; Salthouse & Czaja, 2000; Salthouse & Ferrer-Caja, 2003; Salthouse et al., 1998). Similar attentional impairments are observed post-stroke, often presenting as the most prominent neuropsychological dysfunction (Chao & Knight, 1995; Dee & VanAllen, 1973; Godefroy & Rosseaux, 1996; Leclercq et al., 2000; Leclercq et al., 2002).

Thus, it is evident that different aetiologies affect attentional outcomes following brain injury in different ways. Moreover, impairments are more likely to be observed on specific types of task, for example those that are complex and resource demanding. Furthermore, attentional impairment following brain injury is an important consideration given that it is associated with reduced cognitive productivity, even when other cognitive functions remain intact (Leclercq et al., 2002).

2.6.4 Attention and ageing

Although hemianopic field loss can occur at any age, the condition is more common with advancing age, with a much higher prevalence in people aged 60 years and over (Gilhotra et al., 2002). Therefore, it is important to consider the role of attention in normal ageing, as well as the potentially compounding effects of attentional deficits as a result of a brain injury.

Advancing age is accompanied by a systematic decline in performance on a wide variety of cognitive tasks (Birren & Fisher, 1995; Salthouse, 1996; Salthouse, Fristoe

& Rhee, 1996; VanDerLinden & Collette, 2002). A difficulty frequently observed in older adults is selective visual attention (Bertsch et al., 2009; Deiber et al., 2010; Lavie, 2005; Madden, 2007; Madden & Whiting, 2004; Parkin & Walter, 1992; Parkin et al., 1995; Salthouse & Czaja, 2000; Salthouse et al., 1998). Although the mechanisms underpinning these difficulties are subject to debate, the literature suggests that older people have problems filtering out irrelevant stimuli (Birren & Fisher, 1995; Salthouse, 1996; VanDerLinden & Collette, 2002), and they have a tendency to respond more slowly than younger people, which is more pronounced during functional complex reaction time (CRT) tasks (Albert & Kaplan, 1980; Andres & VanDerLinden, 2001; Bryan et al., 1999; Crawford et al., 2000; Leclercq et al., 2002; Luchies et al., 2002; Parkin & Walter, 1992; Perfect, 1997; Reitan & Wolfson, 1994; Salthouse & Czaja, 2000; Salthouse & Ferrer-Caja, 2003; Salthouse et al., 1998).

More specifically, studies have shown age-related differences in the ability to select a single input in the presence of competing inputs (VanDerLinden & Collette, 2002). Although this effect has been demonstrated through different paradigms, including visual search tasks and response competition tasks, these age differences were not evident when specific task parameters were present. For example, when relevant stimuli were cued by a physical attribute such as location, there was no need to process irrelevant stimuli that did not contain those physical characteristics (VanDerLinden & Collette, 2002). However, when central processing was required for selective attention the magnitude of age-differences increased; older adults typically performed more poorly when searching for a target among stimuli that could not be identified on the basis of peripheral cues, such as when the location of target information was uncertain, or when the target information was physically integrated with distracting information (VanDerLinden & Collette, 2002).

Thus, the deficits observed on selective attention tasks have typically been interpreted as evidence of a specific age-related deficit, with the failure to ignore irrelevant information attributed to an age-related decline in the efficiency of inhibitory processes (Hasher & Zacks, 1988; VanDerLinden & Collette, 2002; Zacks & Hasher, 1994).

Age-related effects on divided attention have generally led to the assumption that there is some overarching resource (cognitive capacity) upon which all cognitive operations are based, and this resource reduces with advancing age (VanDerLinden & Collette, 2002). Although evidence from dual task studies seems consistent with this theory (Hartley, 1992), some researchers argue that it is premature to attribute age differences in dual tasks to a reduction in resources (VanDerLinden & Collette, 2002). This is because some studies have shown that the performance of older adults on some dual task experiments was not significantly worse than younger adults. However, the discrepancy here may be due to differences in task complexity, and the role of practice effects (VanDerLinden & Collette, 2002).

In addition, some authors have suggested that the slowing of cognitive processes associated with age may closely resemble the effects of traumatic brain injury, and the two processes may influence common neural mechanisms (Bashore & Ridderinkhof, 2002). Thus, the most commonly observed deficits in cognitive function associated with brain injuries (e.g. in the domains of working memory, attention and information-processing speed) are likely to be compounded by advancing age, in that older adults have the problem of generalised cognitive slowing in addition to the impairments produced by their brain injury (Bashore & Ridderinkhof, 2002). It is therefore likely that older adults would perform less well on a functional basis following a brain injury than younger adults with the same injury.

Thus, the interaction of age with visual attention and aetiology is an important consideration when designing a framework to study visual perception resulting from field loss, given the possibility that advancing age may influence cognitive task performance.

2.7 Paradigms for studying visual attention

Evidence in the psychological literature indicates that despite actively searching a visual scene and fixating on targets, adequate attentional processing does not necessarily occur (Galpin, Underwood & Crundall, 2009). For example, covert attentional orienting describes the phenomenon whereby attention is drawn to a stimulus in the absence of overt signs of the eyes orienting (Styles, 2005). Thus, this paradigm suggests that fixation is not necessarily the focus of attention. Evidence can also be derived from inattention research. Mack and Rock presented observers (n=5000) with a stimulus in the area of fixation (a cross), and asked them to determine which arm of the cross appeared longer. In one of the trials, a critical stimulus was presented within two degrees of fixation, and the participants were asked if they could identify the stimulus. The results demonstrated that approximately 25 percent of observers failed to detect the presence of the critical stimulus. The authors attributed this failure to inattentional blindness, which indicates that the focus of attention is not synonymous with attention (Mack & Rock, 2000).

This phenomenon has also been referred to as 'look without seeing', and a number of possible explanations have been proposed. Firstly, it is possible that people experience time gaps with attention diverted by images and thoughts unrelated to the task (Chapman, Ismail & Underwood, 1999). Alternatively, it is possible that although eye movements may scan a scene in a normal fashion, an automated process may overwrite the guidance of saccades and fixations. Thus, attention is not directed to the target and conscious processing does not occur (Martens & Fox, 2007).

More recently, researchers have studied looking without seeing in the context of change blindness. Change blindness refers to the phenomenon that people fail to notice large changes to the visual scene if the motion signals that usually accompany change are masked (Rensink, O'Regan & Clark, 1997). This has been shown to be a robust theoretical model that has been used in a number of different attentional research capacities (Batchelder, Rizzo, Venderleest & Vercera, 2003; Caird, Edwards, Creaser & Horrey, 2005; Galpin et al., 2009; Lees, Sparks, Lee & Rizzo, 2007; Rensink, 2001; Simons & Ambinder, 2005).

Typical change blindness studies present an image to an observer, followed by a brief visual disruption before presenting an altered version of the first image (Rensink et al., 1997; Simons, 2000). However, subsequent research identified that it is not actually necessary to have a visual disruption to fail to detect changes: change blindness can occur if the transition of a changing object is very gradual, and the steps are smaller than the threshold of detection (Simons, 2000). Some studies have indicated that performance is worse in a gradually changing object than if there were a sudden visual disruption (Simons, 2000).

Several paradigms have been developed in change blindness research, including the forced choice paradigm where the observer is forced to make a decision about changes in the scene, and the saccade-contingent paradigm where blurring of the retinal image during saccades masks the transient motion signals to the changes (Simons & Rensink, 2005). Similarly, there have been several models used to induce the visual disruptions (or inter-stimulus intervals; ISIs) including blank screens (Rensink et al., 1997), blinks (O'Regan, Deubel, Clark & Rensink, 2000), saccades (Grimes, 1996), mud-splashes (O'Regan, Rensink & Clark, 1996), and motion picture cuts and changes in camera angles (Simons & Rensink, 2005).

The stimulus images (scenes) used in change blindness research have varied from static to dynamic, and length of presentation has also varied; in some studies they have been presented only once (forced choice, based on correct or incorrect response), and others have used a multiple presentation model (flicker, based on time and number of presentations to identify a change) (Simons & Rensink, 2005). The flicker paradigm is a progression of the forced choice and saccade contingent models, and was developed in order to allow normal viewing conditions where an image is repeated, and alternated with a modified version of the image with brief ISIs (Rensink et al., 1997). This method allows the ISI manipulations of a brief display technique, as well as the free-viewing conditions of the saccade-contingent method. Stimuli are presented for long durations, which provides the best opportunity for an observer to build a scene representation, and it is proposed that the flicker caused by the blank fields swamps the local motion signals (visual transients) to the change, preventing attention being drawn to its location (Rensink et al., 1997).

Initial studies adopting the flicker paradigm presented participants with colour images of real-world scenes followed by a modified version for varying lengths of time (Rensink et al., 1997). The ISIs were blank grey fields, and each modified version contained a single, highly visible change. The changes were rated by independent observers as to the degree of interest; central or marginal. Results from this experiment indicated that under flicker conditions, it took much longer than expected for the participants to correctly identify the change, and objects of central interest were identified more quickly than objects of marginal interest, despite the marginal interest objects being on average 20 percent larger (Rensink et al., 1997). When presented with the same stimuli without ISIs, change identification was significantly faster, with no differences between objects of central or marginal interest. Based on these findings, the authors proposed that the visual perception of change in an object occurs only when that object is selectively attended, and in the absence of selective attention, the contents of visual memory are overwritten by subsequent stimuli and therefore cannot be used to make a comparison.

Further experiments revealed that memory was not a limiting factor for change detection (Rensink et al., 1997). Based on the findings from other memory research where it has been found that 400 milliseconds is required to process and consolidate an image to memory (Potter, 1976), Rensink and colleagues (1997) repeated the original experiment with the presentation of the images for 560 milliseconds thus allowing sufficient time for memory consolidation. The effects found in this study were robust under these conditions. To ensure that the 'flicker' was not reducing the visibility of the image, a further experiment was performed using valid and invalid cues. If visibility affected performance, it would be expected that large effects of cueing would not be observed and the target would remain difficult to find. However, the results demonstrated that valid cues always caused detection to be faster, demonstrating that the flicker was not reducing the visibility of the stimulus (Rensink et al., 1997).

Thus, it has been argued that the key factor mediating change blindness is attention; visual perception of change in any given scene occurs only when the change is being selectively attended. This fits within the framework of perception of change being mediated through an attentional bottleneck, with attention attracted to parts of the scene based on high-level interest (endogenously), and provides support for the presence of an iconic memory store (Rensink et al., 1997).

Subsequent studies using the change blindness framework have investigated visual performance in the context of higher-level semantic features. For example, experience (or familiarity with) and exposure to particular scenes have been shown to affect change blindness (Werner & Thies, 2000). One such study found that coaches, players and referees of American football detected more changes in static football scenes than did those unfamiliar with the game, and this effect was most pronounced when the changes were significant to the football formation or game play. These results support the theory that meaning and familiarity increase the selective power of visual attention (Werner & Thies, 2000).

Studies have also used the change blindness paradigm in a more functional capacity, for example using driving scenes involving complex intersections or older drivers. One study investigated the effects of driving experience at complex intersections using a dynamic change blindness paradigm (Famewo, Trick & Nonnecke, 2006). The results demonstrated that the paradigm could differentiate between drivers with varying levels of experience. Experienced drivers tended to correctly identify safety-related changes (new vehicle appearing in the scene) more often than inexperienced drivers, whereas there were no significant group differences in ability to detect non-safety related changes (colour of the car), which fits well with previous research on familiarity with a scene affecting responses to a target. The authors interpreted the results as increased experience leading to more skill in knowing what and where to attend. They suggest that improved allocation of attention may be an important factor in improving driving skills (Famewo et al., 2006).

Similarly, Galpin and colleagues found that driving-related targets were identified more quickly than non-driving related targets in a static change blindness experiment (Galpin et al., 2009). The authors interpreted these results as evidence for the participants viewing the scenes from the perspective of a driver through the images activating a driving-related schema that guided attention to relevant scene details (Galpin et al., 2009). These results suggest that the static format may be a useful (and more easily experimentally manipulated) paradigm to explore attentional performance for peripheral objects in driving scenes.

In an older driver study, Batchelder and colleagues considered change detection in static driving-related images (Batchelder et al., 2003). They used a gradual change method, presenting normal traffic scenes and blended them with a changed image over a 4000 millisecond rotation. The results confirmed the expectation that older drivers detected change with reduced accuracy and increased reaction time, and responded with more false positives than the younger drivers. The authors suggest that this could be attributable to findings that older drivers have decreased visual processing speed and reduced visual attention relative to younger drivers (Batchelder et al., 2003). These findings are also consistent with general cognitive slowing associated with ageing.

Evidence presented in this chapter identified that visual scanning patterns and visual attention can be disrupted by cognitive load (Recarte & Nunes, 2000). Richard and colleagues (2002) investigated visual search performance while concurrently performing a secondary (auditory) task. Images of driving scenes were presented in a flicker task, and the participants were asked to identify the region of change with an auditory message (working memory span task) presented on half of the trials. The results, as expected, indicated that top-down operations (e.g. voluntary scanning of a visual scene for information) were impaired by the concurrent auditory task, and consistent with previous research, the results also indicated that response times were significantly faster when identifying driving-related changes than non-driving related changes. The authors interpreted this as suggestive that visual search is strategic in nature (Richard et al., 2002).

Smyser and colleagues also investigated the concurrent task phenomenon using a change blindness flicker paradigm to identify the effects of cognitive load on the ability to detect change in the visual environment (Smyser, Lee & Hoffman, 2003). A speech-based email task of varying complexities was presented to participants concurrently with a flicker visual search task. Results indicated that detection of scene changes took significantly longer when cognitively loaded with the email task. The authors interpret these findings to mean that change detection was sensitive to cognitive load, with endogenous control of visual attention being affected by the introduction of the email task (Smyser et al., 2003). This study highlights the importance of interacting aspects of the complexity of the scene and the task.

In summary, the change blindness paradigm is a technique that has been used to investigate selective attention in a number of domains. The premise behind change blindness is that the visual perception of change occurs only when selective attention is employed, and in the absence of selective attention, the contents of visual memory are overwritten by subsequent stimuli and therefore cannot be used to make a comparison. The flicker paradigm allows stimuli to be presented for long durations, providing the best opportunity for an observer to build scene representations. Furthermore, the static format appears useful in exploring attentional performance for peripheral objects in driving scenes.

2.8 Proposal for current research

The evidence presented thus far has identified several aspects of interest regarding hemianopic visual field loss and driving. Firstly, it is clear that people with hemianopia and quadrantanopia have varying levels of impairment of visual function. However, this impairment does not necessarily translate into impairment of functional vision, or functional activities. For example, a number of driving studies have identified that a subset of people with hemianopia perform as well as controls on driving tasks (Racette & Casson, 2005; Schulte et al., 1999; Tant et al., 2002; Wood et al., 2009). However, the challenges are to objectively measure functional performance, and adequately identify and characterise those who perform well (or poorly) on these functional tasks.

The most common approach for investigating hemianopic performance on functional tasks is to study eye movements. Evidence from eye-tracking studies presented in this chapter indicates that parameters of visual search in hemianopia differ to those of normally sighted individuals, and tend to be characterised by small-amplitude 'staircase' saccades toward the blind hemi-field, along with frequent repetitions of scanpaths during visual search and inspection (Pambakian et al., 2000; Zihl, 1995).

It has been suggested that the characteristic scanpaths observed in people with hemianopic field loss are the result of an inability to develop a brief and comprehensive overview of the visual space available; however, more recent research identified that these scanpaths can be simulated in healthy individuals by occluding part of the visual field using goggles to create a scotoma (Tant et al., 2002). This provides some evidence that the observed scanpaths are visually guided rather than driven by specific cortical damage, and is suggestive of an attempt to engage an adaptive strategy to bring some of the visual scene into the blind region of the visual field.

Eye movement patterns are typically interpreted as the behavioural interface between attention and information acquisition by the individual from the environment (Recarte & Nunes, 2003), and thus researchers have interpreted the altered scanpaths observed in hemianopia as indicative of compensatory mechanisms. However, it remains unclear as to whether these scanpaths provide any functional benefit in terms of task performance, and whether all people with hemianopia use these scanning patterns to the same extent. For example, visual search that results in fixation of a stimulus of interest does not necessarily imply attentional processing, as demonstrated by psychological paradigms such as covert attentional processing (directing attention to a location in the absence of overt signs of orienting) and inattentional blindness (where fixation is not necessarily consistent with the focus of attention). Effective visual search requires more than a response to sensory input: it also requires a range of cognitive processing skills such as attention, object recognition, and application of stored knowledge from memory. Even when active visual scanning and fixation of relevant targets is evident, cognitive processing may not necessarily occur. Thus, it is important to identify that hemianopic scanpaths actually correlate with *attentional* processing of a target. This would provide evidence that these strategies hold functional benefit for the individual, and can therefore be accurately interpreted as compensatory.

To investigate compensation for hemianopic visual field loss in the current research, it was considered essential to study not only the visual scanning strategies employed but also the effectiveness of processing of relevant information across the visual field. Thus, a visual attention task based on the change blindness paradigm was proposed. The theoretical framework underpinning the change blindness paradigm argues that the key factor in producing change blindness is attention: visual perception of change in any given scene occurs only when the change is being selectively attended (Rensink, 2000, 2001; Rensink et al., 1997; Simons & Ambinder, 2005; Simons & Rensink, 2005).

An experimental change blindness task was developed specifically for this research. Forced responses were required to identify targets across the horizontal visual field (subtending 140^{0} of horizontal visual angle), with eye movements permitted. This allowed responses to be measured at peripheral locations in both blind and seeing regions of the visual field. It was proposed that this method would permit the assessment of several parameters simultaneously: selective visual attention, information processing, scene perception and visual scanning. If individuals with hemianopia failed to correctly identify changes in the blind region it would be indicative of a failure to selectively attend the relevant information, implying that the scanpaths used to perform the task had no functional advantage.

2.8.1 Aims

The overall aim of this research was to investigate compensation in hemianopia by examining performance on a visual attention (change blindness) task using naturalistic driving scenes. There were also two specific objectives. The first objective was concerned with understanding the mechanisms underpinning compensation. The focus here was to describe the characteristics of scanpaths used by individuals with hemianopic field loss. It was expected that successful performance on the change blindness task would be associated with altered scan paths, suggesting compensation. The second objective was to investigate the relationship between performance on the change blindness task and cognitive and vision tests commonly used in driving research and assessment. The general approach was to compare the characteristics of individuals with hemianopia who performed well with those who did not; and ultimately to identify the variables that best predicted performance on the change blindness task.

Chapter 3 Methodology

3.1 Experimental design

A cross-sectional, case-control experimental design was employed for this study. Given the wide range of ages of the potential participants (cases) with hemianopic field loss, a matched-subjects design was considered most appropriate to maximise statistical power of independent variable manipulations and reduce the confounding effects of age and gender. Between-group differences (cases versus controls) were of interest in this study, however *individual performance* was also central to the objective of identifying those individuals who were/were not able to compensate for their visual field loss, and the characteristics associated with compensatory behaviour.

3.2 Participants

3.2.1 Inclusion and exclusion criteria

A total of 41 individuals with hemianopic field loss (cases) were recruited to participate in this research. Ten cases did not meet the inclusion criteria and thus were excluded from participation, leaving a total of 31 cases. In addition, 31 matched controls were recruited for the study. Cases were included on the basis of a clinically confirmed diagnosis of hemianopia or quadrantanopia, and field loss that was present for a minimum of six months that was considered stable by the healthcare provider. Participants with any degree of hemianopic or quadrantanopic field loss (with or without macular sparing) were considered for inclusion and there were no restrictions on aetiology causing the field loss.

All participants were required to have held a driver's licence, either at the time of testing or prior to field loss. Participants were excluded on the basis of neglect, epilepsy, neurological conditions not associated with the field impairment, major psychiatric disturbance, and medications considered likely to affect attention. Screening for the exclusionary criteria was performed prior to participation in the study by asking participants a range of questions regarding their field loss. More detailed assessments were used to screen for gross cognitive impairment and neglect, which are described in detail later in this chapter.

Controls were matched to the participants on the basis of age (± 3 years) and sex. It was not possible to match on the basis of driving experience as the guidelines in Australia preclude individuals with hemianopic or quadrantanopic field loss from holding an unconditional licence, and as a result many of the hemianopic participants ceased driving following diagnosis.

3.2.2 Ethics approval

Primary ethics approval was received from the Monash University Human Research Ethics Committee, and all research was conducted in accordance with these principles. In addition, ethics approvals were received from several hospitals, clinics and health boards, including: the Royal Victorian Eye and Ear Hospital, St Vincent's Hospital (and associated private clinics), the Alfred Hospital, the Austin Hospital, and Southern Health.

3.2.3 Recruitment

Several strategies were employed to recruit participants, including: clinicians from participating health services handed out the study information during regular consultations; letters and information brochures with signed endorsement from the regular healthcare providers were sent to potential participants; recruitment was conducted in clinic waiting rooms by a researcher from the associated clinic; brochures and posters were placed in clinic waiting rooms across several health networks; discipline-wide emails were sent out via professional bodies (for example, generic emails to neuropsychologists through their Association); and advertisements were placed in local publications and newsletters targeting stroke and vision audiences (for example the Vision Australia newsletter/website).

Furthermore, a large number of institutions in Victoria supported the research and provided access to participant medical files, including: the Royal Victorian Eye and Ear Hospital; St Vincent's Hospital and associated private clinics; the Austin Rehabilitation Hospital; the Alfred Hospital; Vision Australia; Guide Dogs Victoria; Brainlink; and a number of private optometrists, ophthalmologists and psychologists.

After contact details were received from the healthcare provider, potential participants were contacted by telephone to describe the research and answer any questions. Those who agreed to participate were sent an information pack including a letter confirming the appointment, a brochure and an explanatory statement (see Appendices 1-3). On the day prior to testing, participants were contacted by telephone to remind them of their appointment time and the location of the testing venue.

Recruitment of control participants (without visual field loss) was conducted after the relevant case had completed testing in order for them to be matched on selected demographic variables. Potential participants were contacted through an existing Monash University Accident Research Centre (MUARC) database of people who had participated in prior research and indicated their interest in future studies. Potential matches were contacted by telephone to provide an explanation of the tasks and time commitment involved in the study. Upon establishing interest in participation, recruitment procedures were the same as the cases.

3.3 Procedures

Pilot testing of the research protocols and refinement of the experimental tasks took place at MUARC between September and December 2007. Four phases of pilot testing were undertaken, with three to five participants in each pilot session. Experimental testing for the study was undertaken over a period of 18 months (between February 2008 and August 2009). Participants were asked to attend at least one session at MUARC, which took between three and six hours depending on level of impairment. The testing was conducted in three blocks (i) demographics and vision testing, (ii) change blindness experiment, and (iii) cognitive tasks. Participants were invited to take breaks as required during testing, and were given the option of completing the testing over two or three sessions if preferred. The order of the testing blocks was the same for each participant, regardless of the number of sessions. Most participants (97%) completed the testing in two sessions, with the first session comprising the demographic, vision and change blindness tasks, and the second session incorporating the cognitive tasks.

The demographic component also included a questionnaire to ascertain medical, vision and driving history, and a range of vision tests were performed to assess visual function, including visual acuity, contrast sensitivity and binocular visual fields. All participants were asked to complete the change blindness task designed for this study, which aimed to assess selective visual attention, visual scanning and information processing The final set of tasks involved a battery of cognitive assessments designed to assess visual, perceptual and attentional functioning. The cognitive battery also included screening measures for gross cognitive decline and neglect.

On arrival for the first testing session, the research aims and procedures were explained to the participant. Explanatory statements and consent forms were used to establish the participants' understanding of the study and willingness to participate (see Appendix 4). In accordance with ethics guidelines, a unique identifier was assigned to each participant and all information de-identified for storage. Consent forms were kept separate from the assessment information. The testing checklist is included in Appendix 5.

3.4 Experimental assessments

3.4.1 Questionnaire

The first task for the participant was to complete a researcher administered questionnaire (designed for this study) incorporating sections on demographics, vision/clinical information and driving history (see Appendix 6). This information was used to describe the clinical characteristics of each of the cases, and to compare the crash and infringement histories of those with and without visual field loss.

The basic demographic information included aspects such as date of birth, gender, marital status, educational attainment and area of residence (metropolitan or rural). The vision and medical history section was concerned with (i) the primary visual impairment and associated brain injury, (ii) co-morbid visual impairments, and (iii) medical co-morbidities. The primary visual impairment was defined as the hemianopic field defect, and participants were asked about their aetiology, time since onset/diagnosis, extent of field loss, self-reported level of impairment and participation in any rehabilitative programs. Medical and visual co-morbidities were defined as any vision or medical condition not associated with the hemianopic field loss (including refractive errors) and any medications at the time of testing.

The final section of the questionnaire was concerned with driving history, and included questions about licence status, years of driving experience, self-regulation, driving exposure and crash and infringement history.

3.4.2 Vision assessments

3.4.2.1 Visual fields

Visual field assessments are used to determine the extent and severity of visual field loss. In this study, visual fields were assessed using a Humphrey Field Analyser (HFA) which is a computer based automated perimetry test. Participants are required to indicate when they see spots of light of different levels of brightness, which are flashed onto the inner surface of a projection bowl. The field plots are generated automatically, and there are a variety of test strategies and types of field plots available (Landers, Sharma, Goldberg & Graham, 2003).

All participants were tested by the same researcher to ensure standardisation of data collection. The instrument automatically calibrates the brightness of the background to 31.5asb, and testing was completed in a room with low levels of ambient light. Fixation was monitored by observation through the in-built video camera. Two software programs were used to assess the visual field data derived from the HFA: (i) the 24-2 SITA standard strategy and (ii) the Esterman functional fields.

The 24-2 threshold program assesses the central thirty degrees of the visual field (24 temporal and 27 nasal) using a grid of 54 points. Visual field sensitivity is measured at each of these 54 locations using a SITA (Swedish Interactive Threshold Algorithm) thresholding algorithm which reduces testing time whilst still determining an accurate measure of visual sensitivity (Landers et al., 2003). Trial lenses were used to allow clear vision at the working distance of the bowl, and were automatically calculated by the instrument and fitted for participants where required.

The test was performed for each eye separately, and the results were merged to determine the mean decibel deviation for binocular fields. The merged fields used the points of highest sensitivity for the corresponding visual field locations in each eye, excluding the points in the blindspot region where only the opposite eye scores were used (Nelson-Quigg et al., 2000). This method provides a gross measure of field loss, but does not consider location, and thus the clinical condition (i.e. quadrantanopia or hemianopia and side of field loss) were used in addition to the mean decibel deviation for analysis.

The second visual field test that was conducted was the Esterman binocular functional field test. This test weights areas of the visual field based density of points in that region, for example, there are more points in the inferior and central fields because they are considered of more value than the peripheral fields (Esterman, 1982). Scoring is automated using a relative value grid which divides the visual field into 120 unequal units, and scores are based on whether the stimulus is seen or not seen at the 10dB level. The test was performed binocularly using the habitual spectacle correction while maintaining steady gaze. The Esterman test was selected because of its routine use in vision assessment for fitness to drive, and because it is purported to assess functional vision relevant to driving (Austroads, 2006).

3.4.2.2 Visual Acuity

Visual acuity is a measure of the sharpness (or acuteness) of vision, with the standard definition of normal visual acuity being the ability to resolve a target which subtends a visual angle of one minute of arc. This measure was selected as it is a standard measure of visual function which is used in both clinical settings and for driver licencing, and provides a gross measure of general vision loss.

Both distance visual acuity and near visual acuity were assessed for this study. Near acuity was measured given that the cognitive tasks were conducted at shorter working distances, and was used as a screen to ensure that the test scores were not affected by near acuity deficits. Distance acuity was measured using the LogMAR Visual Acuity Chart manufactured by the National Vision Research Institute of Australia. The LogMAR chart was developed by Bailey and Lovie (Bailey & Lovie, 1974) and is an optotype test using letter size and spacing which follow a logarithmic progression, with visual acuity expressed as the logarithm of the minimum angle of resolution (Taylor, 1978). The smallest letters that can be correctly recognised provide a measure of visual acuity (Bailey & Lovie, 1974). Corrected visual acuity has been reported to be a relevant assessment of visual health (Taylor et al., 1997), therefore distance visual acuity was tested with habitual vision correction in this study. The luminance on the chart was 85 candelas/metres squared (cd/m^2).

The testing procedure followed the protocol of the Melbourne Visual Impairment Project (Taylor et al., 1997). The participant was positioned directly in front of the chart with their eyes at a distance of four metres. The right eye was tested first with the left eye occluded. The participant was asked to read the smallest line that they could see, and was encouraged to read each letter on that line. If the participant could read a given line successfully, they were encouraged to continue reading until they could no longer complete a line. The same procedure was followed for testing the left eye and for binocular assessment. Each letter correctly reported was scored as -0.02 log units. This is the standard protocol for measurement, and allows parametric procedures (such as regression analyses) to be conducted on the data (Lovie-Kitchin, 1988). Normative data suggests that normal (or near normal) visual acuity falls within the range of -0.2 and +0.2 logMAR units (Colenbrander, 2001).

Near visual acuity was assessed using logMAR word reading cards designed for use at a distance of 25 centimetres. The test was performed according to the method used successfully in the Melbourne Visual Impairment Project (Taylor et al., 1997) where the card was held at the participant's preferred reading distance rather than a standardised distance, and this measurement was recorded on the card. Habitual near vision correction was used. The test was performed monocularly (right then left) with the eye not being tested occluded, and then binocularly using separate cards. Acuity was based on the last word that could be read, adjusted for the distance at which the card was held from the eye.

3.4.2.3 Contrast Sensitivity

Contrast sensitivity is the ability (or sensitivity) of the eye to discriminate between the contrast of an object against its background. Contrast sensitivity was selected as a routine assessment of visual function that is indicative of general vision loss (Faye, 2005). The Pelli-Robson chart was used for this study, which is an optotype wall chart comprising eight lines of letters (of the same size) which reduce in contrast down the chart (Pelli, Robson & Wilkins, 1988). Each line has six letters with the first three (triplet) on the left having more contrast than the right. The contrast decreases moving down the lines, with the contrast being highest on the top line (1 or 100%) and lowest on the bottom (0.006 or 0.6%).

Testing was undertaken at a distance of one metre from the chart with luminance of 85cd/m^2. Habitual vision correction was worn, and the participant was instructed to start from the top left, working horizontally and then move down to the next line. The test was undertaken monocularly (each eye tested using the same letters) and binocularly (using a separate chart with different letters). Letter contrast sensitivity was scored by each letter correct representing 0.05 log units. Normative data suggests that most people without vision impairment score 1.65 log units or above, with the lower limit for adults aged 50 years and older being 1.5 log units (Elliott, Sanderson & Conkey, 1989; Mantyjarvi & Laitinen, 2001).

3.4.3 Cognitive assessments

3.4.3.1 Mini Mental State Exam

The Mini Mental State Exam (MMSE) was used to screen for gross cognitive impairment (Folstein, Folstein & McHugh, 1975). The test is an eleven question assessment that assesses five areas of cognitive function; orientation, registration, attention and calculation, recall, and language. The maximum score is 30 with a score of 23 or lower being indicative of gross cognitive impairment, which was therefore set as the cut-off for participation in this study. The MMSE was selected as one of the most widely used clinical screening measures, and has been shown to be a reliable (0.82 to 0.95) and valid measure of gross cognitive impairment (Mitrushina & Satz, 2006; Spreen & Strauss, 1991; Strauss, Sherman & Spreen, 1998).

3.4.3.2 The Balloons Test

The Balloons Test was used to screen for neglect. This task is designed to detect visual inattention following brain injury and provides a method for establishing whether unilateral omissions are attributable to visual field defects by generating indices of generalised and lateralised inattention, or neglect (Edgeworth, Roberston & McMillan, 1998). There are two subtests, each of which are carried out within a specified time limit. In subtest A participants are presented with a stimulus sheet containing a random array of 220 items (circles and balloons). The task is to cross off all of the balloons in three minutes. After 90 seconds a different coloured pen is provided to allow analysis of their search pattern. Subtest B follows the same process as Subtest A, except the participant is asked to cross off the circles instead of the balloons. All other parameters remain the same.

The test is based on the visual perception phenomenon of 'popouts' which were discussed in the literature review. Detection of the targets in subtest A is a relatively parallel process which acts as a control measure where the attentional demands required for a serial search are minimal. However, subtest B is a more difficult task and employs serial search, where the targets are not subject to the popout phenomenon. Instead, the targets require effortful search in a serial fashion which is likely to place greater demands on attention. Therefore, individuals with neglect would be significantly more impaired on this task (Edgeworth et al., 1998).

The test is scored on three dimensions: (i) the number of balloons cancelled on subtest A, (ii) the number of circles cancelled on subtest B, and (iii) the laterality score, which is the number of circles cancelled on the left of subtest B expressed as a percentage of the total number of circles cancelled. A subtest B score of 17 or less, and a laterality score of less than 45% indicates the presence of neglect, and participants were excluded on this basis (Strauss et al., 1998). Reliability has been reported as 0.83, and validity has been established with correlations of between 0.64 and 0.78 when compared with other cancellation tasks (Edgeworth et al., 1998).

3.4.3.3 Line Bisection Task

The line bisection task was used as an additional screening measure for visual neglect when it was indicated by performance on the Balloons test. To undertake the task, the participant was presented with a line (18-20 centimetres in length) on a piece of paper, and was asked to mark with a pencil the midpoint of the line. Many people with left hemisphere neglect tend to mark the line well to the right of the apparent midline, whereas people with a left hemianopia but no evidence of neglect tend to bisect the line slightly to the left (Paton et al., 2004). The standard clinical protocol was adopted in this study which defined the cut-off point as a deviation of 6mm or more from the midpoint. This test was selected as it is routinely used in clinical settings, it is brief to administer, and it has been shown to accurately discriminate between neglect and hemianopia when used in conjunction with cancellation tasks (Paton et al., 2004).

3.4.3.4 Concentration Endurance Test (D2)

The Concentration Endurance Test (known as the D2) is a measure of selective attention and mental concentration, where 'attention and concentration' are defined as performance-oriented, continuous and focussed selection of stimuli (Brickenkamp & Zillmer, 1998). The test assesses the ability to selectively orient to certain relevant internal or external aspects of a task while simultaneously screening out irrelevant ones, and to analyse these dimensions rapidly and correctly. The test relies upon adequate functions of drive and control, and is concerned with three components of behaviour: (i) the speed and number of stimuli which are processed within a given time (conceptualised as an aspect of drive); (ii) the quality and accuracy of the processing which is inversely related to the error rate (conceptualised as an aspect of attentional control); and (iii) the relationship between speed and accuracy of performance which provides information regarding working behaviour, such as initial activity, stability and consistency, fatigue and attentional and inhibitory efficiency (Brickenkamp & Zillmer, 1998).

The test involves a paper and pencil cancellation task which assesses sustained attention and visual scanning ability in a short period of time (under 5 minutes). The test is composed of 14 lines with 47 letters each, with the target being a letter "d" with two dashes. The target stimuli are presented with either two marks below, two marks above, or one mark above and one mark below. Distractors are the letter "p" with one to four marks, or the letter "d" with one, three or four marks. The participant's task is to mark as many targets per line as possible, within a 20 second per line time limit.

The scoring profile used for this study was overall performance, which represented the total number of items processed minus errors. Therefore a higher number of processed items indicates better performance. The test has been reported as being an internally consistent and valid measure of visual scanning accuracy and speed in young adults (n=364), with internal consistency reported within the range of 0.80 to

0.95 (Bates & Lemay, 2004). Test-retest reliabilities are high, ranging from 0.89 to 0.92 (Spreen & Strauss, 1991).

3.4.3.5 Motor-free Visual Perception Test

The Motor-free Visual Perception Test (MVPT) is designed to assess visual perception skills without reliance on motor responses (Colarusso & Hammill, 2003). The full battery incorporates tasks for object matching, figure-ground, visual closure, visual memory, and form discrimination. In this study, only the Visual Closure sub-test (MVPT-VCS) was used. This subtest is frequently used in the driving domain, for example as part of the Gross Impairments Screening Battery of General Physical and Mental Abilities which is a measure used in occupational therapy for licence re-assessment (Fildes et al., 2004).

The MVPT-VCS measures the ability to identify an object, shape or symbol from a visually incomplete or disorganised presentation, and to then complete the partial image. To conduct the test, participants were presented with a stimulus sheet consisting of one complete image at the top and four incomplete options in a row below. The participant was asked to determine which of the four images would complete the stimuli by adding lines without moving or removing any others (Colarusso & Hammill, 2003). Responses were given either verbally or by pointing. Scoring was based on number of errors from a possible eleven; therefore a higher score indicates a poorer performance.

Impaired scores on the MVPT-VCS have been reported to predict at-fault motor vehicle crashes; one study demonstrated that after adjusting for annual mileage, those that made four or more errors on the MVPT-VCS were 2.10 times as likely to be involved in an at-fault motor vehicle collision (Ball et al., 2006). Another study investigated driving capability of older adults (n=255) using an on-road assessment conducted by a trained Occupational Therapist (also trained as a driving assessor). The results of this study reported that MVPT scores significantly predicted driving performance (measured as capable/incapable based on a predicted probability model) during an on-road driving test (Oswanksi et al., 2007). The MVPT-VCS was therefore selected for this study based on its utility in screening for cognitive ability relevant to driving.

3.4.3.6 Useful Field of View Test (UFOV)

The Useful Field of View test (UFOV) was administered to assess visual attention. The UFOV is a computer-based task which is purported to assess visual processing speed, selective attention and divided attention. The 'useful field of view' is defined as the visual area in which useful information can be acquired in a single glance without eye or head movements (Ball et al., 1993).

The task consists of three subtests designed to measure (i) information processing speed, (ii) divided attention and (iii) selective attention (divided attention with distractors). The three components are administered sequentially following practice trials for each task. In Subtest 1, participants are presented with an image of either a car or a truck in the centre of the screen followed by a distractor screen (black, white and grey random pattern). The participant is then asked to choose whether the stimulus was a car or truck. This process is repeated adjusting the length of stimulus presentation as required. After two correct responses, presentation time is reduced for the subsequent stimulus, or if two responses are incorrect the time is increased. Presentation of stimuli can vary from as short as 14 presentations to many more depending on the consistency of the participant's responses. No feedback is provided and the participant's processing speed is recorded in milliseconds. A lower score indicates a better performance.

Subtest 2 follows the same process as Subtest 1, with the additional task of locating a simultaneously presented car in the periphery at either 8, 17 or 24 degrees along one of the eight cardinal meridians. The first screen displays either a truck or a car in the centre of the screen with a car in the periphery, followed by a distractor screen. Two selection screens are then presented, the first asks the participant to indicate whether they saw a car or a truck in the centre of the screen. The second requires the selection of one of eight trajectory options for the location of the peripheral car. This process is repeated, adjusting the length of stimulus presentation in milliseconds as required, until a stable measure of the participant's threshold is determined. Subtest 3 is identical to Subtest 2 except that the car displayed in the periphery is embedded in a field of 47 distractors (triangles). All other procedures, conditions and scoring techniques remain the same.

Performance on the UFOV is expressed as a composite score assessing the three variables assessed in the subtests: minimum target duration required to perform the central discrimination task, the ability to divide attention between central and peripheral tasks successfully, and the ability to filter out distracting stimuli. Scores are calculated by the program as milliseconds to complete each subtest, and the percentage reduction scoring technique was used in the present study. This technique converts UFOV scores to a percentage reduction (in degrees) in field of view from 'ideal', (i.e. a higher percentage reduction indicates a worse performance) and this was completed according to the user manual (Ball et al., 1993).

The UFOV has been shown to correlate with driving performance and crash risk. One study found that older drivers who failed the UFOV test had approximately four times more crashes than those who passed, and those who failed were involved in 15 times more crashes than those with a normal UFOV (Ball & Owsley, 1991; Fildes et al., 2004). Another study in a sample of New Zealand drivers demonstrated significant associations between two measures of the UFOV (divided and selective attention) and driving performance during an on-road assessment (Fildes et al., 2004). Furthermore, studies have shown a disproportionate increase in error rates at greater eccentricities in older adults, leading to the conclusion that the UFOV of older adults is restricted compared to younger adults (Ball & Owsley, 1991).

3.4.3.7 Trail Making Test (Trails A and B)

The Trail Making Test was administered as a measure of visual conceptual and visuomotor tracking skills (Tombaugh, 2004). It is a paper and pencil test comprising two parts: Trails A requires the participant to draw lines to connect consecutively numbered circles without lifting the pencil from the paper as quickly as possible (within a maximum tolerance of three minutes). Errors are pointed out during the task and the participant returns to the last correct response, adding to the total time to complete the task. Trails B follows the same process as Trails A, but requires the participant to draw lines to connect consecutive numbers and letters in an alternating sequence (therefore the sequence would be 1-A-2-B etc). The test is scored using the time taken to complete in seconds, and a longer time indicates a poorer performance (Bowie & Harvey, 2006).

The test has been shown to be sensitive to a range of neurological impairments and processes (Misdraji & Gass, 2009; Spreen & Strauss, 1991). Trails A is presumed to be a test of visual search and motor speed skills, whereas Trails B also tests higher level cognitive skills of executive control such as mental flexibility and working memory (Bowie & Harvey, 2006). The test was selected as it is brief to administer (5-10 minutes) and the final scores correlate highly with results on mental ability tests and severity of cognitive impairment. Normative data is available for comparison, and a score of 180 seconds or more on Trails B can be considered indicative of impaired driving performance (Hester, Kinsella, Ong & McGregor, 2005; Reger et al., 2004; Spreen & Strauss, 1991; Steinberg, Bieliauskas, Smith & Ivnik, 2005; Tombaugh, 2004).

Performance on Trails B has been used widely in driving assessment, and has been correlated with poor driving outcomes in normal and clinical populations of older adults. For example, Trails B performance has been shown to correlate with increased crash rates and impaired driving performance (simulated and on-road) in older adults with dementia (Reger et al., 2004). Another study investigating crash risk of older drivers (n=1,910) found that those who took 147 seconds or longer to complete Trails B were 2.01 times as likely to be involved in an at-fault motor vehicle crash (Ball et al., 2006). Trails A and B were therefore considered an important test for inclusion in the cognitive battery.

3.4.4 Clinical review

To confirm the diagnosis of hemianopia or quadrantanopia, medical records were reviewed for each participant. Records were requested with respect to clinical information regarding their brain injury, vision history and the most recent HFA visual field charts. These records were then compared to the visual field assessments undertaken as part of the research to ensure accuracy of testing, and each visual field assessment was reviewed by an optometrist to confirm the diagnosis.

3.4.5 Change blindness task

3.4.5.1 Overview

The visual attention task developed for this study was based on the change blindness paradigm and was intended to assess the extent to which individuals with hemianopic field loss attend to targets in their blind hemi-field. It was proposed that compensation could be investigated by measuring the accuracy (and speed) of stimulus identification of changing objects presented across the visual fields. The change blindness task involved presenting stimuli to participants where one item in the display rapidly changed and recording the responses to the targets.

3.4.5.2 Apparatus

Stimuli (photographs) were presented on a translucent rear projection screen (Da-Lite Fast Fold Deluxe Professional Screen®) measuring 2290mm by 3050mm, with the net picture area equating to 2180mm by 2950mm. The participant was seated in a height adjustable chair with their head movements restricted using a chin rest fixed at one metre above the floor. The chin rest was set to a distance of 95cm from the screen, with the corresponding visual angle subtending 140^{o} horizontally and 60^{o} vertically.

The stimuli consisted of real-world road images taken from the perspective of the driver, with a Canon IXUS digital camera with a resolution of 7.1 Megapixels. All scenes were photographed in and around metropolitan Melbourne, and included arterial roads, dual carriageways, freeways and highways with varying levels of traffic. The images were manipulated using Adobe Photoshop© to remove or superimpose one element (referred to as the target), see Figure 3 for an example.

Figure 3 Example stimulus

Target (pedestrian with bicycle circled in red) presented in lower right quadrant

The screen was divided into quadrants, and the images were categorised by the region in which the target was located: lower left (LL), lower right (LR), upper left (UL) and upper right (UR). A total of 111 stimuli were presented to each participant, with 25 images containing targets in each of the four quadrants, eight images containing central targets, and three no-change catch trials to reduce false reporting. The individual stimuli were coded for several additional parameters: (i) complexity, rated by independent observers (n=10) on a three-point scale (high, medium and low with reasonable inter-rater agreement at 67%), (ii) mean contrast, which represented the mean difference in luminance between the target (sampled at 3 locations using a light meter) and background (also sampled at three locations using a light meter) rated as low (<33 lux), medium (34-66 lux) or high (>66 lux), and (iii) size of the target, measured in mean pixels.

The targets were also sorted for task relevance, by categorising them into either traffic-related (including cars, trucks, motorcycles, pedestrians and traffic signals), or non-traffic related (such as trees or roadside advertising). Some examples of the range of stimuli are presented in Figure 4.

UL stimuli: non-traffic related (tree)

UR stimuli: non-traffic related (sign)

LL stimuli: traffic-related (car)

LR stimuli: traffic-related (car)

Figure 4 Example stimuli: Quadrants and categories

The stimuli were presented using a laptop computer-based program designed specifically for the task using a Delphi application. The program used input files to select image pairs (original image and image containing target) and presented them in an alternating sequence until the target was perceived or the task timed out. All parameters could be modified by altering the input files. The target locations were defined by their x and y co-ordinates.

Eye movement data was obtained during the task using a Seeing Machines FaceLAB system Version 4.0 (Seeing Machines, 2004). This system comprises two small cameras calibrated for angles and depth of the seated participant in order to establish movement parameters of the eyes and head in three dimensions. The cameras were mounted horizontally onto a perspex stand that was placed slightly in front of the lower part of the screen (Figure 5). This method ensured that there was no shadowing or obstruction of the image, except where the cameras were placed.

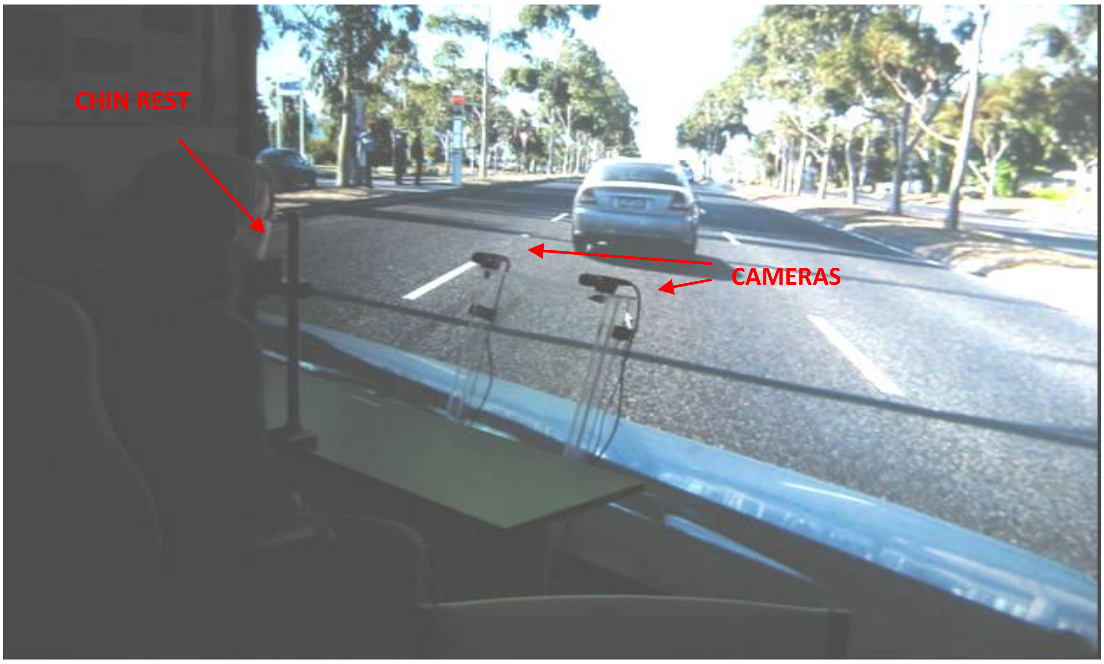


Figure 5 Camera positioning for change blindness task

Camera images and recordings were linked to a user-operated computer interface. The system recognises and tracks facial features and markers placed on the participants face. The system automatically recognises the iris, pupil and eyelids, however the operator can adjust size and shape parameters of the eyes to achieve optimal recordings of the gaze where required. A camera (Scenecam) was fixed to a wall behind the participant in a position that provided a full view of the screen (Figure 6). The software was calibrated with FaceLAB, and allowed a full recording of the image with real-time information on eye movement patterns (Seeing Machines, 2004). The parameters of interest were number and duration of fixations and saccade amplitudes.

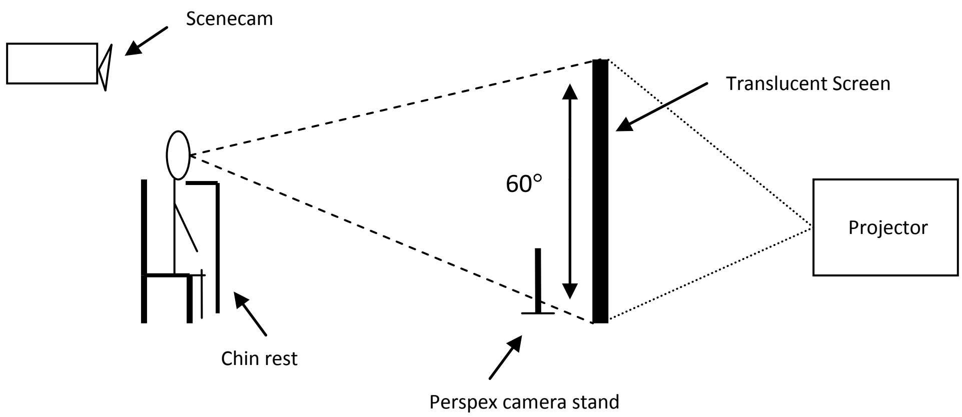


Figure 6 Experimental set-up

The participant viewed the translucent rear projection screen at a distance corresponding to a visual angle of 140° horizontally and 60° vertically.

3.4.5.3 Protocol testing

Pilot testing was performed to test the protocols prior to conducting experimental sessions. Four pilot sessions were completed, each with between three and five participants. Sessions were conducted to ensure accuracy of data collection for (i) the change blindness program, (ii) FaceLAB performance under low light levels, (iii) FaceLAB capabilities under low light levels when vision correction (spectacles) were used, and (iv) to ensure the accuracy of overall data collection.

3.4.5.4 Procedure

All testing was conducted in a laboratory at Monash University Accident Research Centre with black-out facilities. The participant adjusted the seat to a height suitable for the chinrest. Three laptops were located behind the participant and used to collect data; one running the FaceLAB software, one running Scenecam and one running the change blindness task. The laptops were time synchronised using NTP FastTrack software which utilises the *Network Time Protocol* to synchronise each computer independently to Universal Time Coordinated (Seeing Machines, 2005). This allowed the change blindness task performance data to be linked with the eye-tracking data collected during the task. Gaze calibration was performed using a standardised rectangle on the screen. Recording of eye movements and gaze quality were monitored throughout the session to ensure that the eye movements were being recorded and the gaze quality remained within appropriate levels.

Participants were given ten practice trials for familiarisation with the change blindness task, with the option of further practice if required. A centrally located fixation cross was presented for 100ms prior to each stimulus. The original image (non-target) was presented for 400ms, followed by the modified image (target) for 400ms, with an inter-stimulus interval (ISI) consisting of a blank grey field for 100ms between each presentation. The stimuli were presented in sequence until the target had been perceived, or for a maximum of 45 seconds (Figure 7). All participants viewed the same stimuli, with the order of presentation of the image pairs randomised for each participant.

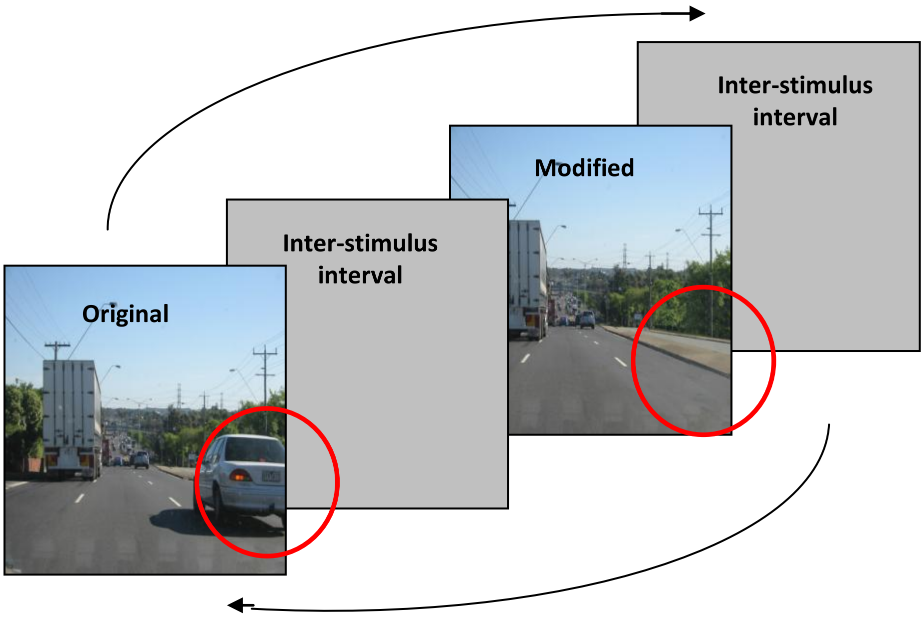


Figure 7 Sequence of stimulus presentation

The original image was presented for 400 milliseconds, followed by the modified image for 400 milliseconds on a continuing basis until the change had been perceived or until the task timed out. Each presentation was separated by an ISI of 100 milliseconds (grey).

The participants were given a standardised set of instructions by the experimenter, and advised to freely search for any targets while keeping their head still. Given that hemianopia is a condition most commonly associated with CVA and trauma, fine motor skills and hand dexterity are frequently affected. In order to reduce bias introduced by slowed motor responses in the case group, a verbal response measure was adopted for all participants in both case and control groups.

Participants were asked to respond verbally, “stop”, when a change was perceived. When the participant responded, the experimenter pressed the right mouse button to pause the stimulus image, and the participant was then required to verbally report *what* the change was and *where* it occurred. The experimenter selected the location on the screen where the participant indicated. A coding scheme was developed to ensure consistency across responses. Participants were asked to note the location of the target (upper left, upper right, lower left, lower right or central) and the type of target with the following options: car, van, truck, motorcycle, bicycle, pedestrian, traffic signal, road sign, advertisement, power pole, bridge or tree. Participants were familiarised with these options during the practice trials. Location and stimulus type were both required for a correct response.

3.4.5.5 Data collection

Data for the change blindness task and eye-tracking measures were collected separately and linked at a later stage using time coding from the initiation and conclusion of each trial. For the change blindness task, data was collected as correct or incorrect response, and response time to detect the target. Errors were recorded in three categories (i) overall (total number of) errors, (ii) errors of omission, and (iii) errors of commission. Response time in milliseconds was recorded for each trial, with a time-out resulting in an incorrect response at 45 seconds.

The parameters of interest from FaceLAB were measurements of gaze (fixations) and saccades. Gaze rays were recorded separately for the left and right eyes, with each ray consisting of an origin point and a vector. The origin point is located at the centre of the eye, and the unit vector travels from the origin point toward the object being fixated (Seeing Machines, 2004). Saccades were defined as fast movements of the eye to change the gaze point between fixating points. A physiological model of saccadic eye motion was used to detect saccades and optimally filter the gaze direction data. Saccade measurements were binary (saccade or not). Information about fixation patterns and saccade parameters were extracted using FaceLAB software, and linked to performance variables from the change blindness task.

3.5 Thesis structure and hypotheses

In order to fully explore performance on the change blindness task, the experimental section of the thesis is structured in four chapters: **Chapter 4** clinical characteristics of the sample; **Chapter 5** change blindness task performance; **Chapter 6** eye movement parameters; and **Chapter 7** neuropsychological (and other) correlates of task performance.

3.5.1 Chapter 4: Clinical characteristics

Chapter 4 describes the clinical and demographic characteristics of the sample. Given the variation in visual field loss (for example location of field loss, aetiology, and macular sparing) the individual clinical characteristics of each case is identified and described. Performance on the vision and cognitive measures is also described, as well as the demographic characteristics of the sample (including driving history, driving exposure and crash and infringement history). This chapter sets the context for investigating performance on the change blindness task in greater detail.

3.5.2 Chapter 5: Change blindness performance

Chapter 5 focuses on performance on the change blindness task. The key question of interest was whether some people with hemianopic field loss performed well on the task: if a participant was able to accurately detect targets presented in their blind region, this would suggest some level of functional compensation given there was no visual function in that area. Hence, error scores were the most important aspect to determine compensation. Response time was also used as a supplementary factor in determining functional compensation. The final consideration in this chapter was to examine the usefulness of a classification system for performance among the hemianopic participants. This was undertaken using a three-level outcome process for assessing functional performance based on data from the control group.

3.5.3 Chapter 6: Eye-tracking data

Chapter 6 considers the eye movement data with several questions of interest. The first question was whether the hemianopic cases explored the scenes differently to controls. Previous research has found that individuals with hemianopia explore scenes using scanpaths that differ from controls; however there is limited evidence on scanpaths in naturalistic scenes and search tasks, and therefore it was of interest to examine the patterns of scanpaths under these conditions. The second question was whether eye movement parameters explained the variance in change blindness task performance among the hemianopic group. If the cases who made fewer errors on the change blindness task were using scanpaths as a mechanism for compensating for their field loss, it would be expected that the eye movement parameters would differ between good performers and poor performers, i.e. the scan patterns had functional benefit for the individual. To address these questions, the eye movement data were considered in two ways: to explore any general differences in eye movement patterns between the case and control groups; and also within the case group, to explore differences in scan patterns associated with performance data (using a good/intermediate/poor classification of performance on the change blindness task as detailed in Chapter 5).

3.5.4 Chapter 7: Performance correlates

The final experimental chapter (Chapter 7) considered in detail how well the vision, cognitive and demographic variables explained performance on the change blindness task (i.e. a measure of functional compensation). This was undertaken by determining which vision, cognitive, clinical or demographic variables *individually* predicted accuracy and response times on the change blindness task, and secondly whether a *combination* of these variables better predicted performance on the task.

3.6 Hypotheses

The overall aim of this research was to investigate compensation in hemianopia by examining performance on the change blindness task. It was hypothesised that if individuals with hemianopic field loss were compensating, they would be able to accurately identify targets, even when the targets were presented in their blind regions, albeit with slower overall search times. The literature described in Chapters 1 and 2 demonstrates variability in the extent to which individuals with hemianopia are able to compensate and successfully perform functional tasks. Thus it was expected that while group differences would be apparent in the present study, there would be a level of variability in performance on the change blindness task among the case group, with some cases displaying no functional impairment, and others having great difficulty with the task.

The first specific objective of the research was to investigate whether visual scanning strategies represented a mechanism underpinning functional compensation on the change blindness task. Firstly, it was hypothesised that the hemianopic cases would adopt altered scanning strategies on the task (hemianopic scanpaths). Thus, it was expected that the cases and controls would differ in their visual search patterns. Furthermore, it was also hypothesised that if hemianopic scanpaths were a mechanism underpinning compensation, differences in task performance would be reflected in the scanning strategies (i.e. the good performing cases would adopt different search strategies to the poor performing cases).

The final objective was to investigate the relationship between performance on the change blindness task and cognitive and vision tests commonly used in driving research and assessment. As the change blindness task was purported to be a measure of functional vision, it was hypothesised that change blindness task performance would be more highly correlated with tasks requiring cognitive processing (functional vision) than those measures which test only visual parameters (visual function).

3.7 Statistical analyses

3.7.1 Clinical characteristics

All data were analysed using PASW Statistics (SPSS) v.18. The clinical characteristics of the sample were compared with controls using descriptive analyses. Variables of interest included demographics and performance on standardised vision and cognitive tests. Numbers and proportions were used to describe categorical variables, and means and standard deviations or medians and interquartile ranges were used for continuous variables.

3.7.2 Change blindness performance

A number of statistical techniques were employed to investigate performance on the change blindness task. Between-groups performance was studied for cases and controls using means, standard deviations and t-tests. A critical analysis for the change blindness data was the study of individual case performance on a matched-pairs basis. This minimises the effects of age by looking at the difference between two participants (case and control) of the same age rather than a group with a wide age range. As such, regression analyses were performed to explore differences for error and response time data. Where the outcome measure was dichotomous, binary logistic regression was used. This approach, while similar to linear regression, was appropriate because it does not require the predictors to be normally distributed, linearly related, or of equal variance in each group, nor does it require the predictors to be discrete. Instead, the predictors can be any mix of continuous, dichotomous or discrete; hence this approach was well suited to the data resulting from this study (Tabachnick & Fidell, 2001). Univariate regression models were used to investigate several parameters of the error data, including performance differences when targets were presented in blind regions.

Where the outcome was continuous (response time), linear regression models were applied to the data to investigate performance differences between the groups (cases and controls) and between the individual matched pairs. Statistical significance was reported at the $p<0.05$ level. Heterogeneity of variance was expected in this study given the wide clinical and age variation in the sample, therefore tests of homogeneity were performed.

3.7.3 Eye-tracking performance

Two-sample t-tests were used to test for differences between the cases and controls on the continuous eye-tracking parameters. Statistical significance was reported at the $p<0.05$ level. ANOVAs were used to compare a range of eye movement parameters for the different visual field loss groups (quadrantanopia, left hemianopia and right hemianopia) as well as performance groups based on the change blindness task. Where statistically significant results were found, Tukey Honestly Significantly Different (HSD) post-hoc analyses were performed.

3.7.4 Performance correlates

A number of statistical techniques were employed to investigate the relationships between performance on the change blindness task and the demographic, vision and cognitive variables. Bivariate analyses were used to investigate the relationships between error performance on the change blindness task and the cognitive and vision measures using Pearson correlations for each variable. Regression modelling was performed to investigate predictors of performance on the change blindness task, using logistic regression for dichotomous outcomes (correct responses) and linear regression for continuous outcomes (response time). Statistical significance was reported at $p<0.05$.

Both univariate and multivariate regression modelling were performed. The univariate models were used to determine which individual variables predicted performance on the change blindness task, and the multivariate model was used to determine which combination of variables best predicted performance. The multivariate model employed a step-wise logistic regression method to overcome any problems of association between the variables. This method represents an iterative variable-selection procedure where the inclusion and exclusion of predictors from the equation is based solely on statistical criteria (Tabachnick & Fidell, 2001). Sensitivity and specificity analyses were also conducted to determine the probability of the individual or multiple variables predicting performance on the change blindness task.

3.7.5 Analytical assumptions

All continuous data were checked for normality of distribution, which was set to skewness and kurtosis values of <2. Where the data was not normally distributed, logarithmic transformation was performed to stabilise the variance. Continuous (response time) data were also checked for independence of the errors using autocorrelation analysis prior to fitting the models. For chi-squared comparisons, an expected cell count of ≤2 was used as the underlying statistical assumption.

3.7.6 Data cleaning

All data were checked for completeness, and no cells contained missing data. Two participants were identified as outliers using errors from the change blindness task. These two cases were excluded from all group analyses. However, they were included in the individual analyses where each case was compared only with the matched control, and included in group performance analyses where appropriate.

Chapter 4 Clinical characteristics

4.1 Overview

Hemianopic visual field loss presents in a number of different ways depending on the location, aetiology and severity of the associated brain injury. These factors determine the form and extent of the hemianopic loss; the extent of field impairment can range from complete loss of vision in one hemi-field of each eye (hemianopia), to loss of part of a quadrant with islands of preserved vision (quadrantanopia). The mechanism and extent of brain injury can also affect cognitive functioning, for example diffuse damage caused by a stroke is likely to affect an individual differently to an isolated injury caused by surgical intervention.

As discussed previously, the conditions leading to hemianopic field loss are most prevalent among older adults, particularly following stroke (Arumugam et al., 2010; Feigin, Lawes, Bennett & Anderson, 2003; Truelsen, 2010). In addition to an increased prevalence of medical conditions resulting in field loss, ageing has also been shown to affect a range of attentional aspects, including selective visual attention (Bertsch et al., 2009; Deiber et al., 2010; Lavie, 2005; Madden, 2007; Madden & Whiting, 2004; Parkin & Walter, 1992; Parkin et al., 1995; Salthouse & Czaja, 2000; Salthouse et al., 1998). For example, a number of experimental studies have shown that older people have a tendency to respond more slowly to targets than younger people, and the effect of age is more pronounced during complex reaction time (CRT) tasks which are functional in nature (Albert & Kaplan, 1980; Andres & VanDerLinden, 2001; Bryan et al., 1999; Crawford et al., 2000; Leclercq et al., 2002; Luchies et al., 2002; Parkin & Walter, 1992; Perfect, 1997; Reitan &

Wolfson, 1994; Salthouse & Czaja, 2000; Salthouse & Ferrer-Caja, 2003; Salthouse et al., 1998).

Studies have also shown that older adults seem to assimilate information as well as younger adults, however they take longer to react to targets (Myerson, Robertson & Hale, 2007). These findings suggest a generalised pattern of cognitive slowing associated with age, and some researchers have suggested that the pattern of impairment associated with age may actually resemble the pattern seen in traumatic brain injury (VanDerLinden & Collette, 2002)

In addition to age, there are a number of factors that could potentially influence task performance in this study. Lateralisation of brain injury (side of field loss) in particular was considered a potential confound, given that right hemisphere lesions (left sided field loss) are more often associated with perceptual impairment (Arlinghaus et al., 2005; Bertelson, 1982; Farah, 2000). Extent of field loss was another potential influence, given that in general, quadrantanopic field loss has been found to be less functionally debilitating that hemianopic loss (Luu et al., 2010).

Similarly, aetiology of the underlying brain injury was important, as attentional impairments are often observed post stroke (Chao & Knight, 1995; Dee & VanAllen, 1973; Godefroy & Rosseaux, 1996; Leclercq et al., 2000) and subsequent to traumatic brain injury (Ponsford & Kinsella, 1992; Robertson, Manly, Andrade, Baddeley & Yiend, 1997; Schmitter-Edgecombe, Marks, Fahy & Long, 1992; VanZomeren & Brouwer, 1994; Veltman, Brouwer, VanZomeren & VanWolffelaar, 1996). Another potential confound is time since onset of the lesion given the potential for spontaneous recovery of function following brain injury. Furthermore, there is some evidence to suggest that the onset of neurocognitive impairment following brain injury can be delayed (Arlinghaus et al., 2005; VanZomeren & VanDenBurg, 1985).

Given the complex relationships between aetiology, extent of field loss, age and cognitive impairment, it was considered important to fully describe the clinical and demographic characteristics of the sample in the present study before investigating the interactions in greater detail in later chapters. Characteristics are described in individual sections; demographics, visual function, cognitive performance and driving history. For each aspect, the characteristics of the control and hemianopic (case) groups are discussed in the context of population-based normative data (where available), and between-groups comparisons of relevant variables are presented.

4.2 Demographics and clinical history

Sixty-two participants were included in this study, 31 cases with hemianopia or quadrantanopia and 31 control participants with normal visual fields matched on age (±3 years) and sex. In total, forty-one cases with hemianopia were recruited, however ten were excluded based on: cognitive impairment (n=1); the presence of neglect (n=2); or other medical conditions/medications (n=7) considered likely to affect performance. The mean age of the sample was 49.2 years (*SD*=17) with a range of 22 years to 79 years. The case and control groups were each composed of 14 males (45%) and 17 females (55%).

Both the cases and controls were predominantly married/defacto (61% of controls and 52% of cases) or never married (29% of controls and 32% of cases), with the remainder either separated/divorced (controls 7% and cases 13%) or widowed (controls n=2, 3%; and cases n=1, 6%). Most of the controls lived in metropolitan areas (97%) with one participant (3%) residing in a rural area. Similarly, most of the cases resided in a metropolitan area (84%), with the remainder living in a country town (10%) or rural area (6%).

A high proportion of the control participants were tertiary educated (university/college or equivalent) (77%), with the remaining 23% attaining a technical education (4-6 years high school or trade school). The most frequently reported level of education attained among cases was technical/high school (4-6 years of high school or trade school) comprising 55% of the sample, followed by tertiary (college or university) with 42%, and one (3%) primary school educated. The proportion of tertiary educated people in this sample is higher than the general Australian population; in 2009 a total of 23% of Australians aged 15-64 years had a highest level of attainment at the tertiary level (Australian Bureau of Statistics, 2009).

Overall, the controls were more likely than the cases to be: married (61% versus 52%); live in a metropolitan area (97% versus 74%); and tertiary educated (77% versus 42%). A summary of the demographic characteristics of the sample is presented in Table 4.

As shown in the table, 32% of controls reported at least one chronic medical condition. This equated to a mean 0.58 medical conditions per person (SD=0.99). Among the cases, 42% reported at least one chronic medical condition *in addition* to the brain injury associated with their visual field impairment. There were no significant between-groups differences in number of medical conditions for the controls (M=0.58, SD=0.99) compared with the cases when excluding the medical condition associated with the brain injury (M=0.84, SD=1.21) $t(60)=0.92$, $p=0.36$.

Nearly 40% of the controls reported the use of prescription medications at the time of testing, with a mean 0.81 medications per person (SD=1.42). In contrast, nearly 70% of the cases reported the use of prescription medications at the time of testing, with a mean of 2.03 medications per person (SD=2.18). The number of medications was significantly higher for the cases $t(60)=2.62$, $p<0.05$.

Table 4 Demographic characteristics of participants

	CASES		CONTROLS	
AGE				
Mean (years)	49.2	*SD*=16.8 Range 22-79	49.2	*SD*=16.8 Range 22-79
GENDER				
Male (n)	14	45%	14	45%
Female (n)	17	55%	17	55%
MINI-MENTAL STATE EXAMINATION				
Mean score	27.9	Range 23-30	29.4	Range 26-30
CO-MORBID MEDICAL CONDITIONS				
Yes (n)	13	42%	10	32%
No (n)	18	58%	21	68%
CURRENT MEDICATIONS				
Yes (n)	21	68%	12	39%
No (n)	10	32%	19	61%
TYPE OF FIELD LOSS				
Hemianopia (n)	26	84%	n/a	n/a
Quadrantanopia (n)	5	16%	n/a	n/a
TIME SINCE BRAIN INJURY				
Mean years since onset	8	*SD*=7 Range 1-31	n/a	n/a
AETIOLOGY				
CVA (n)	21	67%	n/a	n/a
Neurosurgery (n)	4	13%	n/a	n/a
Congenital abnormality (n)	2	6%	n/a	n/a
TBI (n)	2	6%	n/a	n/a
Aneurysm (n)	1	1%	n/a	n/a
Arteriovenous malformation (n)	1	1%	n/a	n/a

There was no evidence of neurological disease or trauma in the controls based on self-report at the time of testing. Scores on the MMSE ruled out the presence of gross cognitive impairment when the cut-off was set at 23 or less (M=29.6, SD=0.96, range 26-30). Amongst the cases, one participant performed just above the exclusion cut-off score with an MMSE score of 24. The case group mean MMSE score was 27.1 (SD=2.63, range 24-31). Although there was no evidence of gross cognitive impairment in either group, the controls had significantly higher MMSE scores than the cases $t(60)=5.0$, $p<0.001$.

The aetiology for visual field loss was predominantly CVA, equating to 67% of cases (n=21). The remainder had a brain injury associated with neurosurgery (n=4; 13%), congenital abnormality (n=2; 6%), traumatic brain injury (n=2; 6%), aneurysm (n=1; 3%) or arteriovenous malformation (n=1; 3%). All participants had visual field loss for more than 6 months at the time of testing, with a mean duration of 8 years (SD=7, range 1-31 years). The specific visual field loss characteristics of the sample are presented in the next section.

4.3 Vision assessments

The participants undertook a range of vision tests to assess visual function, including contrast sensitivity, visual acuity and functional visual fields. The tests were selected on the basis that they are common measures used in clinical assessment. A summary of the measures and scoring techniques is presented in Table 5.

Table 5 Summary of vision assessments

ASSESSMENT	DESCRIPTION
Contrast Sensitivity Pelli-Robson binocular	An optotype wall chart used to measure the ability to detect differences in contrast between objects and their background. Scores were expressed as binocular log contrast sensitivity (Faye, 2005; Pelli et al., 1988).
Visual Acuity LogMAR binocular	An optotype wall chart used to measure the eye's ability to discriminate fine detail at distance. The scores were expressed as binocular LogMAR (Bailey & Lovie, 1974).
Esterman Binocular functional field	Automated static suprathreshold perimetry test (Humphrey Field Analyser) performed binocularly with normal vision correction. Scores were recorded as number of errors from a possible 120 stimuli (Esterman, 1982).
24-2 Merged mean deviation	Automated static threshold perimetry test (Humphrey Field Analyser) performed monocularly and merged using the average eye method (Nelson-Quigg et al., 2000). Scores are expressed as binocular mean decibel deviation.

The controls had normal levels of visual acuity and contrast sensitivity for age. The mean binocular visual acuity (LogMAR) was -0.10 (SD=0.10, range -0.2 to +0.3), which represents a Snellen notation of 6/4.8. The mean binocular contrast sensitivity was 1.50 (SD=0.13, range 1.20 to 1.65). The cases also had normal visual acuity (LogMAR M=0.0, SD=0.10, range -0.20 to +0.60, Snellen notation 6/6) and normal contrast sensitivity (M=1.50, SD=0.13, range 1.20 to 1.80). The cases had a slightly better mean visual acuity compared to the controls $t(60)=-2.61$, $p<0.05$, however the difference was marginal and both groups' scores were within the normal range of -0.2 to +0.2 logMAR (Colenbrander, 2001). This difference was most likely accounted for by one participant in the control group whose distance acuity score was low which was associated with a refractive error that was not well corrected at the time of testing (LogMAR +0.3). However, this result was not considered likely to affect performance on the change blindness task as near acuity, contrast sensitivity and visual fields were all normal for this participant.

No differences in contrast sensitivity were observed between the cases and controls $t(60)=0.71$, $p=0.5$. Nine of the controls (29%) and five of the cases (16%) reported a refractive error which was corrected with spectacles or contact lenses at the time of testing.

Visual field loss was confirmed using three methods (i) clinical notes requested from the regular healthcare provider, (ii) the last visual field charts conducted by the participant's ophthalmologist or optometrist, and (iii) HFA 24-2 and Esterman visual field assessment conducted at the time of testing. All of the controls had normal visual fields based on an HFA 24-2 and Esterman binocular functional field tests. Representative (normal) visual field plots for two control participants are presented in Figure 8. These plots represent right and left monocular 24-2, and binocular Esterman charts. No evidence of field loss was identified on either the 24-2 or the Esterman.

All of the cases had a clinically established hemianopic field defect. In these participants, field loss was predominantly hemianopic (84%) rather than quadrantanopic. Twelve cases presented with right hemianopia (39%), fourteen with left hemianopia (45%) and the remaining five cases with quadrantanopia (16%) (two left and three right). Example visual field plots are presented in Figure 9 to illustrate the differences between the hemianopic and quadrantanopic visual field loss. The plots demonstrate the different characteristics of visual field loss (extent, complete/incomplete, macular sparing) and errors (or missed points) corresponding to the region of field loss on the Esterman functional test.

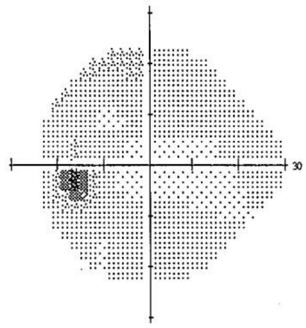
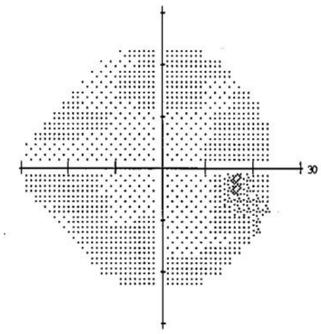
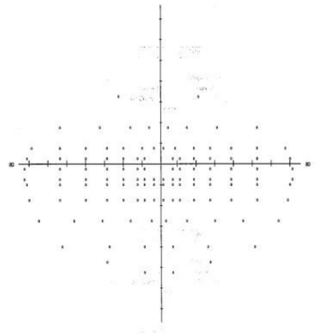
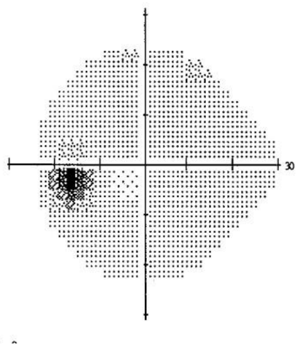
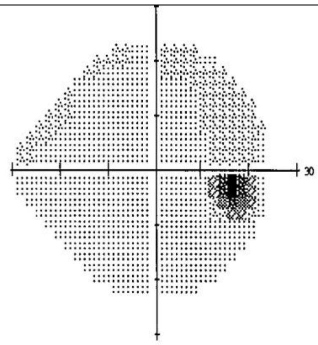
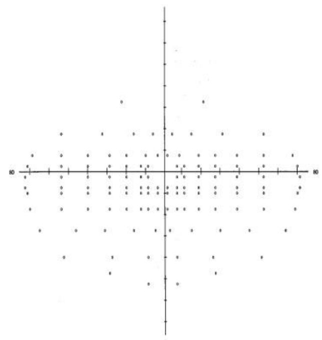
NORMAL VISUAL FIELD PLOT FOR CONTROL (CASE C05)		
24-2 Left eye	24-2 Right eye	Binocular Esterman
		
NORMAL VISUAL FIELD PLOT FOR CONTROL (CASE C10)		
24-2 Left eye	24-2 Right eye	Binocular Esterman
		

Figure 8 Normal visual field plots from the control group

Dark regions on the 24-2 plots represent the physiological blind spots. The dots on the Esterman represent correctly identified threshold points.

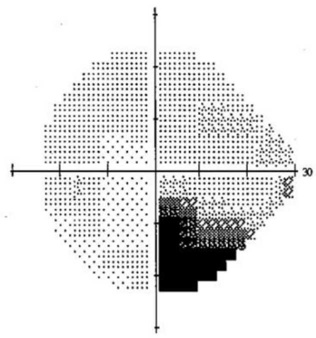
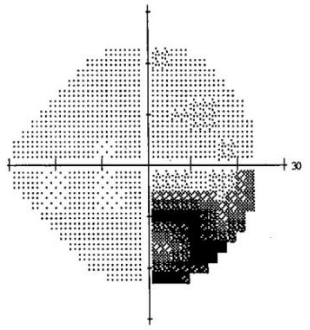
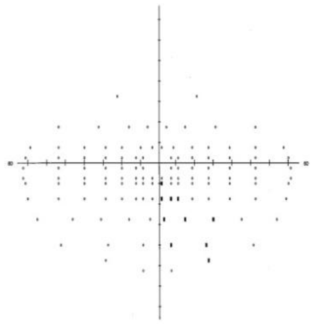
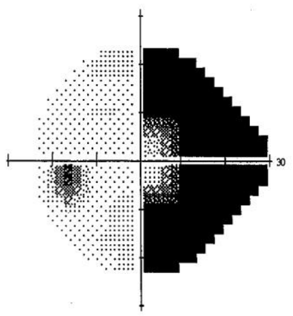
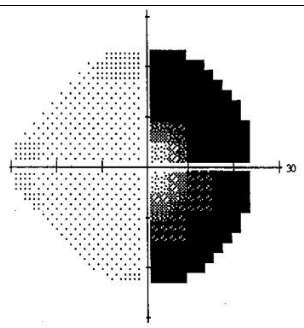
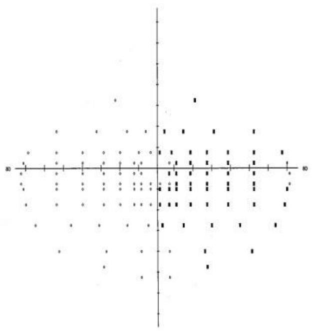
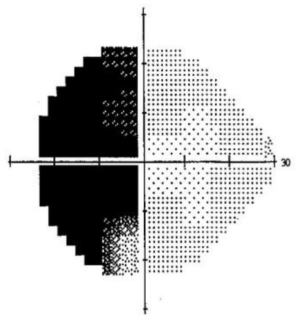
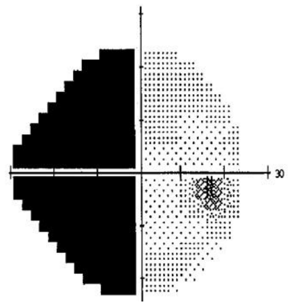
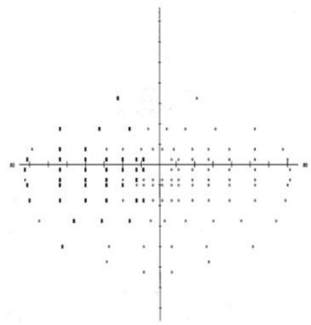
RIGHT INCOMPLETE INFERIOR QUADRANTANOPIA (CASE P10)		
24-2 Left eye	24-2 Right eye	Binocular Esterman
		
RIGHT COMPLETE HOMONYMOUS HEMIANOPIA WITH MACULAR SPARING (CASE P12)		
24-2 Left eye	24-2 Right eye	Binocular Esterman
		
LEFT COMPLETE HOMONYMOUS HEMIANOPIA WITH MACULAR SPLITTING (CASE P7)		
24-2 Left eye	24-2 Right eye	Binocular Esterman
		

Figure 9 Visual field plots for cases

Dark regions on the 24-2 plots represent visual field loss. The dots on the Esterman represent correctly identified threshold points and the squares represent missed points.

Visual field loss was reported in several ways. Firstly, the 24-2 binocular field charts were merged using the average eye method previously reported in the literature to determine a binocular mean decibel deviation score as described in Chapter 3 (Nelson-Quigg et al., 2000). Secondly, the number of missed points on the Esterman binocular functional visual field test was reported. Finally, field loss was coded as hemianopic versus quadrantanopic, right versus left, complete versus incomplete and whether macular sparing was present or not. The quadrantanopic group was also coded into superior versus inferior field loss.

Not surprisingly, there were significant differences between the cases and controls on both visual field measures (see Table 6 for a summary). The mean deviation (MD) for controls (*M*=-0.72, *SD*=1.09) was significantly lower than for cases (*M*=-12.4, *SD*=4.68) $t(60)=13.5$, $p<0.01$, and the mean number of missed stimuli on the Esterman was significantly higher for cases (*M*=34, *SD*=19) compared with the controls (*M*=1, *SD*=2) $t(60)=9.877$, $p<0.01$. The individual field loss characteristics of each case are presented in Table 7.

Table 6 Summary of vision assessment comparisons

MEASURE	CONTROLS		CASES		BETWEEN-GROUP DIFFERENCES	
	MEAN	***SD***	***MEAN***	***SD***	***t***	***p***
Visual acuity (logMAR)	-0.10	+0.10	0.0	0.10	2.61	<0.05
Contrast sensitivity (log units)	1.50	0.13	1.50	0.13	0.71	0.5
24-2 Mean Deviation	-0.72	1.09	-12.4	4.68	13.5	<0.01
Esterman (points missed)	1	2	34	19	9.88	<0.01

Table 7 Individual field loss characteristics of the hemianopic group

CASE ID	TYPE OF VISUAL FIELD LOSS	MACULAR SPARING	AETIOLOGY	YEARS INJURED	AGE (years)
QUADRANTANOPIA					
4	Left incomplete inferior	✓	CVA	5	48
8	Left incomplete superior	✓	CVA	6	57
10	Right incomplete inferior	✓	Neurosurgery / tumour	2	61
18	Right incomplete superior	✓	CVA	4	78
19	Right incomplete inferior	✓	TBI (closed) assault	1	31
RIGHT HEMIANOPIA					
1	Complete homonymous hemianopia	✓	CVA	8	48
2	Complete homonymous hemianopia	X	CVA / surgery for benign meningioma	5	66
12	Complete homonymous hemianopia	✓	Congenital abnormality	9	23
30	Complete homonymous hemianopia	X	Neurosurgery / benign pituitary tumour	31	69
5	Incomplete homonymous hemianopia	✓	CVA	6	51
9	Incomplete homonymous hemianopia	X	CVA	17	34
17	Incomplete homonymous hemianopia	✓	Suspected congenital abnormality	19	36
23	Incomplete homonymous hemianopia	✓	CVA	10	38
25	Incomplete homonymous hemianopia	✓	CVA/neurosurgery for congenital malformation	9	60
27	Incomplete homonymous hemianopia	X	Neurosurgery for benign tumour	2	72
28	Incomplete homonymous hemianopia	✓	Neurosurgery / benign pituitary tumour	4	65
29	Incomplete homonymous hemianopia	✓	CVA / surgery for benign meningioma	4	53

Table 7 (cont'd) Individual visual field loss characteristics of the hemianopic group

CASE ID	TYPE OF VISUAL FIELD LOSS	MACULAR SPARING	AETIOLOGY	YEARS INJURED	AGE (years)
LEFT HEMIANOPIA					
6	Complete homonymous hemianopia	X	CVA / surgery to repair aorta following MVA	3	74
7	Complete homonymous hemianopia	X	CVA	7	53
15	Complete homonymous hemianopia	X	CVA	16	39
16	Complete homonymous hemianopia	X	CVA	3	47
20	Complete homonymous hemianopia	X	Aneurysm	1	23
22	Complete homonymous hemianopia	X	CVA	1	60
26	Complete homonymous hemianopia	X	Surgery / arteriovenous malformation	9	51
3	Incomplete homonymous hemianopia	X	CVA	4	79
11	Incomplete homonymous hemianopia	X	CVA	10	72
13	Incomplete homonymous hemianopia	X	CVA	12	36
14	Incomplete homonymous hemianopia	✓	CVA associated with cardiac surgery	2	74
21	Incomplete homonymous hemianopia	X	CVA	23	42

4.4 Cognitive assessments

All participants were assessed using a battery of cognitive tests, selected on the basis that they were common clinical neuropsychological assessment tools, they measured cognitive skills relevant to the driving task, and as a set of measures, assessed a broad range of skills of relevance to those with brain injuries. These tasks are also used by some Occupational Therapy driving specialists to assess fitness to drive. The measures were described comprehensively in Chapter 3 and are summarised in Table 8.

Table 8 Description of cognitive assessments

ASSESSMENT	DESCRIPTION
D2 Concentration Endurance Test	Paper and pencil cancellation task designed to assess sustained attention and visual scanning accuracy and speed (Bates & Lemay, 2004; Brickenkamp & Zillmer, 1998). Scores are expressed as an attention profile representing the total number of correctly processed stimuli.
MVPT-VCS Motor Free Visual Perception Test	Visual closure subtest, designed to assess visual perception without reliance on motor skills (Colarusso & Hammill, 2003). Scores are expressed by the number of errors from a maximum 11.
Trails B Trail-making test part B	Paper and pencil test which measures visual search and higher level cognitive skills of executive control such as mental flexibility and working memory (Bowie & Harvey, 2006). Scores are expressed by total time to complete the task in seconds.
UFOV Useful Field of View	Computer based task designed to assess decline in visual sensory function, slowed visual processing speeds and impaired visual attention skills (Ball, Beard, Roenker, Miller & Griggs, 1988). Scores are expressed based on a percentage reduction from maximum (i.e. ideal = 100%) (Ball et al., 1993).

Significant differences between cases and controls were observed on all of the cognitive measures that were assessed. These differences are summarised in Table 9.

Table 9 Between-group comparisons of cognitive performance measures

MEASURE	CONTROLS		CASES		BETWEEN-GROUP DIFFERENCES	
	MEAN	*SD*	*MEAN*	*SD*	*t*	*p*
D2 *Stimuli correctly processed*	428	74	333	106	4.08	<0.01
MVPT-VCS *Number of errors*	1.0	1.0	1.8	1.6	2.38	<0.05
TRAILS B *Seconds to complete*	57	19	100	57	4.01	<0.01
UFOV *Percentage reduction*	21	18	54	18	8.00	<0.01

Normative data for the D2 suggests that between 360 and 471 correctly processed stimuli falls within the normal range (Brickenkamp & Zillmer, 1998; Spreen & Strauss, 1991). Scores for the controls fell well within this range (*M*=428, *SD*=74). The D2 scores for the cases were on the lower end of normal (*M*=333, *SD*=106) falling between the 35th and 50th percentiles of performance depending on age. These scores indicated lower overall scanning speed and accuracy for the cases (*M*=333, *SD*=106) compared with controls (*M*=428, *SD*=74) $t(60)=4.08$, $p<0.01$.

On the MVPT-VCS, the cases made significantly more errors and their performance was more variable (*M*=1.8, *SD*=1.6, range 0-7) compared with controls (*M*=1.0, *SD*=1.0) $t(60)=2.38$, $p<0.05$. As the MVPT-VCS represents a subtest, normative data is not available, however, it is frequently used in the driving domain to assess visual perception skills independent of motor skills, and increased errors on the task have been associated with increased crash risk (Mathias & Lucas, 2009; Tarawneh, McCoy, Bushu & Ballard, 1993). The higher number of errors in the cases indicates poor visual perception skills unrelated to motor responses.

The mean time to complete Trails B for the controls was 59 seconds (*SD*=19) which represents an above average performance around the 70th percentile (Tombaugh, 2004). The cases were slower to complete the Trails B, with a mean response time at the lower end of the scale (*M*=100, *SD*=57), which falls around the bottom 10th percentile of performance. However the standard deviation was quite large on this measure reflecting heterogeneity of performance within the group. The difference between the cases and controls was significant, with the cases taking almost twice as long to complete the task $t(60)=4.01$, $p<0.01$.

The mean percentage reduction in UFOV for controls was within the normal range (*M*=21%, *SD*=18%); the cut-off for a fail in driving assessment is generally set at 40% reduction. This suggests there was no evidence of a general decline in the useful field of vision or selective/divided attention in the control group. However, it should be noted that some (n=4) participants in the control group had scores approaching the cut-off. These participants were all older in age, and thus this finding likely represents normal age-related declines; the UFOV has been reported previously to reduce with advancing age (Owsley, Ball, Sloane, Roenker & Bruni, 1991). In contrast, the mean UFOV scores for the cases fell outside the normal range (*M*=54%, *SD*=18%) $t(60)=8.00$, $p<0.01$. This is not an unexpected result given the test requirements of selectively attending a target and simultaneously identifying a peripheral target (i.e. in the blind field). The individual performance results from the cognitive tests are depicted for the D2 (Figure 10), MVPT-VCS (Figure 11), Trails B (Figure 12) and UFOV (Figure 13).

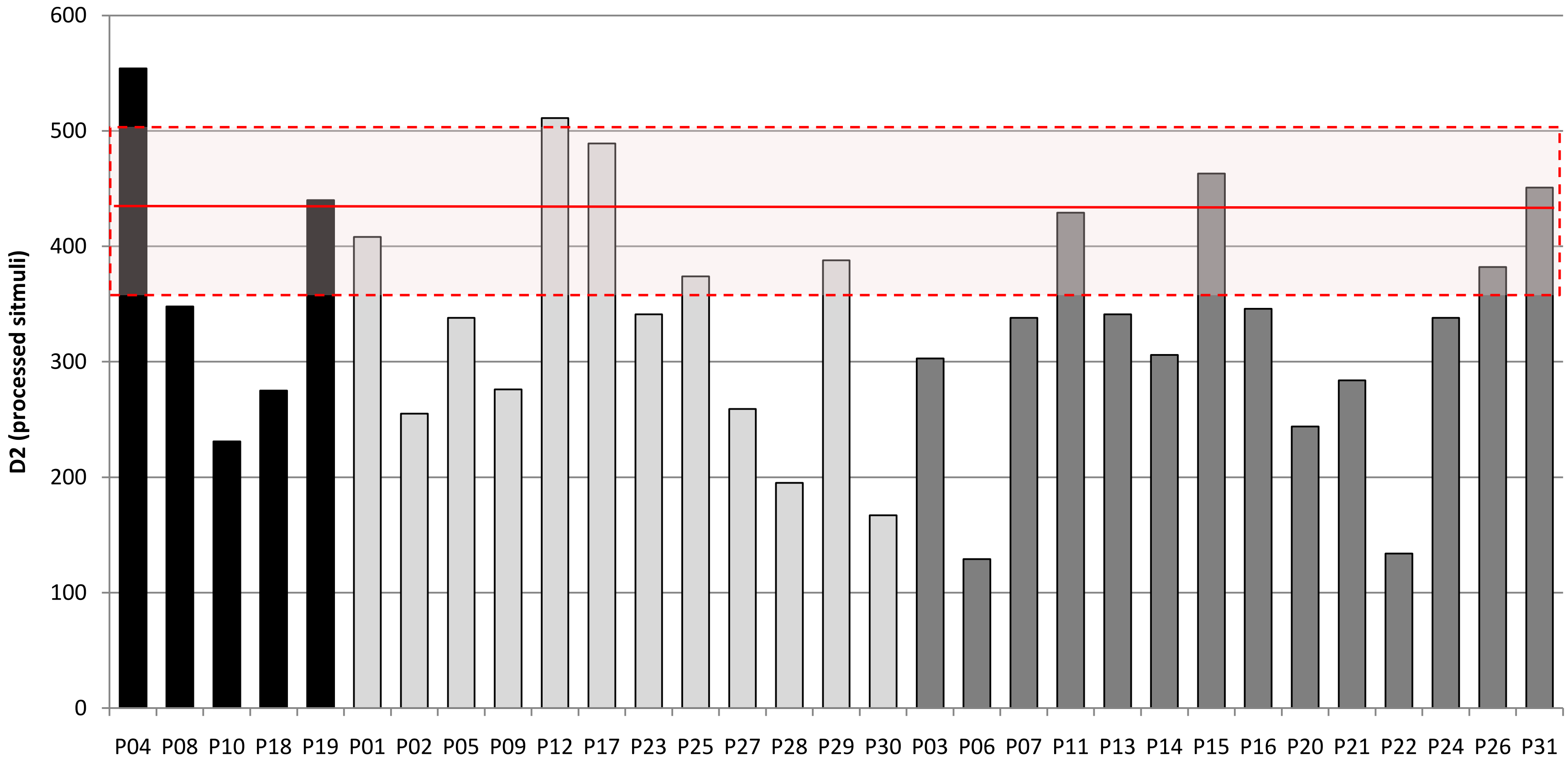


Figure 10 D2 individual case and mean (±1*SD*) control performance

The graph depicts correctly processed stimuli for the D2, and the red lines indicate the mean (±1SD) performance for controls. A higher score indicates a better performance. Black bars represent quadrantanopic cases, light grey represent right hemianopic cases and dark grey bars represent left hemianopic cases.

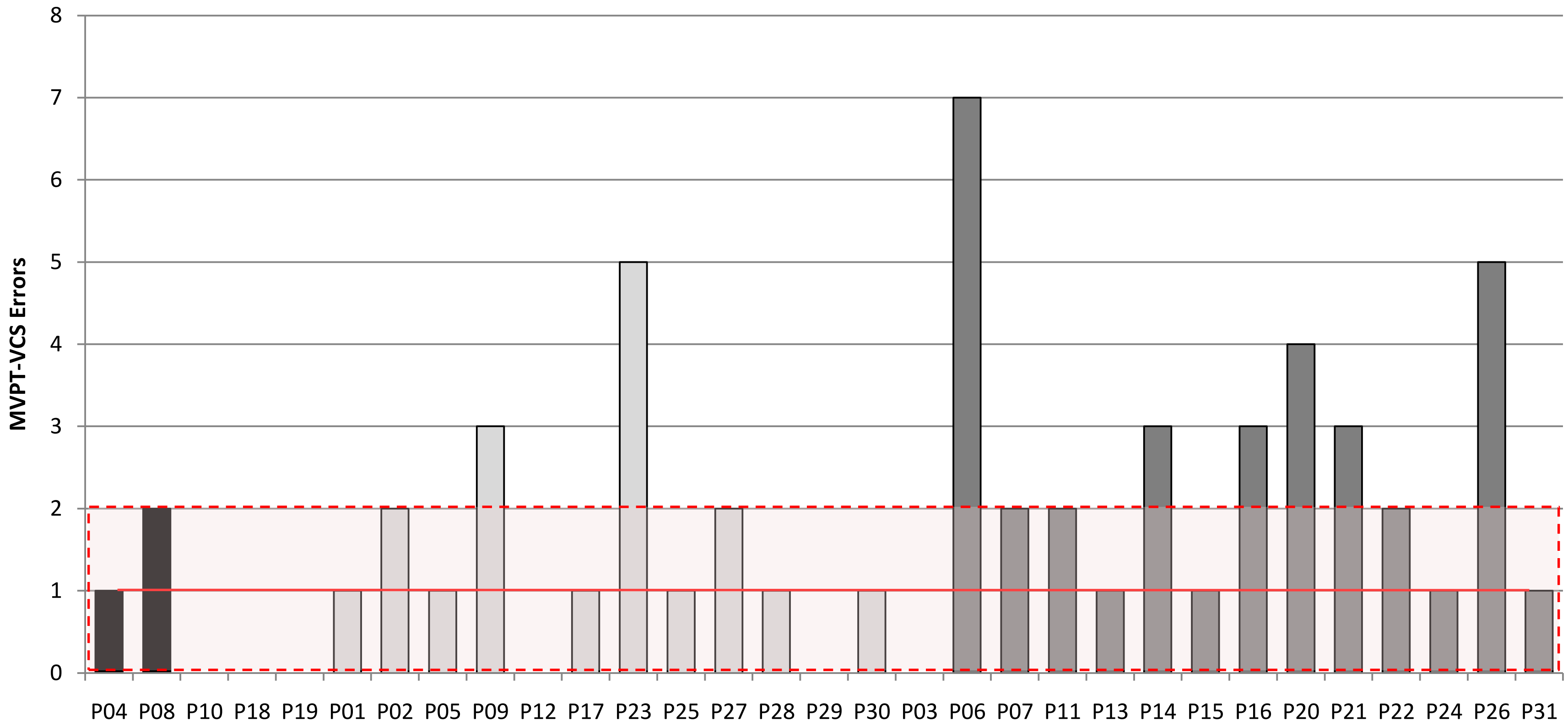


Figure 11 MVPT-VCS case and mean (±1*SD*) control performance

The graph depicts the number of errors made on the MVPT, and the red lines indicate the mean (±1SD) performance for controls. A lower score indicates a better performance. Black bars represent quadrantanopic cases, light grey bars represent right hemianopic cases and dark grey bars represent left hemianopic cases.

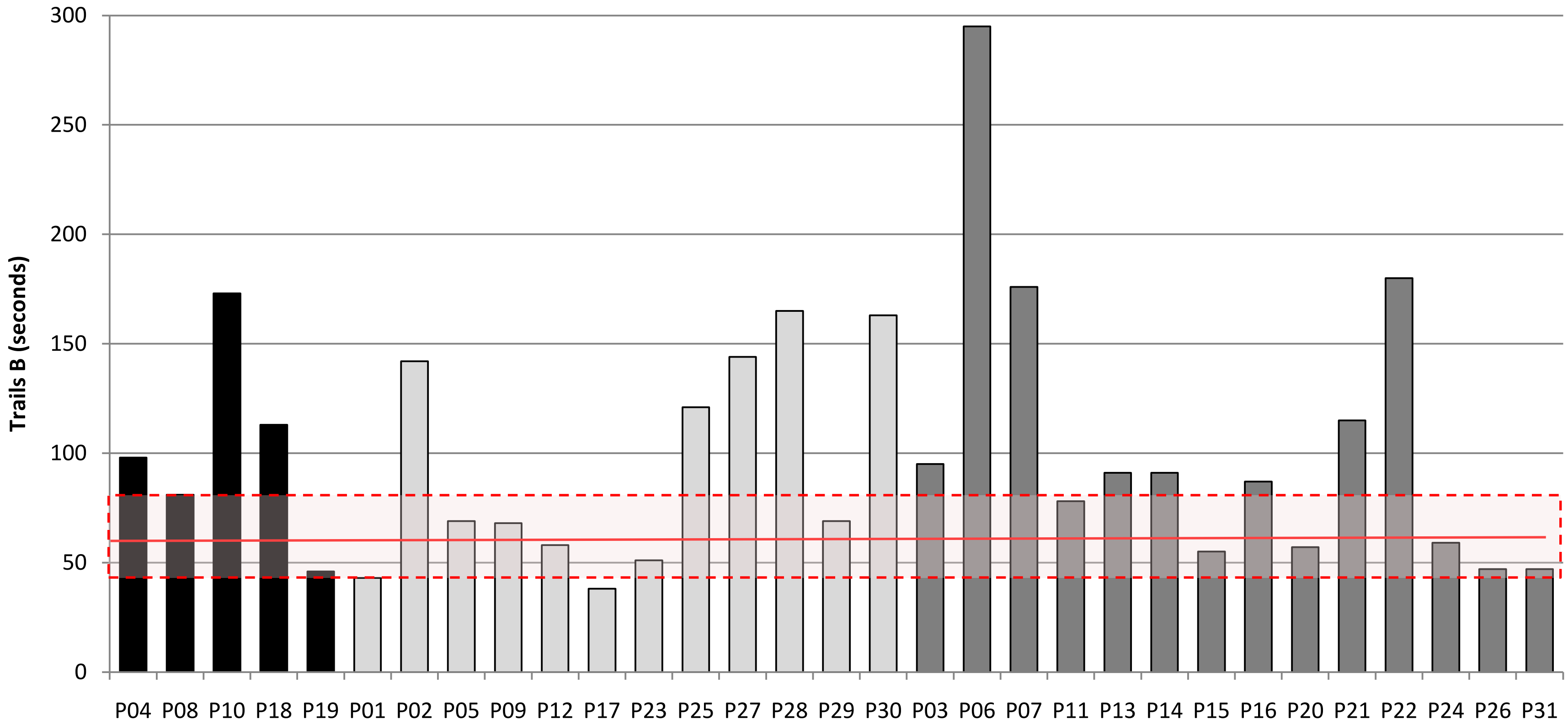


Figure 12 Trails B individual case and mean (±1*SD*) control performance

The graph depicts the time taken to complete the Trails B, and the red lines indicate the mean (±1SD) performance for controls. A lower score indicates a better performance. Black bars represent quadrantanopic cases, light grey bars represent right hemianopic cases and dark grey bars represent left hemianopic cases.

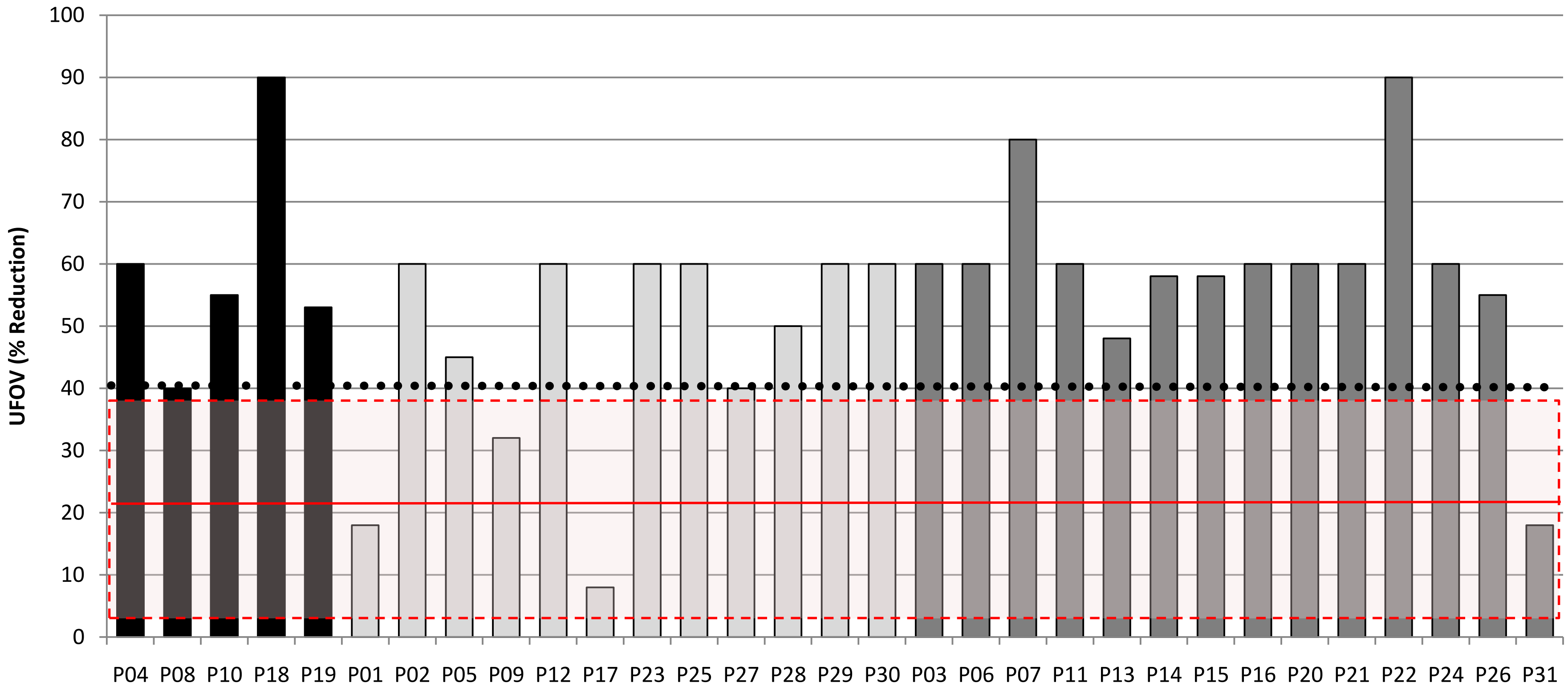


Figure 13 UFOV individual case and mean (±1*SD*) control performance

The graph depicts the percentage reduction from perfect on the UFOV, and the red lines indicate the mean (±1SD) performance for controls. A lower score indicates a better performance. Black bars represent quadrantanopic cases, light grey bars represent right hemianopic cases and dark grey bars represent left hemianopic cases. The dotted black line denotes the standard 40% cut-off for a fail on the task (i.e. those above the 40% mark would fail the assessment).

These figures highlight a number of interesting findings among the cases. For the D2 test of sustained attention, around one third of the cases fell within one standard deviation (or performed better than) the controls. Case numbers P4, P12 and P17 performed particularly well on this task. Notably all three were relatively young (48, 23 and 36 years respectively). It was also evident that some of the cases performed very poorly on the task, processing relatively few items, and overall there was significant variability in performance.

The cases performed better on the MVPT-VCS, with only one-third of the sample making more errors (mean +1*SD*) than the controls, and several of the cases did not make any errors at all on this task. Three cases had difficulty with this task (P6, P23 and P26). Only one of these cases was older (P6 at age 74). Interestingly, the remaining two cases who performed poorly on this task (P23 and P26; age 38 and 51, respectively) did not perform particularly poorly on the D2.

Case performance was quite variable on the Trails B. Around one-third of the cases (n=9) were faster than the mean of the controls, and an additional four cases fell within one standard deviation of the controls. However, some of the cases seemed to have significant difficulty with this task, with one case taking almost five times as long as the controls to complete the task.

Most cases performed poorly on the UFOV, with only a few (n=4) performing better than the mean of the controls, and a total of six cases performing at a level that would be considered a ‘pass’ (i.e. 40% reduction or less). A number of the hemianopic group performed at 60% reduction, and two were as high as 90% reduction. This suggests this task was particularly difficult for the cases, although it was very interesting to note that three cases with hemianopia performed better than the mean for the controls (P1, P17 and P31; again, these participants were younger, aged 48, 36 and 43 years respectively).

4.5 Driving history

All of the controls were fully licensed and active drivers at the time of assessment, while half of the cases were fully licensed and active drivers. This finding was not unexpected given that in Australia, individuals with hemianopic field loss are not legally eligible to drive without special consideration from the licensing authorities. The majority of the quadrantanopic group were active drivers at the time of assessment (n=4) and the remaining case had voluntarily stopped driving. Of the twelve right hemianopic cases, just over half were active drivers (n=6), five had voluntarily ceased driving and the remaining case had a suspended licence. Among the left hemianopic group, the majority had a suspended licence (n=7), with five active drivers and two who had voluntarily ceased driving. Four of the cases who were active drivers had been through a driver licence medical review process after reporting their condition (representing 26% of the active hemianopic drivers). One of the suspended licenses was for reasons unrelated to their medical/vision condition, and the remainder were suspended on the grounds of their visual field impairment.

The mean number of active driving years was higher in the controls (M=34, SD=16) than the hemianopic group (M=27, SD=17) although this did not reach statistical significance $t(60)=1.67$, $p=0.09$. A larger proportion of controls (74%) had been involved in a minor crash over their entire driving history (defined as a crash not resulting in significant injury or damage to the vehicle) compared with cases (58%). None of the crashes in the cases were subsequent to visual field loss. Two serious crashes resulting in significant injury or damage to the vehicle were reported in the cases, however both of these occurred prior to the visual field impairment and resulted in the associated brain injury.

The controls also had a higher proportion and mean number of traffic infringements, however the crash and infringement figures are likely to simply reflect exposure levels given that almost 50% of the cases were not active drivers at the time of assessment; crashes/infringements per driving years did not differ (0.05 crashes and 0.07 infringements in each group). These results are summarised in Table 10.

Table 10 Summary of driving histories

	CASES		CONTROLS	
CURRENTLY DRIVING?				
Yes (n)	15	48%	31	100%
No (n)	16	52%	0	0%
LICENCE STATUS				
Full licence and active driver (n)	15	48%	31	100%
Voluntarily stopped driving (n)	8	26%	0	0%
Suspended licence (n)	8	26%	0	0%
DRIVING EXPOSURE (YEARS LICENCED)				
Mean years driving	27.2	*SD*=12.3	34.2	*SD*=15.3
Mean years since stopped driving (n=16 cases)	6.4	*SD*=4.2	n/a	n/a
CRASH INVOLVEMENT				
Yes (n)	18	58%	23	74%
No (n)	13	42%	8	26%
Mean number of crashes	1	*SD*=0.05	1	*SD*=0.02
Mean crashes per driving years	0.05	*SD*=0.06	0.05	*SD*=0.07
TRAFFIC INFRINGEMENTS				
Yes (n)	18	42%	22	71%
No (n)	13	58%	9	29%
Mean number of infringements	1	*SD*=0.1	2	*SD*=0.2
Infringements per driving years	0.07	*SD*=0.07	0.07	*SD*=0.04

4.6 Summary and discussion

In summary, there were several differences in demographic, vision and cognitive measures between the cases and controls. Firstly, in terms of demographics, case-control matching was performed on the basis of age and sex, therefore as expected no differences were observed between the two groups on either of these measures. The mean age of the participants was 52 years, with a range from 22-79 years. The control group were more likely than the cases to be married, live in a metropolitan area and have completed a tertiary level education.

Other than the medical conditions associated with visual field loss, there were no significant differences between the groups on number of chronic medical conditions that were considered likely to affect attention. As expected, the cases had a higher number of medical conditions when including the brain injury relating to their field loss. The cases reported more than double the number of prescription medications than the controls, which was not an unexpected finding given that many of the cases were undergoing post-stroke treatment (e.g. anticoagulants to prevent further episodes). However, this was unlikely to affect performance on the experimental task given that all participants were screened for medications that were considered likely to affect attention, including psychotropics, opiate-based medications or anti-epileptics.

On the visual assessment measures, both the cases and controls had normal visual acuity and contrast sensitivity. The cases had marginally better visual acuity than the controls, which is most likely accounted for by one participant in the control group whose distance acuity score was low and was associated with a refractive error that was not well corrected at the time of testing (LogMAR +0.3). This result was not considered likely to affect performance on the change blindness task as near acuity, contrast sensitivity and visual fields were all normal for this participant.

As expected, significant differences were found between the cases and controls on both measures of the visual fields; 24-2 merged binocular fields and the Esterman binocular functional field test. These results reflect the presence of visual field loss in the cases compared with normal visual fields of the controls. Although it could be expected that a more extensive field loss would result in a poorer performance on a range of visually guided tasks, this research was primarily concerned with compensation for field loss. Therefore, on the change blindness task it was possible that individuals with less extensive field loss (i.e. quadrantanopia) may perform better than those with more extensively impaired visual fields. However, it was also anticipated that some individuals, even with extensive field loss, would compensate and ultimately perform as accurately as controls by adopting compensatory search strategies.

Significant case-control differences were found on all of the cognitive measures; the D2, MVPT-VCS, Trails B and UFOV which suggests a general reduction in visual attention, processing and scanning in the case group. However, it is important to note that no evidence of gross cognitive impairment (MMSE>23) was found for either the cases or controls, despite slightly higher MMSE scores for the control group. These findings are not unexpected in the context of the brain injury and associated field loss. Both aetiology and laterality of the brain injury have been shown to generally affect cognition, and attention is one aspect that is frequently involved (Leclercq et al., 2002). There was also wide variability in scores among the cases, which represents a broad spread of performance.

The majority of brain injuries in the present study were attributed to either CVA or TBI, and attentional impairments are frequently reported as a result of these types of injury. For example, the most consistent finding of attentional impairment in TBI is mental ‘slowness’, which is conceptualised as a global, non-specific slowing of information processing (Benton, 1986; Blackburn & Benton, 1955; Hicks & Birren, 1970; Leclercq et al., 2002; Miller, 1970; Norrman & Svahn, 1961). More recent evidence suggests that the presence of specific attentional impairments may depend on the nature and complexity of the task (VanZomeren & Brouwer, 1994). Studies using complex resource-demanding tasks performed under time pressure suggest that TBI may actually be associated with some degree of impairment of focused attention, vigilance, sustained attention, and divided attention (Couillet, Leclercq, Martin, Rosseaux & Azouvi, 2000; Leclercq & Azouvi, 2002; McDowell, Whyte & Desposito, 1997; Park, Moscovitch & Robertson, 1999; Ponsford & Kinsella, 1992; Spikman, VanZomeren & Deelman, 1996; VanZomeren & Brouwer, 1994; Veltman, Brouwer, VanZomeren & Wolffelaar, 1996).

Attentional impairments are also observed post-stroke, occurring in over half of cases, and are often referred to as the most prominent stroke-related neuropsychological change (Chao & Knight, 1995; Dee & VanAllen, 1973; Godefroy & Rosseaux, 1996; Leclercq et al., 2002). Impairments following CVA have been found on perceptual-motor slowing and alertness, vigilance and sustained attention, divided attention and focused attention (Dee & VanAllen, 1973; Godefroy, Lhullier & Rosseaux, 1996; Godefroy & Rosseaux, 1996). In a review of attention and stroke, Leclercq and colleagues reported that impaired attention post-stroke has been associated with reduced cognitive productivity even when other cognitive functions remain intact (Leclercq et al., 2002).

However, a number of studies investigating attention following TBI or CVA demonstrate that although slowed processing is observed on a number of different tasks (including perceptual, cognitive and motor), error rates are not increased when the task is subject to self-paced timing (Brouwer & VanWolffelaar, 1985; Craik & Salthouse, 2000; Gronwall & Sampson, 1974; Leclercq et al., 2002; Miller, 1970; Ponsford & Kinsella, 1992). The effects of self-paced timing have been interpreted in the context of speed-accuracy trade-offs, and have been frequently observed in tasks such as Trails B.

In the present study, case performance on the cognitive tasks was found to be consistent with previous literature on attentional performance following brain injury: cases were slower to complete the self-paced cognitive tasks (Trails B), and made more errors or processed fewer stimuli on the forced-paced tasks (MVPT-VCS and D2). Given that the change blindness task used in this study was self-paced, it would be expected that the cases would be slower to respond to stimuli. However, as the task aimed to assess whether stimuli could be perceived and processed in the blind region (rather than how fast it could be achieved), the key outcome of interest was performance accuracy.

Laterality of brain injury is also an important factor in cognitive performance, particularly given that attention is thought to be largely a frontal lobe and right hemisphere function (Arlinghaus et al., 2005; Bertelson, 1982; Farah, 2000). Right-sided injuries (resulting in left visual field loss) are more often associated with visual neglect and perceptual problems. In contrast, left-sided injuries (resulting in right visual field loss) tends to be associated with language or reading problems (Farah, 2000). Given the perceptual difficulties associated with right-sided lesions, it was possible that the cases with left-sided visual field loss would take longer to respond to targets (i.e. the visual aspects of the task would take longer to process). However, functional compensation is more likely to be attributable to a combination of factors, and it was expected therefore that laterality of brain injury alone would not be a strong predictor of compensation.

Results for driving experience and exposure showed that all of the controls were active drivers with full licence at the time of assessment, and around half of the cases were active drivers. The controls had a higher mean number of years licensed than the cases, although there were no differences after adjusting for number of active driving years. The number of minor crashes and traffic infringements per years of active driving did not differ between the cases and controls. Driving variables (experience/exposure) were of interest because it is possible that longer driving experience might be reflected in change blindness error scores given the task used naturalistic driving scenes and thus familiarity may have been a factor. However, it also is possible that the experience of active drivers at any level may be sufficient to generate an effect of scene familiarity, therefore no differences between cases and controls would be expected.

Overall, there were a number of key differences between the cases and controls on the demographic, vision and cognitive measures. These differences are explored in greater detail in Chapter 7 with respect to their impact on performance on the change blindness experimental task.

Chapter 5 Change blindness performance

5.1 Introduction

The review of research in Chapter 1 identified conflicting evidence as to whether individuals with hemianopic visual field loss are safe to drive. Few studies have specifically considered driving performance and safety in hemianopic field loss, however research on visual field loss more generally has found mixed results. In some studies, individuals (even with extensive field loss) passed formal on-road driving tests and demonstrated driving skills that were indistinguishable to controls (Racette & Casson, 2005; Schulte et al., 1999; Tant et al., 2002; Wood et al., 2009). In contrast, other studies have found that visual field loss increases the relative risk of crashes (Burg, 1967). These inconsistencies probably reflect the interaction of multiple complex factors which are likely to affect driving performance in hemianopia; such as extent and location of field defect, time since onset of field loss, co-morbid medical conditions, gross cognitive impairment, age, and individual adaptation (or compensation) for field loss.

Several demographic and clinical factors have been reported as potential explanatory variables for driving performance in the context of visual field impairment. However, one critical factor that remains subject to debate in the literature is the degree to which individuals can *compensate* for their loss. Much of the debate has arisen from the difficulties in the objective measurement of a construct such as compensation, which is likely to vary widely among individuals.

Typically, compensation has been studied using visual parameters, where it has been found that visual scanpaths in those with hemianopia differ from those with normal vision (Zihl, 1995). These 'hemianopic scanpaths' tend to be characterised by increased saccades toward the blind hemi-field, and frequent repetitions of scanpaths during visual search and inspection (Tant et al., 2002). Eye movement patterns are typically considered the behavioural interface between attention and information acquisition by the individual from the environment (Recarte & Nunes, 2003), and thus researchers have interpreted hemianopic scanpaths as indicative of compensation for field loss.

However, there is limited evidence that these visual scanning patterns lead to positive functional outcomes in everyday tasks. Furthermore, visual search that results in fixation of a stimulus of interest does not necessarily imply attentional processing, as demonstrated by psychological paradigms such as covert attentional processing (direction of attention to a location in the absence of overt signs of orienting) and inattentional blindness (fixation is not necessarily the focus of attention). Effective visual search requires more than a response to sensory input; it also requires a range of cognitive processing skills such as attention, object recognition, and application of stored knowledge from memory.

In this study, a visual attention paradigm was employed to investigate functional compensation in hemianopia. Of interest was whether individuals were able to employ selective attention to accurately identify targets in their blind regions. This was conducted using the *change blindness* paradigm, which refers to the phenomenon that people fail to notice large changes to a visual scene when the motion signals that normally accompany change are masked (Rensink et al., 1997). The theoretical framework underpinning the change blindness paradigm argues that the key factor in producing change blindness is attention; visual perception of change in any given scene occurs only when the change is being selectively attended (Rensink, 2000, 2001; Rensink et al., 1997; Simons & Ambinder, 2005; Simons & Rensink, 2005).

Using the change blindness paradigm, an experimental task was developed specifically for this research. Forced responses were required to identify targets across 140 degrees of the horizontal visual field, with eye movements permitted. It was proposed that this method would assess several parameters simultaneously, including selective visual attention, information processing, scene perception and visual scanning. These are all measures of functional vision, which are arguably highly relevant for driving (e.g. (Anstey, Wood, Lord & Walker, 2005; Ball et al., 1993; Colenbrander & DeLaey, 2006; H. Lee, Lee & Cameron, 2003; Richardson & Marottoli, 2003; Underwood, Chapman, Brocklehurst, Underwood & Crundall, 2003).

Therefore, the overall aim of the component of the study described in this chapter was to investigate the extent to which individuals with hemianopia or quadrantanopia adequately 'compensated' for their visual field loss when assessed on the visual attention (change blindness) task. Compensation was measured by the ability to accurately detect stimuli that were presented in both the blind and seeing regions of the visual field. The ability to detect these stimuli involved two stages: firstly, visual identification of the target was necessary, and secondly, selective attention was required to identify and respond to the target.

It was expected that if individuals with hemianopia compensated effectively, they would be able to correctly identify targets, even when targets were presented in the blind regions, albeit with slower response times overall. If they failed to correctly identify changes in the blind region, it would indicate a failure to selectively attend the relevant information, implying that the way in which they searched the scene provided no functional advantage. Thus, this chapter focuses specifically on the accuracy (and timing) of the responses to the targets, with the underlying mechanisms (visual search patterns) and cognitive and other predictors considered separately in Chapters 6 and 7, respectively.

5.2 Method

Detailed methods for the change blindness experiment are provided in Chapter 3 and are summarised here.

5.2.1 Participants

Sixty-two participants were included in this study, comprising 31 cases with hemianopic field loss and 31 controls matched for age and sex. Detailed information regarding the demographic, clinical, vision and cognitive status of the sample can be found in Chapter 4.

5.2.2 Procedures

Participants viewed images of naturalistic driving scenes on a large rear-projection screen subtending 140 degrees of horizontal visual angle. The images (stimuli) were presented according to the change blindness flicker paradigm; the original stimulus was alternated with a modified stimulus containing a single change (target). Participants viewed the alternating stimuli until the target had been perceived, or 45 seconds elapsed. The targets were counterbalanced for location of presentation (quadrant) and contained a mix of task-relevant (driving) and non-task relevant targets. The targets were also coded for a range of saliency aspects, including size, contrast and scene complexity. Participants viewed 111 stimuli in total; 25 targets in each quadrant, 8 central targets, and 3 stimuli without targets. The dependent variables were accuracy (errors) and response time.

5.3 Results

5.3.1 Error data

5.3.1.1 Between group comparisons: Overall errors

The key question of interest in this chapter was whether the individuals with hemianopic/quadrantanopic visual field loss were able to correctly detect the targets. First, in order to understand the overall pattern of task accuracy within the case group, the number of errors for each case (out of a possible 108, representing all trials with targets) were plotted relative to the mean number of errors (± 1*SD*) for the control group (*M*=6.7, *SD*=2.3). These data included both possible types of errors: errors of commission (incorrect responses to targets that were not present), and errors of omission (time-outs where targets were missed and no response was recorded). As depicted in Figure 14, the results show a wide variation in error scores across the hemianopic group. Just less than half of the cases made more errors than the controls (n=13, 42%); 16 percent (n=5) made fewer errors than the controls, and the remaining 42 percent (n=13) performed around the same as the controls (within 1*SD*). Interestingly, all cases in the quadrantanopic group (i.e. less extensive visual field loss) performed within the mean (± 1*SD*) of the controls.

The results also identified two extreme outliers with hemianopia (P2 and P6). These two cases had very high error scores in comparison with the rest of the sample (n=87 errors and n=83 errors, respectively). Given the extreme values for these two cases, their data (along with age-matched controls) were removed from all group analyses to ensure that they did not skew the data. However, it was considered appropriate to include their data on matched-pairs analyses given that these analyses identified the differences between the individual pairs, rather than performance on a group level.

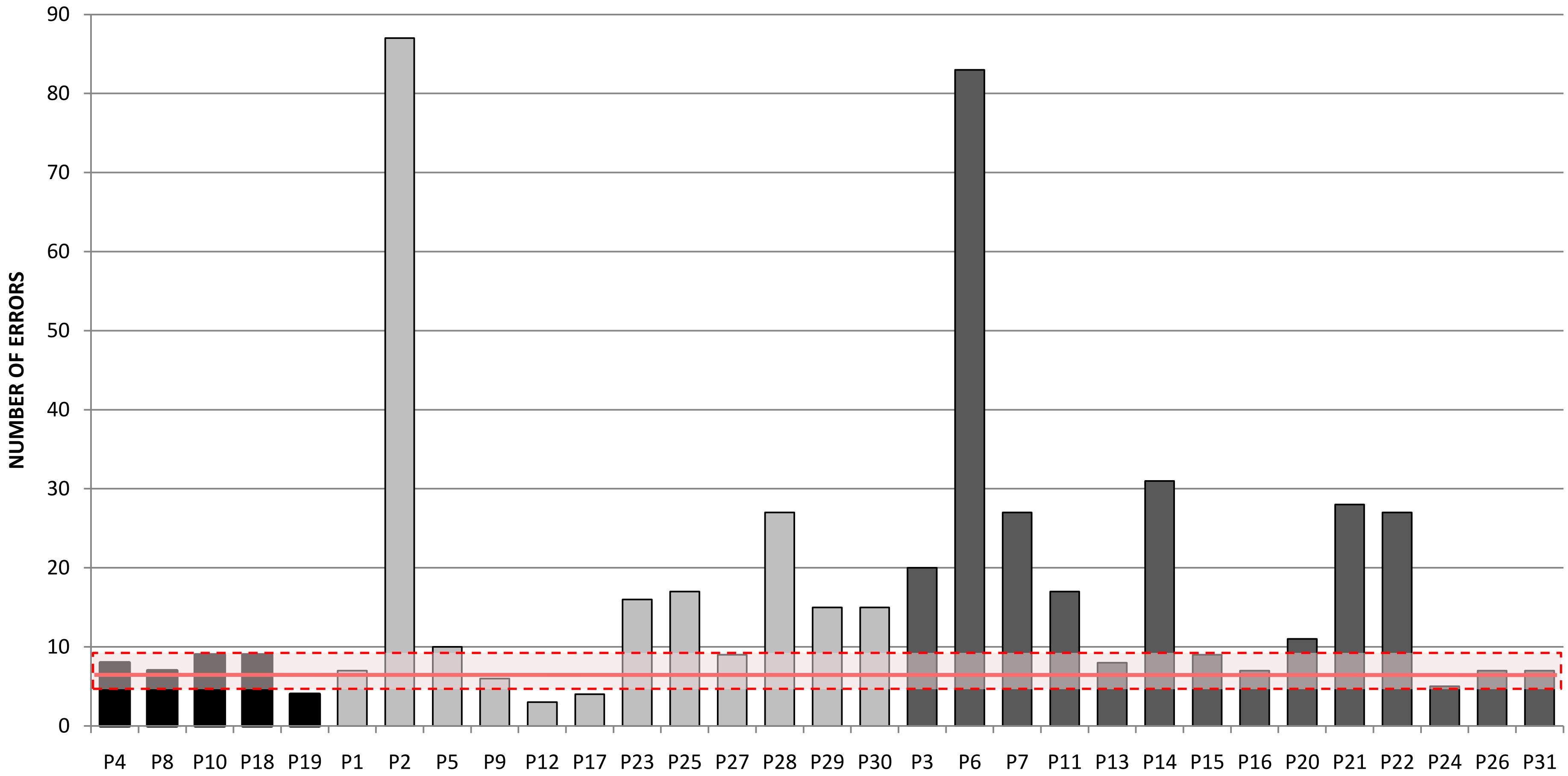


Figure 14 Case errors (n) and mean errors (± 1*SD*) for controls

Black columns represent quadrantanopia, light grey columns represent right hemianopia and dark grey columns represent left hemianopia.

The next analysis of interest compared the relative differences in overall correct responses between control and case groups (pooled across type of visual field loss, location and target features). It was hypothesised that if cases were able to compensate for their field loss, their overall correct detection of targets would be comparable to controls. Where errors did occur, there were two possible types: errors of commission (incorrect responses to targets that were not present), and errors of omission (time-outs where targets were missed and no response was recorded). For the first set of analyses, only *overall correct responses* were considered.

The data were analysed using a binary logistic regression model. To maximise statistical power, all observations (n=108) for each of the participants were included in the model (n=58, after excluding the two outliers and their matched controls). This model used *correct responses* as the outcome and predictive factors included *pair ID* (a measure identifying the matched pairs) and *case status* (case or control).

The results revealed that the case and control groups differed markedly in the odds of responding correctly on the change blindness task. The relative odds of responding correctly were 66% lower for the cases than controls (OR=0.34, CI=0.29-0.41, p<0.001).

Significant heterogeneity of performance was expected for the cases given the clinical characteristics described in Chapter 4. This was observed, and is evident in the wide variation in error performance shown in Figure 14 and further supported with findings showing a significant effect on a test of homogeneity (χ^2_{30}=193, p<0.001). Therefore, additional analyses were conducted to further explore individual differences between individual cases and their matched control.

5.3.1.2 Individual error performance for matched pairs

To identify individual cases who performed well on the task, a second binary logistic regression model was constructed to investigate the likelihood of responding correctly on a matched-pairs basis using *correct responses* as the outcome. This analysis was selected to offset the large effects of variance within the case group. Results were expressed as the odds of each case responding correctly on the change blindness task relative to their matched control across all 108 stimuli. The factors included in the model were *pair ID* and *case-control status*, with an interaction term between *case-control status* x *pair ID*. Given that this analysis considered the performance of each case relative to their matched control, the two outliers were included.

Figure 15 depicts the odds ratios for correct responses in the matched pairs. An odds ratio of 1 (denoted by the red line) indicates that the odds in the matched pair were equal (i.e. the case and matched control had equal odds of responding correctly), an odds ratio of more than 1 indicates that the case had better odds of responding correctly compared with the control, and an odds ratio of less than 1 indicates that the case had lower odds than the matched control of responding correctly.

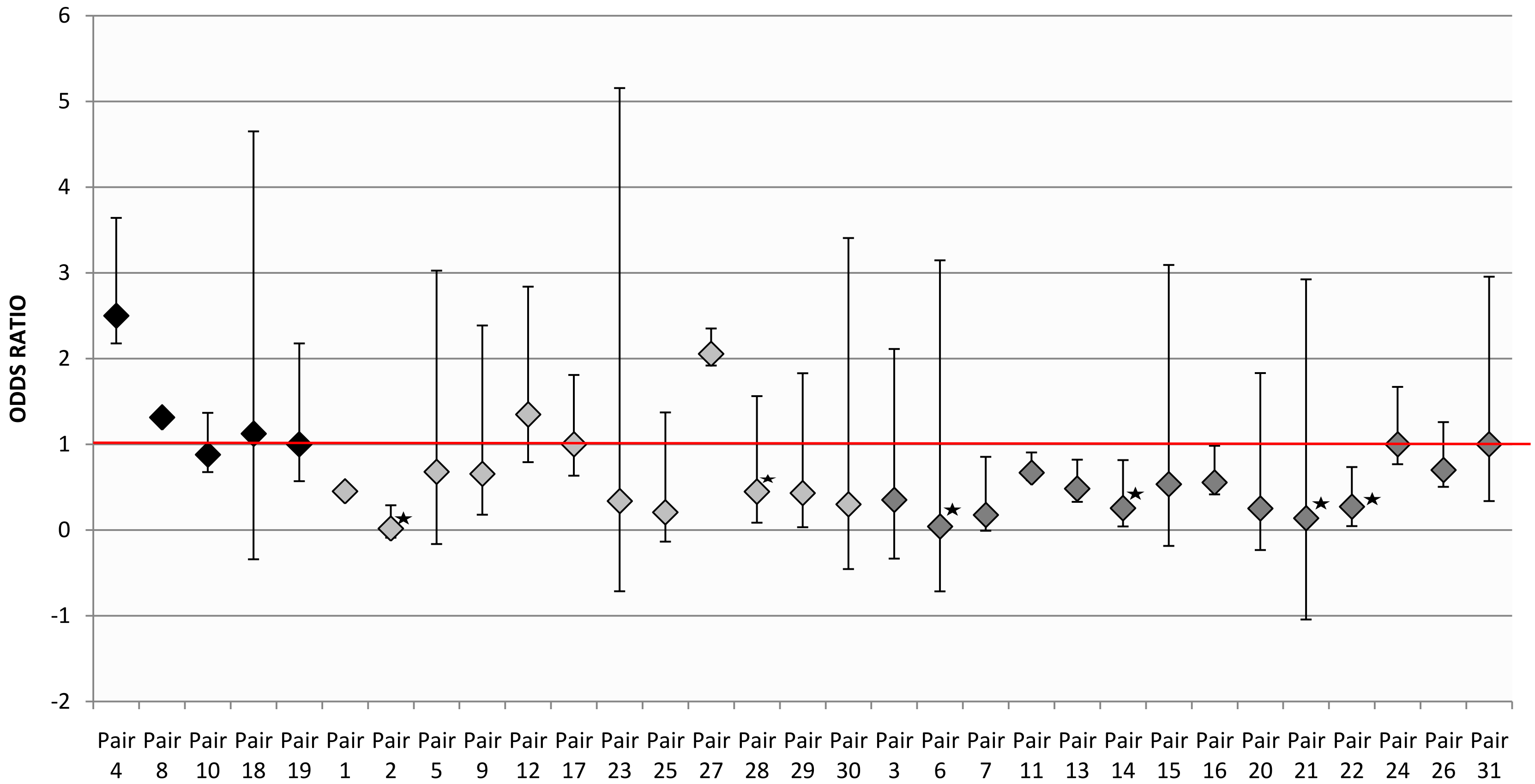


Figure 15 Odds ratios for matched pair errors

Red line indicates equal odds of responding correctly, OR > 1 indicates the case had higher odds of responding correctly, OR < 1 indicates the case had lower odds of responding correctly. Asterisks denote significant ORs. Black = quadrantanopia, light grey = right hemianopia & dark grey = left hemianopia.

The results indicated a wide variation across participant pairs. Six cases had significantly lower odds of responding correctly compared to their control. Nine cases (around 30%) had equal or higher odds of responding correctly on the task relative to their matched control, with odds ratios ranging from 1.0 to 2.5, although none of these reached statistical significance. The values for the individual pair odds ratios and confidence intervals are shown in Appendix 8.

Visual field loss group performance

Responses were also compared by type of visual field loss. As shown in Figure 16, in the left hemianopic group, four cases performed significantly worse than their matched control. In the right hemianopic group, two cases performed significantly worse than their control, and no cases in the quadrantanopic group performed significantly worse than their control. To explore this further, a group analysis for the total number of errors (outliers excluded) was performed between the three visual field loss groups. The results showed higher mean error scores for the left hemianopic group (M=15.5, SD=9.6) compared with the right hemianopic group (M=12.0, SD=7.4), although the difference did not reach statistical significance $F(2, 27)=1.04$, p=0.17. Interestingly, the quadrantanopic group had a mean error rate less than half that of the left hemianopic group (M=7.4, SD=2.1).

These data demonstrate how the participants performed across the entire 140^{0} of horizontal visual field. It was also of interest to consider whether the pattern of errors was different when the targets were presented in the intact versus the impaired visual fields. Thus, the following set of analyses focuses on performance in the blind versus the seeing regions.

5.3.1.3 Error performance in blind regions versus seeing regions

As described in chapter 4, there was significant variation in the case group in terms of extent and location of visual field loss. Therefore, in order to analyse the error rates in the blind and seeing regions, targets were coded for location of presentation: either a blind or seeing location depending on the quadrant of presentation and region of field loss. For example, in a right hemianopic case, each target presented in the upper and lower right quadrants was coded as blind, and the targets in the upper and lower left quadrants were coded as seeing. The matched control was coded in the same way to ensure the reactions were being compared for the same visual space. All of the central targets and no-change stimuli were removed prior to analysis.

A logistic regression model was again applied to the total error data to investigate the likelihood of responding correctly in the blind region(s) versus the seeing regions as a group. As this was a group analysis, the two outliers were removed. The model used *correct responses* as the outcome, with predictor factors: *pair ID*, *case status* and *region* (blind or seeing), and an interaction variable *case-control status* x *region*. The group-based relative odds are presented in Figure 16.

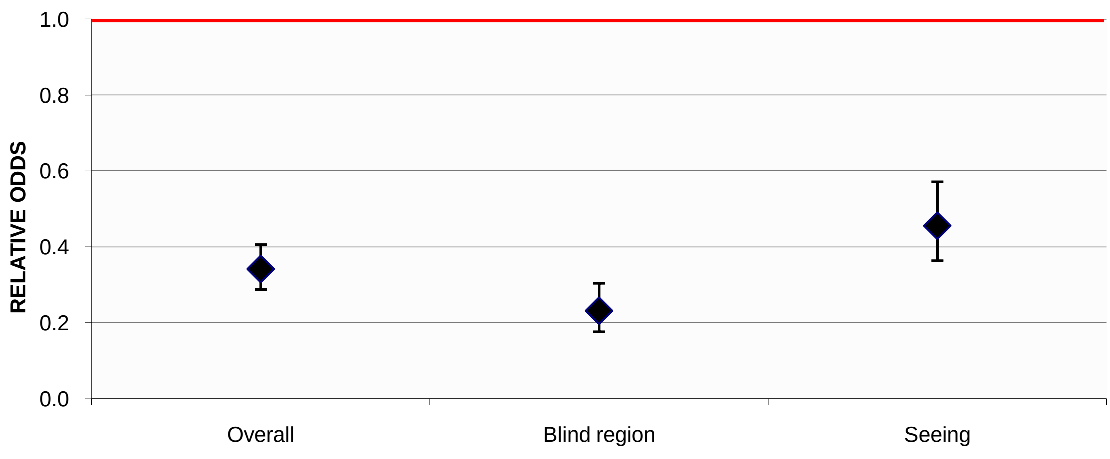


Figure 16 Relative odds for cases' correct responses in blind regions

Red line (OR=1) indicates equal odds of responding correctly. OR < 1 indicate lower odds of the cases responding correctly

As reported in section 5.3.1.1, when responses were pooled across blind and seeing region, cases showed 66% lower overall odds of responding correctly compared with the controls. When region of target presentation was considered, the odds of responding correctly were more marked for the seeing regions than the blind regions (i.e. the performance of the cases was better in the seeing regions than the blind regions, although both were still poorer the controls). For example, when the stimuli were presented in a blind region, the odds of the cases responding correctly were 77% lower than the controls (OR=0.23, CI=0.17-0.30, $p<0.001$); and conversely, when presented in the seeing regions, the odds of the cases responding correctly dropped to 54% lower than the controls (OR=0.46, CI=0.36 - 0.57).

These findings indicate, as expected, that the cases made more errors relative to their control in the blind regions. It was interesting to note that while the differences were less marked, the cases also had higher odds of making errors in the seeing regions compared with their control. This suggests a potential overall deficit in scanning ability, or could point to higher-order or generalised cognitive problems in the cases. This possibility is explored in later chapters.

Again, to offset the significant heterogeneity observed amongst the cases, a logistic regression model was applied to the error data to consider performance on an individual matched-pairs basis. The model used *total errors* at the outcome, with *pair ID, case status* and *blind region* as factors, and interactions between *pair ID* x *case status* and *pair ID x case status x blind region* built into the model. This analysis was intended to identify whether the relative odds for individual pairs differed when the target was presented in the blind region versus the seeing region.

Most of these results were non-significant. On a descriptive level, almost a third of the cases (9 out of a possible 31) had equal or better odds than their control of responding correctly in the blind regions. Similarly, in the seeing regions, the odds of responding correctly were equal to or higher than controls in ten cases (32%). Although few of the matched-pairs analyses reached statistical significance, the overall case-control differences indicate that the presence of a hemianopic field loss did not necessarily reduce the odds of responding correctly relative to controls, regardless of whether the stimulus was presented in the blind region or not. This suggests that the majority of the cases (but not all) were less effective at scanning the entire visual space, not just the impaired regions. The relative odds of responding correctly on an individual case basis for both blind regions and seeing regions are presented in Appendix 9 (blind regions) and 10 (seeing regions).

5.3.1.4 Role of complexity, contrast and image type on error rates

Given that the stimuli were based on naturalistic driving scenes, it was important to consider the visual characteristics of the stimuli. To investigate the potential role of the features of the stimuli influencing task performance, stimuli were classified in several ways: complexity (high, medium or low); contrast (mean contrast between the target and background: high, medium or low); and task relevance (traffic-related target, such as a car, or non-traffic related target, such as roadside advertising).

Firstly, chi squared analyses were performed to consider the role of the individual features on task performance and whether image features affected the cases and controls differently. The two outliers and their matched controls were removed prior to analysis. The results revealed significant differences for error rates across the three contrast categories in the direction expected. The highest proportion of errors occurred for low contrast targets $\chi^2(2, n=578)=6.72$, $p<0.05$ (<33 lux mean difference to background), and interestingly, neither the cases nor controls made any errors for high contrast targets.

A comparison of performance across complexity categories revealed higher error rates for high complexity scenes compared with the medium or low complexity scenes $\chi^2(2,n=578)=110.33$, $p<0.001$. The results also showed significant differences for image type. When targets were non-traffic related, the proportion of errors was double that of the traffic-related targets $\chi^2(2, n=578)=60.54$, $p<0.01$. Furthermore, no significant differences in the proportion of error rates between cases and controls were detected. The percentage of errors for each image type is presented in Figure 17.

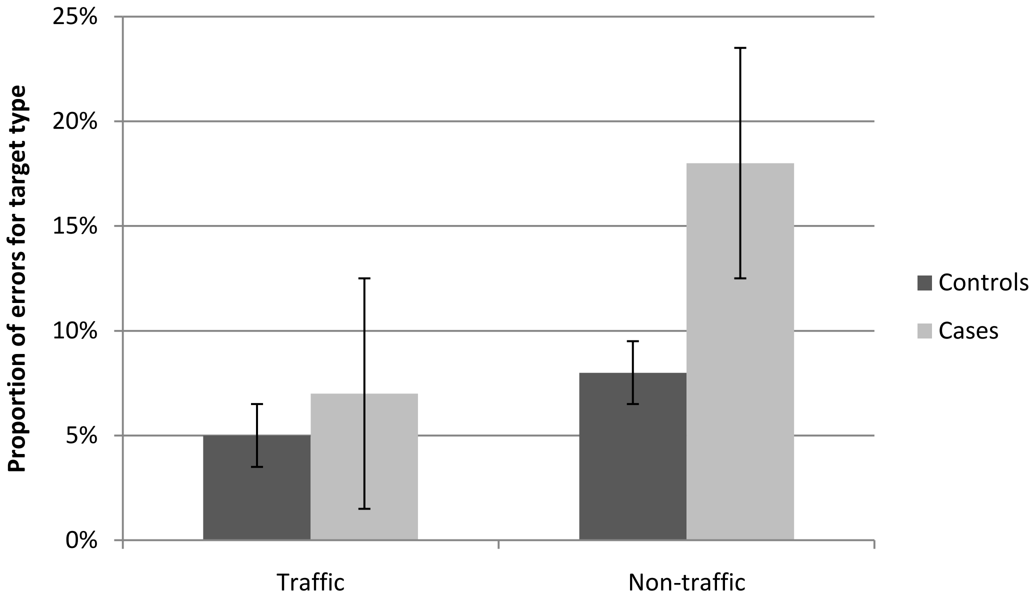


Figure 17 Proportion of errors for traffic & non-traffic related stimuli

5.3.1.5 Observations for different error types

The analyses presented thus far were based on *total correct response* data. However, performance was also analysed for two subtypes of errors: errors of omission and errors of commission. There were insufficient data to apply a logistic regression model to the individual error types, however the patterns of errors are described below. Figure 18 depicts the distribution of error types for both cases and controls (these data exclude the two outliers).

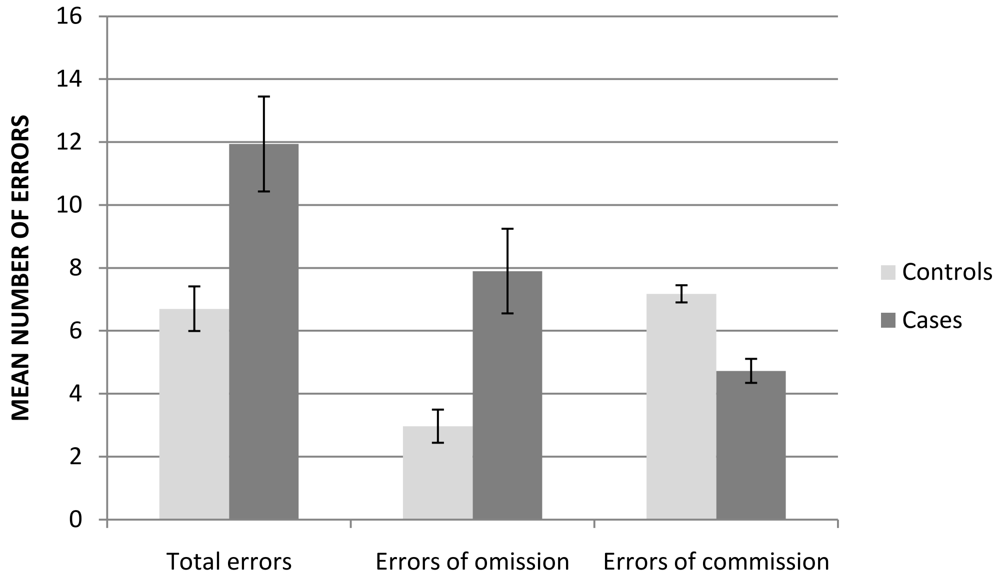


Figure 18 Distribution of error types for cases and controls

Overall, the cases (*M*=11.9, *SD*=1.5) made more errors than the controls (*M*=6.7, *SD*=0.7). When the data were considered separately for each error type, the cases were found to make significantly more errors of omission (*M*=7.9, *SD*=1.3) than errors of commission (*M*=4.7, *SD*=0.4) $t(56)=2.2$, $p<0.05$.

Comparing these error types with controls, it was observed that the range for the errors of commission among the cases was less variable than other error types and more closely mirrored that of the controls: no significant differences were observed between the two groups $t(56)=1.08$, $p=0.29$. In contrast, there were large differences between cases and controls for errors of omission. The cases made on average 7.9 errors of omission (*SD*=1.3) compared with controls who made on average 3.0 errors of omission (*SD*=0.5), $t(56)=3.26$, $p<0.01$.

These findings suggest that the cases and controls may approach the task differently: errors of omission could potentially represent a more cautious approach which was more evident in the cases. To explore this further, the next set of analyses focused on response time performance during the task.

5.3.2 Response time data

5.3.2.1 Autocorrelations and serial dependency

Prior to conducting analyses on the response time data, it was important to rule out any effects of serial dependency of participants' responses across the 108 change blindness trials. Serial dependency, or autocorrelation, in the context of visual inspection describes the correlation among successive data points collected over time (i.e. subsequent points in a data series can be predicted from a previous level of performance). In order to reduce the potential for serial dependency (or learning effects) on this task, the order of stimulus presentation was randomised for each participant given that presenting a number of successive targets in the same location is likely to affect the speed of response. Autocorrelation analysis was also performed across all observations (n=108) at different time lags (16 points) for the control group which confirmed that there was no evidence of serial dependency in the response time data. A summary of the autocorrelation estimates are provided in Appendix 11.

5.3.2.2 Overall response time performance for cases and controls

In order to explore differences between the cases and controls for response times, individual cases were plotted as mean (correct) response time relative to the mean response time (±1*SD*) for the controls as a group (Figure 19). The results again demonstrate a wide range in individual case performance. It was particularly interesting to note that both the extreme outliers (P2 and P6) had long mean response times for those trials in which they correctly located targets.

The mean response times for the cases (M=10.6s, SD=4.1) were significantly longer than the controls (M=7.2s, SD=3.5), $t(56)=4.5$, $p<0.01$. However, as shown in Figure 19, almost 40% of the cases (n=12) responded at or within (+/-) one standard deviation of the mean response time for the control group. Furthermore, four of the cases (13%) responded (correctly) more quickly than the control group's mean response time. Another interesting observation, consistent with the error data, is that after excluding the two outliers, the quadrantanopic group appeared to have shorter response times (*M*=8.7s, *SD*=2.63) compared to the right hemianopic (*M*=9.6s, *SD*=3.46) or left hemianopic groups (*M*=12.1s, *SD*=4.6), although this did not reach statistical significance.

A comparison of the field loss groups and control group found that response times in the quadrantanopic group (*M*=8.7s, *SD*=2.63) were not significantly different to controls (*M*=6.7s, *SD*=2.3). However, both the right hemianopic group (*M*=9.6s, *SD*=3.46; $t(37)=3.05$, $p<0.01$) and left hemianopic group (*M*=12.1s, *SD*=4.6; $t(41)=5.04$, $p<0.001$) were significantly slower than controls. The left hemianopic group appeared the most impaired on the task, with a mean response time almost double that of the controls. Taken together, these findings are consistent with previous literature on the extent of field loss (a larger visual field defect is likely to result in a greater impairment) and laterality of brain injury (left hemianopia is more likely to result in perceptual problems).

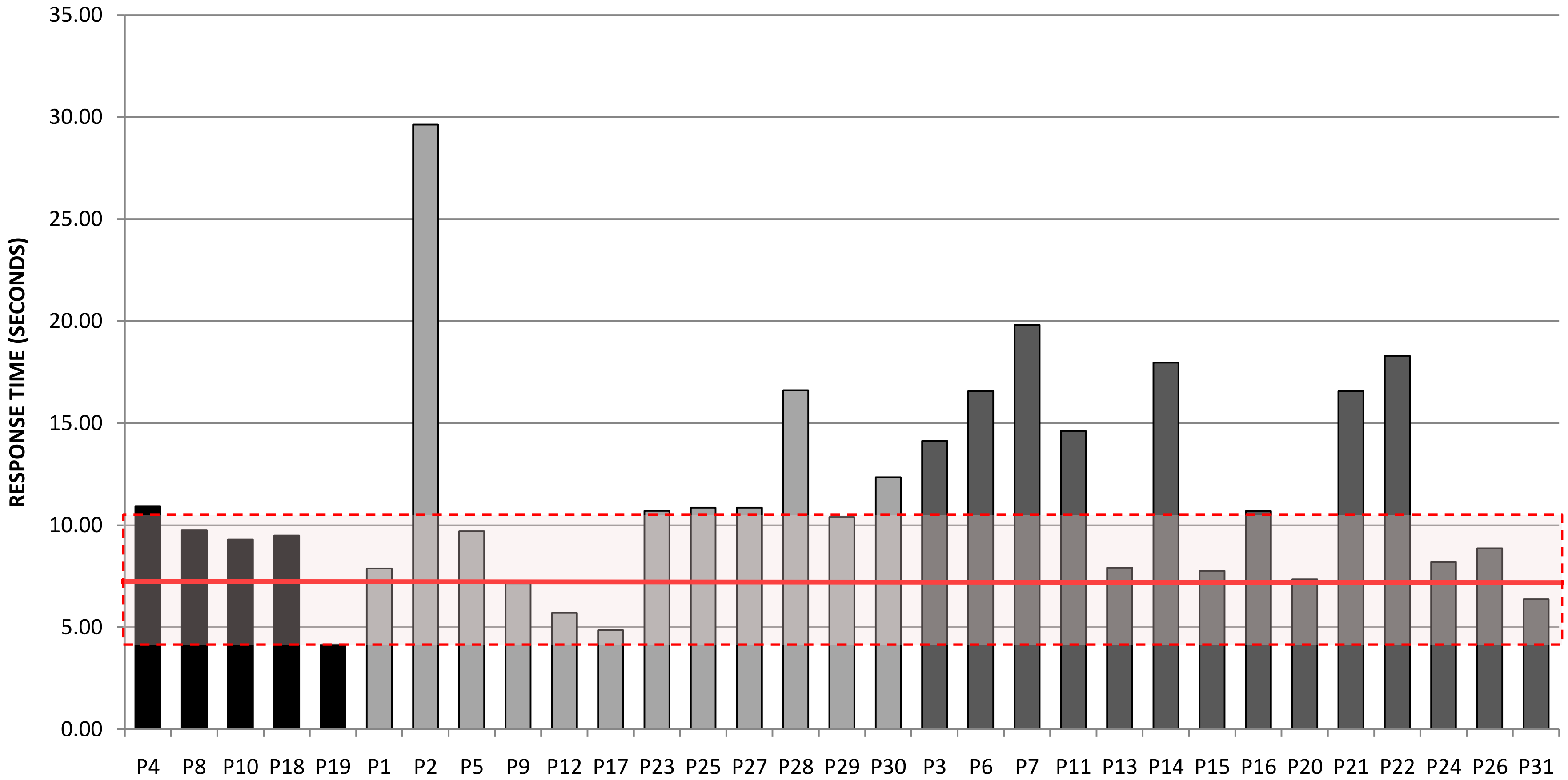


Figure 19 Response times for cases and mean (±1*SD*) for controls

Black columns represent quadrantanopia, light grey columns represent right hemianopia and dark grey columns represent left hemianopia.

5.3.2.3 Individual response time performance

Further analyses were conducted for response time data to explore individual differences amongst the cases. The first analysis considered overall response times (for correct responses only). The response time data were not normally distributed, and thus were log-transformed for analysis. A general linear model was used with *log response time* as the outcome measure and *pair ID* and *case status* as predictive factors. An interaction between *case status* x *pair ID* was included in the model.

Figure 20 depicts the odds ratios for log-transformed response times for the individual matched pairs. An odds ratio of 1 indicates the likelihood of equal response times between case and control. Odds ratios above 1 indicate relative increases in response times for the case compared with the control. The results indicated that only one case had a shorter mean response time relative to their matched control (Pair 18, OR=0.983). However, this was a small difference at less than 2% reduction in response time and did not reach statistical significance. The remainder of the cases had longer response times compared with their matched control. As expected, the two outliers were significantly slower to respond correctly to targets (P2, OR=2.388, $p<0.001$ and P6, OR=2.5, $p<0.001$).

An interesting observation from the graph is that the left hemianopic group appeared to have higher odds of longer response times relative to their matched control than either of the other two groups (right hemianopic or quadrantanopic). These results suggest that although some of the cases were quite accurate on the task, they also took longer to respond. Interestingly, this effect was more evident when data were compared on a matched-pairs basis (i.e. matched by age) than on a group level, which suggests that age may be a factor in performance on the task in general.

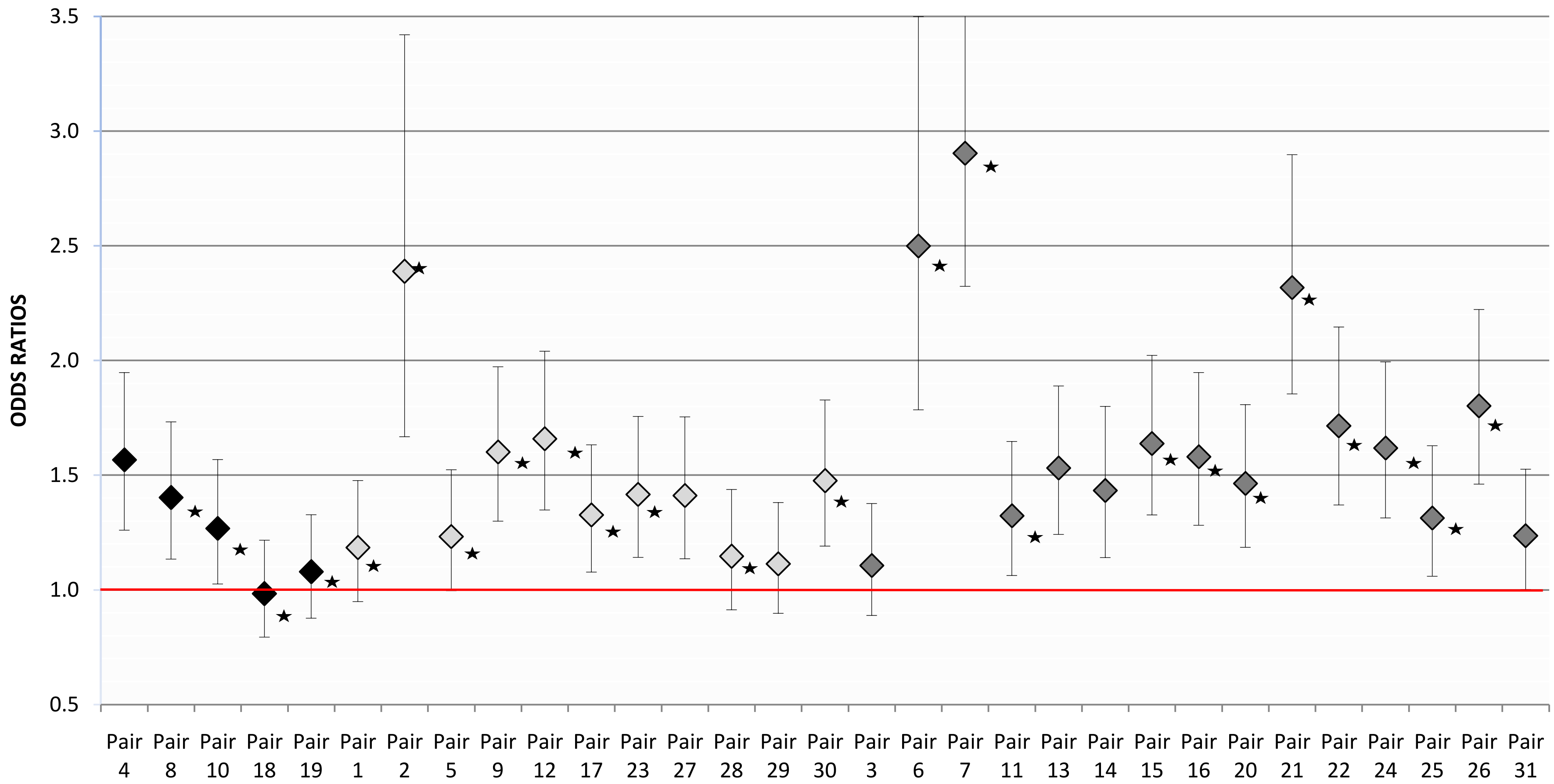


Figure 20 Log response times for individual pairs

Red line indicates OR=1 (equal response times). Odds ratios >1 indicate relative increases in response time for cases, odds ratios <1 indicate relative decreases in response time for cases. Asterisks denote significant results. Black = quadrantanopia, light grey = right hemianopia & dark grey = left hemianopia.

5.3.2.4 Response time performance for blind regions

The analyses for error data presented previously indicated that the cases had higher relative odds of making errors in the blind regions compared to the seeing regions. Therefore, it was of interest to determine whether a similar pattern was observed for the response time data. A general linear regression model was applied to the log response time data to investigate differences in (correct) response times for the blind and seeing regions. The two outliers and their matched controls were removed prior to analysis. The model used *log response time* as the outcome, with *case status* and *region* as factors.

As reported above, across all correct responses, the cases took longer on average than controls to respond to the targets (a relative increase of around 30%). However, when considering the effect of blind/seeing region, the mean *differences* in log response times were found to be larger when the target was presented in the blind regions (a relative increase of around 45%) in contrast to the seeing regions which showed a relative increase of around 25% (see Figure 21). Overall, cases took longer than controls to respond to targets, and these differences were more pronounced in the blind regions than the seeing regions.

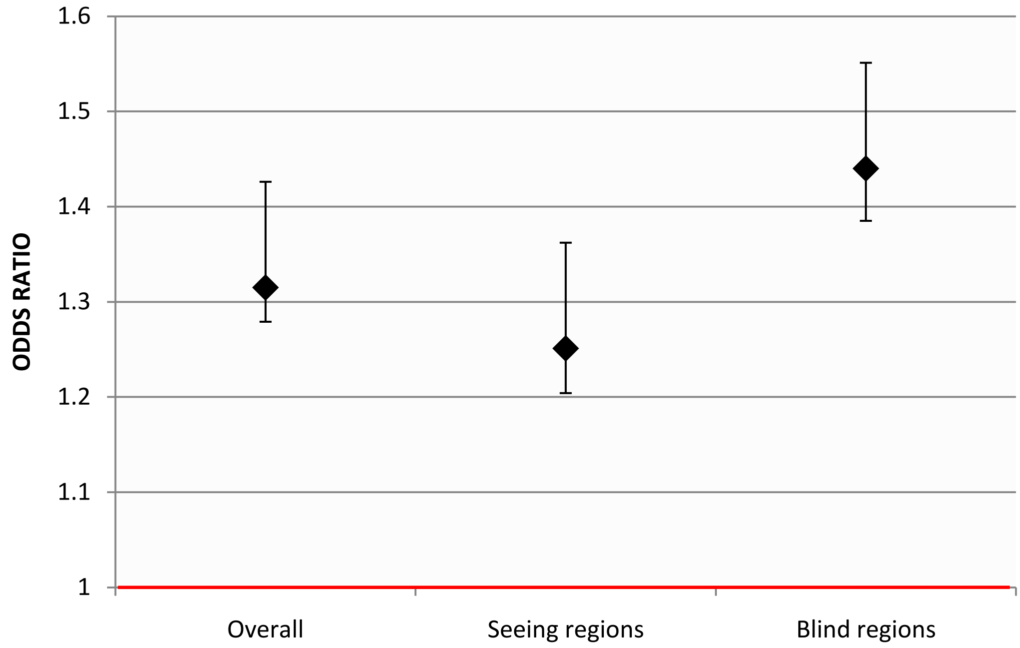


Figure 21 Odds ratios for response times in blind and seeing regions

The red line depicts the likelihood that response times of cases and controls do not differ. Odds ratios OR >1 indicates that cases perform worse (i.e. longer response times) relative to controls

5.3.3 Categories of performance

A key question of interest in this chapter was whether it was possible to identify meaningful categories of performance for the hemianopic participants on the change blindness task. It has been recognised that when considering functional assessments, pass/fail outcomes are too blunt to adequately capture performance (Langford, 2008). The psychometrics literature suggests that it is more effective to select individuals from the top down in terms of 'ability test scores', rather than applying a minimum cut-off score (Anastasi, 1998). A more constructive approach has been suggested, using classification strategies, where performance can be captured and described across the entire sample (Anastasi, 1998). Classification involves two or more criteria, and selecting individuals on the basis of their test scores tends to yield better criterion performance than does accepting all those who exceed a minimum cut-off score (Anastasi, 1998).

Thus, a three-level outcome model was proposed for assessing functional performance on the change blindness task, equating to good, intermediate and poor performance. This approach has been used to assess cognitive functioning across several domains, including ageing (Andrews, Clark & Luszcz, 2002), dementia and alcohol use (Galanis et al., 1999), depression (Baiyewu et al., 2007), psychosis (Verdoux, Liraud, Assens, Abalan & VanOs, 2000), neurobiological activity (Boustani et al., 2007; Usher, Cohen, Servan-Schreiber, Rajkowski & Aston-Jones, 1999), and driving (Valcour, Masaki & Blanchette, 2002).

In addition, this scale reflects clinical classifications in related areas such as brain injury. For example, when grading brain injuries, impairment is not typically defined as impaired/non-impaired, but rather the clinical distinction focuses on the *level* of impairment, defined as mild, moderate or severe (Arlinghaus et al., 2005).

In relation to driving, a three-level outcome has been considered a more useful approach than a binary outcome for reasons related to cost-efficiency and the identification of high-risk individuals. Notably, the American Academy of Ophthalmology advises that when assessing people with hemianopia on driving tasks, performance should be considered on one of three levels: good, intermediate and poor (American Academy of Ophthalmology, 2009). This would provide an opportunity to identify those who require further in-depth assessment, intervention or training (intermediate performers), and identify those that are unlikely to be suitable for return to driving (poor performers). This approach also ensures that ‘good performers’ are not targeted for unnecessary intervention or reassessment. Thus, a three-level model for performance classification was used in the present study.

5.3.3.1 Defining performance categories

Most standardised assessments provide within-group norms, where each individual's performance is evaluated in terms of the 'most nearly comparable standardisation group' (Anastasi, 1998). Data for the control group (i.e. most nearly comparable standardisation group) were used to define cut-off scores for each of the performance categories in the present study. The controls comprised a group of fully licensed drivers with a broad age range and without evidence of visual or cognitive impairment, and thus their data were assumed to be a reasonable representation of Australian drivers. The distribution of error responses for controls is presented in Figure 22.

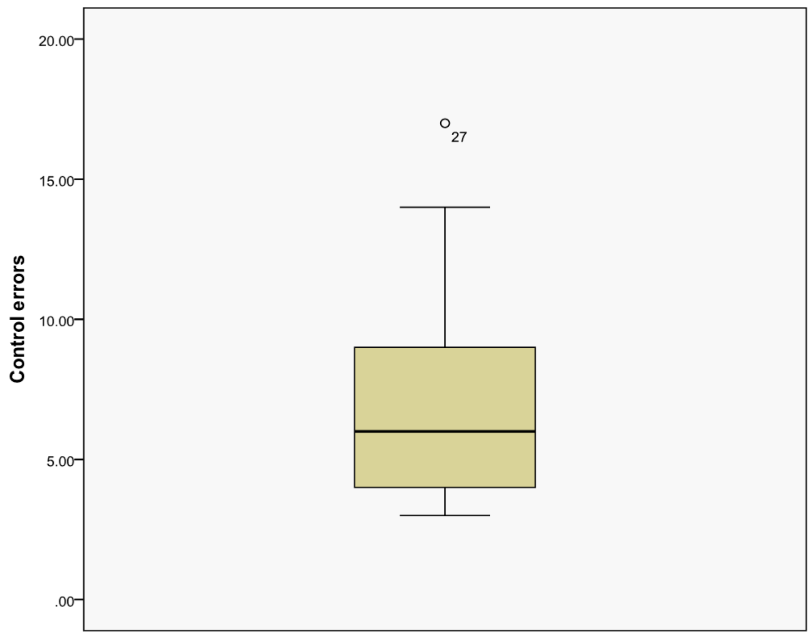


Figure 22 Boxplot for control errors

The data for controls were normally distributed, therefore mean and standard deviations were used to classify cases: better than or equal to the mean number of errors was considered 'good performance' (i.e. they did not display functional impairment on the task relative to a group of fully licensed Australian drivers); equal to or within one standard deviation was considered 'intermediate performance' (representing possible functional impairment on the task); and more than one standard deviation was considered 'poor performance' (i.e. displayed functional impairment on the task). The classification categories are presented in Table 11.

Table 11 Cut-offs for performance scores

CATEGORY	CUT-OFF SCORE	DEFINITION
Good	7 errors or less Mean of controls or better	No functional impairment relative to a group of fully licensed drivers.
Intermediate	8 – 11 errors Equal to or within 1*SD* of the controls	Possible functional impairment relative to a group of fully licensed drivers.
Poor	15 errors or more More than 1*SD* of the controls	Evidence of functional impairment relative to a group of fully licensed drivers.

5.3.3.2 Good performance

The first group of cases represent those who performed well relative to the controls. A summary and description of these cases is reported in Table 12. As shown in the table, the good performers comprised ten cases, representing around 30% of the total case sample. The visual field loss presentation was mixed, and included two individuals with quadrantanopia, three with right hemianopia and four with left hemianopia. There was a wide age range (21 to 57 years) but it should be noted that the majority of this group were at the younger end of the range (<40 years). Further consideration was also given to classification of case performance in the context of the control group mean response time (*M*=7.2s, *SD*=3.5s). Four cases were not only good performers with respect to task accuracy, but also had shorter response times compared with the mean control performance; Case 12 (5.7s), Case 17 (4.9s), Case 19 (4.2s) and Case 31 (6.4s).

Table 12 Good performance case summaries

CASE #	ERRORS	MEAN RT (secs)	CONDITION	AGE (years)
Case 1	7	7.9	Right HH	48
Case 8	7	9.7	Left superior quad	57
Case 9	6	7.2	Right HH	23
Case 12	3	5.7	Right HH	22
Case 16	7	10.7	Left HH	38
Case 17	4	4.9	Right HH	31
Case 19	4	4.2	Right inferior quad	32
Case 24	5	8.2	Left HH	21
Case 26	7	8.9	Left HH	51
Case 31	7	6.4	Left HH	43

5.3.3.3 Intermediate performance

Case summaries for the intermediate performers are shown in Table 13. This group comprised eight individuals, including two individuals with right hemianopia, three with left hemianopia and three with quadrantanopia. There was a wide age-range, spanning from 22 to 77 years. The response times in this group were all longer than the group control response time (7.2s).

Table 13 Intermediate performance case summaries

CASE #	ERRORS	MEAN RT (secs)	CONDITION	AGE (years)
Case 4	8	10.9	Left inferior quad	47
Case 5	10	9.7	Right HH	57
Case 10	9	9.3	Right inferior quad	36
Case 13	8	7.9	Left HH	23
Case 15	9	7.8	Left HH	60
Case 18	9	9.5	Right superior quad	77
Case 20	11	7.4	Left HH	22
Case 27	9	10.9	Right HH	74

5.3.3.4 Poor performance

Summary data for cases classified as poor performers is presented in Table 14. This was the largest of the three performance groups and comprised thirteen cases fairly evenly split between left hemianopia (n=7) and right hemianopia (n=6). Interestingly, but not unexpectedly, this group did not include any of the quadrantanopic cases, suggesting that a less severe visual field was associated with a better performance on the functional task in this study. The ages in this group ranged from 38 to 79 years, although it should be noted that the majority of the group (n=11) were aged 50 years and above, and more than half were aged 60 years and above. It was also evident that the mean response times were slower than those observed in the other performance categories. Thus, the poor performers appear to have difficulty with both the accuracy and time dimensions of the task.

Table 14 Poor performance case summaries

CASE #	ERRORS	MEAN RT (secs)	CONDITION	AGE (years)
Case 2	87	29.6	Right HH	66
Case 3	20	14.1	Left HH	79
Case 6	83	16.6	Left HH	74
Case 7	27	19.8	Left HH	54
Case 11	17	14.6	Left HH	78
Case 14	31	18.0	Left HH	54
Case 21	28	16.6	Left HH	42
Case 22	27	18.3	Left HH	61
Case 23	16	10.7	Right HH	38
Case 25	17	10.9	Right HH	60
Case 28	27	16.6	Right HH	65
Case 29	15	10.4	Right HH	53
Case 30	15	12.3	Right HH	68

5.3.3.5 Between groups differences

Differences between the case group performance categories were analysed after excluding the two outliers (P2 and P6) to ensure the extreme values were not skewing the data. As expected, the error rates were significantly different between the three categories, $F(2,26)=40.4$, $p<0.001$. Tukey post-hoc comparisons confirmed that the differences were between the good (M=5.38, 95% CI [4.04, 6.71]) and poor groups (M=26.67, 95% CI [18.51, 63.99]); and the intermediate (M=11.13, 95% CI [9.06, 13.20]) and poor groups. The good and intermediate groups did not differ.

Significant differences were also observed for response time among the three groups $F(2,28)=40.398$, $p<0.001$. Tukey post-hoc analyses again confirmed that the differences were between the good (*M*=7.31, 95% CI [5.40, 9.22]) and poor groups (*M*=17.23, 95% CI [15.19, 19.27]); and the intermediate (*M*=9.84, 95% CI [8.69, 10.99] and poor groups. The good and intermediate groups did not differ. The mean group response times are depicted in Figure 23.

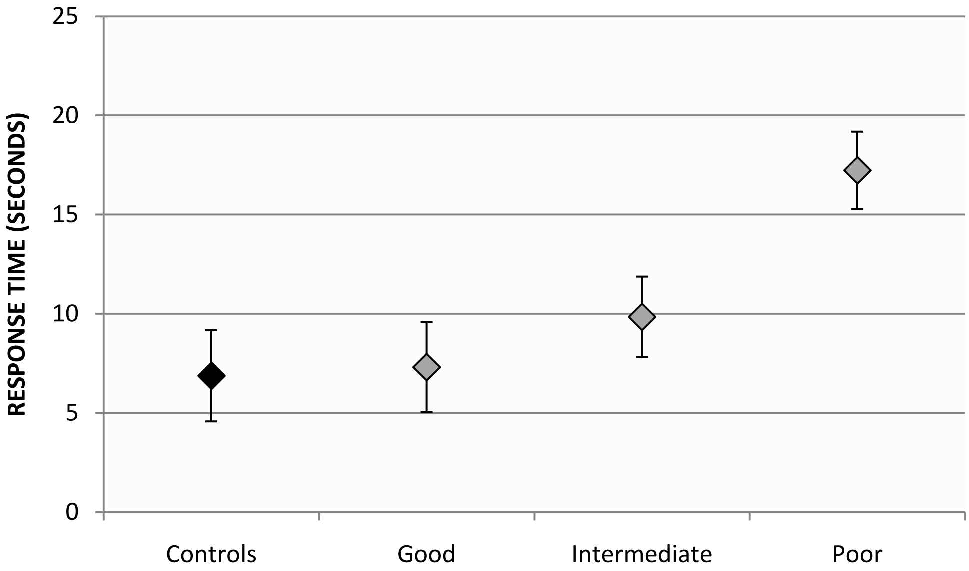


Figure 23 Response times for performance categories

5.4 Discussion

The overall aim of this component of the research was to investigate the extent to which individuals with hemianopia or quadrantanopia adequately compensated for their visual field loss when assessed on the change blindness task. Compensation was measured by the ability to detect stimuli that were presented in both the blind and seeing regions of the visual field. Adequate processing of the target involved two stages: firstly visual identification of the target was necessary, and secondly, selective attention was required to identify and respond to the target. It was expected that if individuals with hemianopia compensated effectively, they would be able to correctly identify targets in both the blind and seeing regions of their visual fields, albeit with slower response times overall. However, if individuals with hemianopia failed to correctly identify changes, specifically in the blind region, it would be indicative of a failure to selectively attend the relevant information, implying that the way in which they searched the scene provided no functional advantage.

In the present study, around one-third of the cases performed at least as accurately as the control group on the change blindness task (good performers). Error rates were considered a critical aspect in determining performance on this task: if the participant was able to respond correctly it is reasonable to assume that they must have been employing some kind of adaptive strategy in the blind region given that there was no visual function in that area. Hence, for the purposes of investigating 'functional compensation', errors and response time were studied separately in this chapter.

The error rates found here are consistent with data using other psychological paradigms in brain injuries: a number of studies have shown that despite reduced speed during timed tasks, people with brain injuries often do not have reductions in accuracy or deficits in performance over time relative to controls (Brouwer & VanWolffelaar, 1985; Gronwall & Sampson, 1974; Miller, 1970; Ponsford & Kinsella, 1992).

Similarly, the finding that one-third of the sample performed (at least) as well as the controls is consistent with research on visual and functional performance in hemianopia. For example, Gassel and colleagues found minimal (or no) evidence of visual dysfunction and no impairment of everyday function in eleven out of thirty-four cases with homonymous hemianopia (Gassel & Williams, 1963). Interestingly, this lack of functional impairment has been observed on a wide range of everyday tasks. For example, a large proportion of people with hemianopia are not functionally impaired on reading tasks: reading problems are observed in less than half of cases (Kasten et al., 1999). This finding is also consistent with the driving literature. Several studies have shown that some people with hemianopic field defects pass simulated or on-road driving tests and display driving skills that are very similar to controls (Racette & Casson, 2005; Schulte et al., 1999; Szlyk et al., 1993; Tant et al., 2002; Wood et al., 2009).

Taken together, these studies suggest that a proportion of people with hemianopia do not demonstrate functional impairment even on highly visual tasks (i.e. reading or driving) despite the presence of visual field loss. The task employed in this study was designed as a functional measurement, which allowed the use of compensatory or adaptive strategies (eye movements or active scanning). The consistency evident across results of the current study and research in other skill domains suggests that the change blindness task is a useful approach for assessing functional ability in hemianopia.

As was expected, the cases made more errors than the controls overall. Of particular interest were the findings for blind versus seeing areas of the visual space. As expected, the error rate for cases was more pronounced when the targets were presented in the blind regions. However, it was interesting to observe that compared with controls, the cases also made significantly more errors in the seeing regions as well. This could be indicative of higher order or more generalised cognitive problems, or alternatively it may be that hemianopic field loss results in an ineffective scanning strategy across the entire visual field. There is a body of evidence to suggest that visual scanning patterns are different in hemianopic field loss, with scanpaths that are characterised by small amplitude staircase saccades and frequent repetitions of fixations (Gassel & Williams, 1963; Pambakian et al., 2000; Zihl, 1995). Therefore it is possible that some of the cases were employing an ineffective search strategy which resulted in increased errors (and generally slower responses) across the entire visual space, not just restricted to the blind regions. This hypothesis is explored in greater detail in Chapter 6.

Higher error rates were also observed for the left hemianopic group compared with the right hemianopic and quadrantanopic groups. The small numbers in these subgroups preclude any firm conclusions to be drawn about the mechanisms underlying these differences; however this result is consistent with the literature on laterality of brain injury. It is recognised that people with right sided lesions (resulting in left visual field loss) are more likely to experience perceptual problems than those with left sided lesions (Arlinghaus et al., 2005; Bertelson, 1982; Farah, 2000). Additionally, those with right sided lesions tend to have increased attentional dysfunction and have been observed to be more functionally impaired in the clinical setting than those with left sided lesions (Farah, 2000). Although this evidence is suggestive of a right hemisphere (left hemianopia) bias, there was no bias evident in the change blindness task used in this study. This suggests that compensation and functional performance are the result of a combination of factors (possibly including other factors such as age or aetiology) rather than a discrete variable such as laterality of injury. This will be explored in detail in Chapter 7.

The visual characteristics of the scene were also considered in the context of the error profiles. As would be expected, reduced contrast led to an increased number of errors in both cases and controls, and high scene complexity was also associated with increased errors. This is consistent with research on both visual complexity and cognitive load increasing the work demands during a task (Duchowski, 2007; Y. Lee, Lee & Boyle, 2009; Recarte & Nunes, 2003). The effects of these parameters did not differ across the case and control groups. Thus, it appeared that cases were not more disadvantaged than controls by low stimulus contrast conditions or high scene complexity.

Task relevance was found also to affect responses in this study. The scenes were taken from the perspective of a driver, and both cases and controls were both more likely to make errors when the targets were non-traffic related compared to traffic-related. This suggests that driving experience did not seem to influence the ability to detect traffic-related targets in this study, and suggests ecological validity of the scenes. Furthermore, the finding of increased errors for non-traffic related targets is consistent with previous research. One study investigated change blindness performance in a driving simulator and found that errors were less likely when the change (or target) represented a safety-related (i.e. task relevant) aspect of the scene (Famewo et al., 2006).

As a group, the cases had longer response times (for correct trials) than the controls, and on a matched-pairs basis it was shown that only one case had significantly higher odds of responding more quickly than their matched-control. However, when the individual performance of each case was compared to the control group as a whole, it was found that around one-third of the cases responded to the targets as quickly as the control group. The comparisons between the case performance groups also showed the same trend: there were significant group differences among the performance categories, with the good performers responding fastest to the targets compared with the intermediate and poor performers.

Response times and accuracy represent two discrete aspects of visual processing, and research on reaction times has shown that most of the delay between presentation of a stimulus and the response by an observer is due to central processing time (Triggs & Harris, 1982). Central (or mental) processing times are composed of a number of different factors: *perception of the sensory input*, which predominantly refers to detection of the target and is affected by the sensory features (size, location, luminance, modality of the target); *recognition* of the target where information stored in memory is applied to the sensory stimulus to interpret the object; *situational awareness* where the target has to be extrapolated from the scene to extract its meaning in the context of the current position of the observer; and *response selection* and programming which refers to the decision-making process as to how to respond (Green, Allen, Abrams, Weintraub & Odom, 2008).

A general slowing of central processing has been demonstrated in a range of brain injuries (Schmitter-Edgecombe et al., 1992; VanZomeren & VanDenBurg, 1985; Veltman, Brouwer, VanZomeren & VanWolffelaar, 1996), which may explain why, as a group, the cases were slower on the task. It is interesting that a subset of cases did not demonstrate this slowing effect. The most likely explanation is that these cases used a range of adaptive (or compensatory) strategies during the task. This will be explored further in chapter 6, particularly with respect to visual scanning.

Similar to the patterns for error performance, response times were observed to be slower for the cases when the target was presented in the blind region. Although the subgroup numbers were small, the left hemianopic group (right sided lesion) had a trend towards slower response times compared with the right hemianopic and quadrantanopic groups. Evidence for lateralised slowing effects has been reported in attentional studies where it has been shown that reaction times were slower in people with right sided lesions compared with left (Rosseaux et al., 2002). The quadrantanopic group appeared to be least impaired on the task in terms of response times, performing at similar levels to controls. This finding is also consistent with research on functional abilities in visual field loss; for example, previous studies have demonstrated that quadrantanopia (i.e. less visual field loss) is associated with less functional impairment on driving performance than a more extensive visual field defect (Racette & Casson, 2005; Wood et al., 2009).

The findings for response times are particularly interesting in the context of the age range of the sample. As described previously, although only one case had significantly faster response times than their control on a matched-pairs basis (i.e. matched on age), around one-third of the cases responded to the targets at least as quickly as the average performance of the control group. An explanation for this finding might be that this subset of cases performed well relative to *older controls*, but not as well when compared with their age-matched control. This proposition is supported by the literature on brain injuries, where some authors have reported that the patterns of cognitive impairment seen following brain injuries resembles those seen with advancing age to the extent that the two processes may influence common neural mechanisms (Bashore & Ridderinkhof, 2002).

Considering response times and ageing more specifically, most experimental studies indicate that older people tend to respond more slowly to targets than their younger counterparts, and the effect of age is more pronounced for complex reaction time tasks such as driving (Luchies et al., 2002). Research has also shown that older adults are as adept as younger adults in terms of assimilating information but they take *longer to react*, highlighting the possibility that the slowing of cognitive processes associated with aging may closely resemble the effects of a traumatic brain injury (Myerson et al., 2007). This is particularly interesting in terms of the present study given that research on functional ability in hemianopia has suggested that some individuals with hemianopia perform as well as older controls. For example, driving research has shown that some people with hemianopia perform *worse* than younger drivers, but *as well* as older drivers on a simulated driving task (Szlyk et al., 1993). This could indicate that although reaction times may be slowed, they might not be any more impaired than might be expected in a group of older adults without visual impairment.

Interestingly, the *pattern* of error types for cases differed to that of the controls in this study. The major differences between the cases and controls were observed for omissions, where the cases made more errors than controls. In contrast, the pattern of commissions closely mirrored that of controls. This may reflect different strategies for approaching the task. Omissions could represent a more cautious approach in that the cases spent more time searching for the target to the detriment of performance (i.e. not responding within the given time frame).

The relationship between response time and overall performance efficiency is complex. Speed-accuracy frameworks suggest that too much emphasis on speed tends to result in chance error rates, and too much emphasis on errors tends to result in greatly prolonged performance with little gains in accuracy (Wickens &

Hollands, 2000). It appears that the cases in the present study may have placed too much emphasis on errors; their tendency toward errors of omission suggest that they spent longer searching without any gains in accuracy. The theoretical models suggest that performance appears to be best at intermediate levels of the speed-accuracy framework, and thus it is reasonable to tolerate a small percentage of errors in order to obtain efficient performance (Wickens & Hollands, 2000), and it appears that the controls adopted a pattern more reflective of the intermediate level of the speed-accuracy framework on this task, whereas the cases did not.

Furthermore, it is important to note that response times do not only reflect whether a target is perceived within the time-frame or not, it is also a function of decision-making. Speed of processing has been shown to be impaired in people with brain injuries (Ponsford & Kinsella, 1992), and thus it is possible that response times on the change blindness task were affected by more general deficits in speed of central processing (Ponsford & Kinsella, 1992), rather than the speed of actually perceiving the target.

The performance classification of cases in this study revealed several important findings: those who performed well on the change blindness task (good group) did not display impairment on either errors or response time relative to the control group, the intermediate performers were borderline on one or both aspects (representing possible functional impairment), and the poor category performed poorly on both errors and response times compared with controls. The most likely explanation for this observation is that the good performers used adaptive strategies to compensate for their visual field loss. The explanation for compensation will be investigated in greater detail in Chapter 6. The other potential explanatory variables for performance on the task, including, for example, extent of field loss, cognitive status, aetiology and age will be discussed in detail in Chapter 7.

5.5 Conclusions

In general, the results of this component of the study showed that the participants with hemianopia performed in the direction that was predicted on the change blindness task. On a group basis, they made more errors than the controls and took longer to respond correctly to targets. These deficits were evident across the entire visual field but were more pronounced in the blind regions. However, when performance was considered on an individual basis, an interesting pattern emerged: approximately one-third of the cases made the same number or fewer errors relative to controls, and similarly this group took the same time or less to respond to targets than controls. Further, the performance classification highlighted some important group differences. A subgroup of the cases (good performers) did not demonstrate any functional impairment on the task. In contrast, the intermediate performers were more variable on their task performance, and the group categorised as poor did not perform well on any aspect of the task.

These results suggest that the change blindness paradigm may be a sensitive tool for investigating individual functional compensation (or impairment) for visual field loss in hemianopia, by assessing a range of visual and cognitive aspects simultaneously. This leads to the next key question of interest as to whether compensation is related to the scanning patterns of visual search employed during the task. The next chapter focuses on eye movement patterns to explain performance, and the final experimental chapter considers the association between functional performance and measures of vision and cognitive processing.

Chapter 6 Eye-tracking data

6.1 Introduction

The change blindness paradigm used in this PhD research provided a tool for investigating compensation for visual field loss in hemianopia. The key results presented in Chapter 5 highlighted the performance-based aspects of the task and indicated that the majority of the cases did not perform as well as the controls with respect to accuracy and response time. However, in a subset of cases (around one-third of the sample), performance was not appreciably different to that of the controls. In this chapter, the issue of interest was whether the observed patterns of performance could be explained by the scanpaths or visual search strategies employed by individuals during the change blindness task.

Visual search tasks used in everyday life require the use of active visual scanning, and the most efficient procedure for active vision is by moving the eyes to scan successive locations using a high resolution (i.e. foveal) area. Vision is a dynamic process in which representations are built up over time from multiple eye fixations, therefore studying the patterns of eye movements during scene viewing is important for understanding how information in the visual environment is dynamically acquired and represented (Henderson & Hollingworth, 1998, 1999; Henderson, Weeks & Hollingworth, 1999). Furthermore, eye movements are critical for the efficient and timely acquisition of visual information during complex visual-cognitive tasks. With the complex nature of the road and traffic scenes and the visual-cognitive nature of the task presented in this research, it was considered important to investigate whether there were specific differences in eye movement strategies between cases and controls.

Visual scanpaths in hemianopia have been shown to differ from normally sighted individuals, and tend to be characterised by small-amplitude 'staircase' saccades toward the blind hemi-field, along with frequent repetitions of scanpaths during visual search and inspection (Pambakian et al., 2000; Zihl, 1995). However, there also appears to be significant variability in the literature as to what constitutes a hemianopic scanpath. For example, some studies have found differences in: the number, duration, spatial position and distribution of fixations, (Chedru et al., 1973; Ishiai et al., 1987; Meienberg et al., 1981; Pambakian et al., 2000; Zihl, 1995); some have found differences in the number, amplitude and latency of saccades (Pambakian et al., 2000); and others have found differences in fixations, saccades and search times in the blind fields (Pambakian & Kennard, 1997; Zihl, 1995). These visual search strategies appear to vary depending on the demands of the task and the complexity of the visual scene, and thus there is no consistent set of parameters that define a hemianopic scanpath.

Furthermore, altered visual search patterns in hemianopia have been interpreted in some studies as unsystematic and ineffective (Chedru et al., 1973), and others as reflecting compensation for visual field loss (Zihl, 1995). The heterogeneity of performance observed on functional tasks suggests that only a subset of individuals with hemianopia appear to compensate adequately for their field loss, therefore it is possible that some aspects of hemianopic visual search underpin compensation, and other aspects are unsystematic and ineffective. Thus, in order to support the assumption that specific parameters of visual search result in compensation, evidence of functional benefit for the individual needs to be demonstrated.

Studying eye movements in the context of compensation is further complicated by the distinction between looking and seeing: fixation is not necessarily synonymous with attention. This is highlighted by two psychological paradigms: covert attentional processing, which refers to directing attention to a location in the absence of overt signs of fixation; and inattentional blindness, which refers to the phenomenon that fixation is not necessarily the focus of attention (reviewed in

Chapter 2). The change blindness task presented in this research provides a unique opportunity to determine whether the visual scanning and search patterns in hemianopia correspond to attentional processing in naturalistic driving scenes, and importantly whether they provide any functional advantage for the individual. This would provide evidence for whether visual search represents a mechanism underpinning compensation for visual field loss.

Thus the two primary aims in this chapter were (i) to investigate whether the visual scanning behaviours elicited during the change blindness search task were different in people with hemianopia and quadrantanopia compared to controls, and (ii) to investigate whether these visual scanning patterns were different in people who performed well on the change blindness task compared with those who performed poorly. It was expected that the cases, as a group, would demonstrate differences in search patterns to the controls. Further, if the visual scanning strategies represented functional compensation, then the strategies observed in the cases who performed well (fewer errors) would differ from those who did not perform well.

6.2 Method

6.2.1 Participants and procedure

The characteristics of the sample are presented in Chapter 4. The method and procedures for the change blindness task and recording the eye movement parameters are discussed in detail in Chapter 3.

6.2.2 Analyses

Analyses of the eye movement data were conducted in several ways to explore differences between groups, as well as specific within-group differences among the cases: (i) case versus controls, (ii) among the three visual field loss groups (quadrantanopia, left hemianopia and right hemianopia), and (iii) among the three performance categories on the change blindness task (good, intermediate and poor). The rationale for studying the data in this way was to explore the hypothesis that cases who performed well (i.e. made fewer errors) were able to compensate through the use of strategic eye movement patterns and that these eye movement patterns would be clearly distinguishable from those who did not perform as well. Analyses were also conducted for blind versus seeing regions.

Differences between case and control groups were first investigated using t-tests. Where appropriate, one-way ANOVAs were used to explore differences between visual field loss types (i.e. quadrantanopia, right hemianopia and left hemianopia). It was not possible to consider the individual features of the quadrantanopic group (i.e. left and right, superior and inferior) due to the limited numbers in each group.

Separate analyses were conducted for each of the dependent measures, and categorised into oculomotor behaviour, scanpaths, and target (task-related) search. The *oculomotor behaviour* parameters included: overall number of fixations across all trials; the region of first fixation (left/right and blind/seeing); fixation on different parts of scene (LL/UL/LR/UR); search in affected field (percentage of total fixations); percentage of search time in affected field; duration of fixations; and saccade amplitudes. *Scanpaths* were recorded according to their similarity to the matched control, and the *target searches* focused on the number of fixations prior to the first fixation on target, and the number of fixations on target.

Separate one-way ANOVAs were also used to compare eye movement parameters between the three case group performance categories on the change blindness task (good, intermediate and poor). Where significant differences were found, Tukey Honestly Significantly Different (HSD) post-hoc tests were used to determine where the differences were. Chi squared analyses were used to determine the region of first fixation (left or right) for case status (case or control) and field loss type (left or right hemianopia). The two extreme outliers identified in the previous chapter

(Cases 2 and 6) and their matched controls were removed prior to all group based analyses, thus the analyses were based on all stimuli (n=108) for the remaining cases (n=29) and controls (n=29).

6.3 Results

6.3.1 Case-control comparisons

The first analyses were concerned with case versus control performance, and differences among the visual field loss groups. A summary of all the parameters considered in this section is presented in Table 15 (page 168). Results are reported for: (i) the cases as a group (n=29) compared with the controls (n=29); (ii) the quadrantanopic n=5), right hemianopic (n=14) and left hemianopic (n=11) groups compared with controls (n=29); and (iii) differences among the field loss groups.

Table 15 Case-control and VFL group eye movement parameters

PARAMETER	CASES	CONTROLS	CASE-CONTROL DIFF. AT *p*<0.05	FIELD LOSS TYPE						FIELD LOSS TYPE: BETWEEN GROUP DIFF. AT *p*<0.05
				Quad	Quad-control diff. *p*<0.05	Right hemi	RH-control diff. *p*<0.05	Left hemi	LH-control diff. *p*<0.05	
Overall number of fixations Mean number across all trials	26.8 *SD*=10.9	18.7 *SD*=1.0	✓	18.9 *SD*=7.5	X	25.9 *SD*=10.6	✓	27.7 *SD*=12.0	✓	X
Search in lower left quadrant Mean number of fixations	24.3 *SD*=12.0	16.7 *SD*=6.3	✓	17.2 *SD*=7.8	X	23.4 *SD*=7.6	✓	27.8 *SD*=15.4	✓	X
Search in lower right quadrant Mean number of fixations	21.2 *SD*=13.2	14.8 *SD*=5.0	✓	16.1 *SD*=8.7	X	24.0 *SD*=18.1	✓	20.5 *SD*=8.9	✓	X
Search in upper left quadrant Mean number of fixations	25.6 *SD*=13.9	17.9 *SD*=5.9	✓	18.2 *SD*=5.4	X	25.2 *SD*=13.5	✓	28.9 *SD*=16.2	✓	X
Search in upper right quadrant Mean number of fixations	29.8 *SD*=13.4	20.7 *SD*=8.1	✓	21.4 *SD*=10.7	X	28.1 *SD*=8.7	✓	34.6 *SD*=16.5	✓	X
Duration of fixations Mean in seconds	0.525 *SD*=0.17	0.534 *SD*=0.12	X	0.500 *SD*=0.04	X	0.476 *SD*=0.09	X	0.573 *SD*=0.23	X	X
Saccade amplitudes Mean in degrees	19.4^{o} *SD*=3.2	21.5^{o} *SD*=2.2	✓	20.1^{o} *SD*=0.9	X	19.4^{o} *SD*=4.0	✓	19.0^{o} *SD*=2.8	✓	X
Fixations prior to target Mean number across all trials	5.4 *SD*=2.6	4.4 *SD*=1.5	X	5.1 *SD*=1.2	X	5.2 *SD*=1.7	X	5.6 *SD*=2.5	✓	X
Fixations on target Mean number across all trials	2.7 *SD*=1.0	3.4 *SD*=1.5	X	2.3 *SD*=0.1	X	3.3 *SD*=1.4	X	3.6 *SD*=1.7	✓	X
Scanpath similarity index Percentage	n/a	n/a	n/a	58% *SD*=7.6	n/a	66% *SD*=6.0	n/a	67% *SD*=5.3	n/a	χ

6.3.1.1 Oculomotor behaviour

Number of fixations

The first analysis compared the number of fixations (pooled across all trials) recorded during the change blindness task. The results showed that while there was a high level of variability amongst cases, as a group they made significantly more fixations on average (*M*=26.8, *SD*=10.9) than controls (*M*=18.7, *SD*=1.0), $t(58)=2.25$, $p<0.01$. Fixations for the quadrantanopic group were not significantly different from controls, with the mean number of fixations being 18.9 (*SD*=7.5), $t(33)=0.059$, $p=0.95$. However, the left and right hemianopic groups made significantly more fixations than the controls: mean 25.9 fixations (*SD*=10.6) for the right hemianopic group $t(39)=1.91$, $p<0.01$; and mean 27.7 fixations (*SD*=12.0) for the left hemianopic group $t(42)=4.17$, $p<0.01$. A one-way ANOVA failed to detect any differences between the three visual field loss groups $F(2,27)=1.23$, $p=0.31$.

Fixations in seeing versus non-seeing regions

The case group data were analysed to examine whether there were any differences in the overall frequency of fixations in the blind and seeing regions, expressed as a percentage of all fixations. No significant differences were observed between the blind (*M*=11.5, *SD*=5.3) and seeing (*M*=11.2, *SD*=5.1) regions of visual space, $t(28)=0.26$, $p=0.79$.

Region of first fixation

The next set of analyses focused on the first fixation for each stimulus presentation to explore whether the hemianopic group first directed their gaze toward the intact or the impaired hemi-field. It should be noted that 'first fixation' refers to the first fixation moving from the central cross, so actually represents the second fixation. Data were pooled across all stimulus locations (the target locations are described in Section 6.3.2.2). It was found that both cases (as a group) and controls had a tendency to first fixate in their right hemi-field: 57% of all presentations for cases and 56% of presentations for controls; however this effect failed to reach significance, $\chi^2(1, n=6567)=1.431$, $p=0.23$.

A chi square analysis was conducted to compare the region of first fixation (left or right) for case status (case or control) and field loss type (left or right hemianopia). There was insufficient data to include the quadrantanopic group in this analysis. No significant differences were found in the region of first fixation when taking into account the type of visual field loss (left or right) $\chi^2(1, n=3111)=1.14$, $p=0.29$). That is, there were no significant differences between the left and right visual field loss groups with respect to the side (left or right) of the first fixation.

To explore this in greater detail, the first fixation for each stimulus was coded according to whether the fixation fell in the blind or seeing hemi-field (shown in Figure 24). The right hemianopic group started searching in their blind hemi-field slightly more often than their intact hemi-field; they directed their gaze first to the right (blind) side in 55% ($SD=21$) of trials. However, the left hemianopic group directed their gaze to the left (blind side) first on only 42% ($SD=20$) of trials. This difference just failed to reach statistical significance $t(28)=1.77$, $p=0.08$, but suggests that the right and left hemianopic groups may employ different strategies when searching their blind visual space.

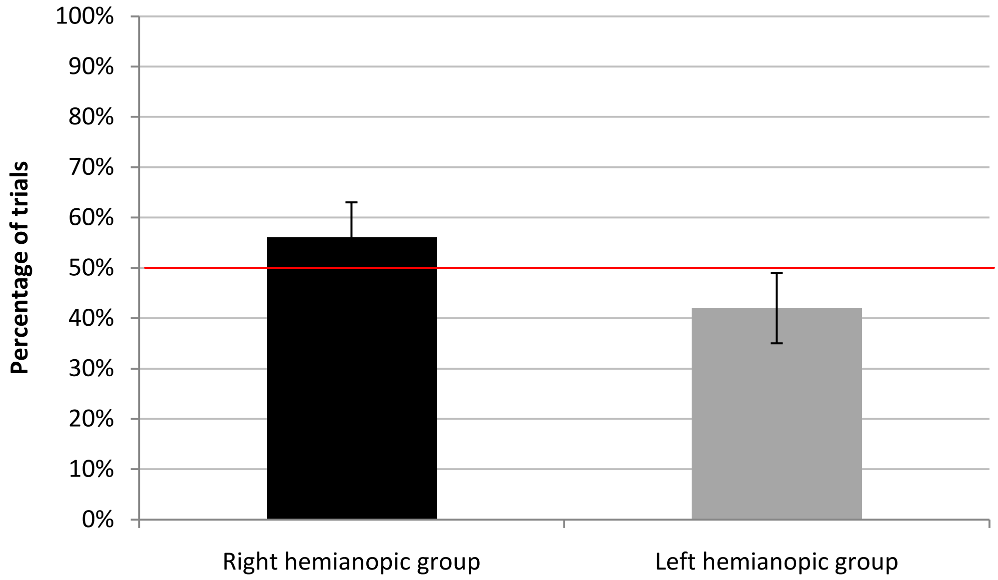
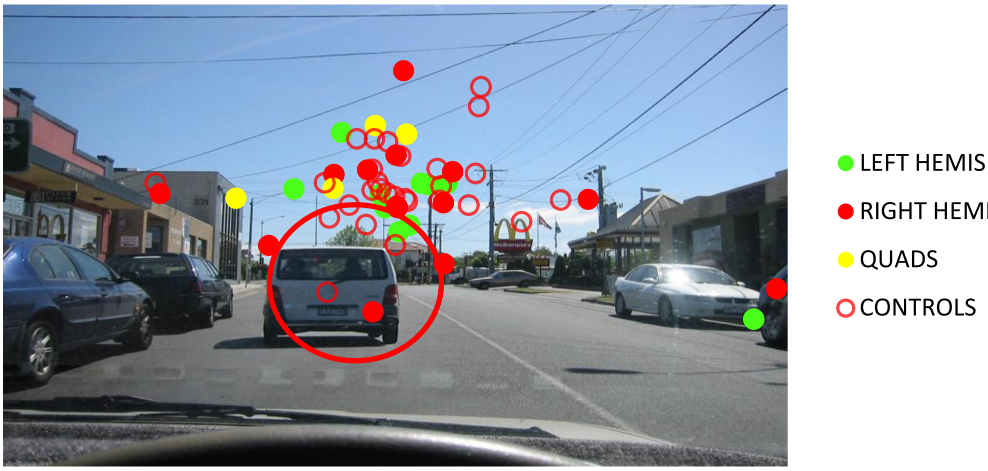


Figure 24 First fixations in blind region

The graph denotes the mean percentage of stimuli that the right hemianopic group first directed to their right hemi-field, and the left hemianopic group first directed to their left hemi-field. The red bar denotes the expected 50% if there was no effect of blind region.

To depict these fixation patterns for the different visual field loss groups, first fixations were plotted for selected stimuli and presented in Figure 25. These plots represent the first fixation point for each participant on two stimuli. The large red circle denotes the target: centrally located in the upper figure and upper right target in the lower figure. These plots show a general clustering of first fixations in the upper central area and slightly to the right of the visual scene in both cases and controls, regardless of where the target stimulus was located.



First fixations for stimulus C5

First fixations for stimulus UR8

Figure 25 First fixation for all participants on selected stimuli

Fixation on different regions of the scene

The data presented in the previous section highlight potential differences between groups in searching different regions of the scene. Thus, analyses were performed to compare the mean number of fixations across groups in each quadrant (LL, LR, UL and UR). The results are presented in Table 16.

There were significant case-control differences in number of fixations for each quadrant, although no significant differences were observed between the three visual field loss groups for any quadrant of the scene. Interestingly, the quadrantanopic group did not differ from controls in the number of fixations in any of the quadrants. However, both the left and right hemianopic groups made significantly more fixations than the controls across all quadrants.

Table 16 Mean fixations on different quadrants of the scene

	LOWER LEFT	LOWER RIGHT	UPPER LEFT	UPPER RIGHT
CASE-CONTROL				
Cases	*M*=24.3 *SD*=12.0	*M*=21.2 *SD*=13.2	*M*=25.6 *SD*=13.9	*M*=29.8 *SD*=13.4
Controls	*M*=16.7 *SD*=12.0	*M*=14.8 *SD*=13.2	*M*=17.9 *SD*=5.9	*M*=20.7 *SD*=8.1
Case-control differences	*t*(58)=3.05 *p*<0.01	*t*(58)=2.47 *p*<0.05	*t*(58)=2.78 *p*<0.01	*t*(58)=3.16 *p*<0.01
QUADRANTANOPIA				
Quadrantanopia	*M*=17.2 *SD*=7.8	*M*=16.1 *SD*=8.7	*M*=18.2 *SD*=5.4	*M*=21.4 *SD*=10.7
Quadrantanopia-control differences	*t*(33)=0.16 *p*=0.9	*t*(33)=0.47 *p*=0.6	*t*(33)=0.11 *p*<0.9	*t*(33)=0.16 *p*=0.9
RIGHT HEMIANOPIA				
Right hemianopia	*M*=23.4 *SD*=7.6	*M*=24.0 *SD*=18.1	*M*=25.2 *SD*=13.5	*M*=28.1 *SD*=8.7
Right hemianopia-control differences	*t*(40)=2.91 *p*<0.05	*t*(40)=2.59 *p*<0.05	*t*(40)=2.45 *p*<0.05	*t*(40)=2.60 *p*<0.05
LEFT HEMIANOPIA				
Left hemianopia	*M*=27.8 *SD*=15.4	*M*=20.5 *SD*=8.9	*M*=28.9 *SD*=16.2	*M*=34.6 *SD*=16.5
Left hemianopia-control differences	*t*(41)=2.71 *p*<0.01	*t*(41)=2.71 *p*<0.01	*t*(41)=3.27 *p*<0.01	*t*(41)=3.72 *p*<0.01
FIELD LOSS GROUP DIFFERENCES				
Visual field loss group differences	*F*(2,27)=1.51 *p*=0.2	*F*(2,27)=0.64 *p*=0.5	*F*(2,27)=1.1 *p*=0.3	*F*(,279)=2.0 *p*=0.1

Search in affected field

Analyses were conducted to examine the amount of time the hemianopic group spent searching in regions of the field of view (left, right, central) as well as in the blind and seeing fields. This was explored by calculating the time spent searching in the designated region across all trials as a percentage of total search time. Central searching was defined as within the area of the centrally presented targets (n=8). Analyses were conducted for cases versus controls, and left and right hemianopic groups compared with controls. The quadrantanopic participants were excluded as the small number of participants in each category (i.e. left and right superior and inferior) precluded meaningful analysis.

No systematic differences between the cases and controls were observed on percentages of time searching in the central, left or right hemi-spaces. Both cases and controls spent 5% (SD=1.9 and SD=1.3 respectively) of their search time in the central region $t(58)=0.67$, $p=0.51$. Similarly, no significant differences were found for percent time searching times in the right hemi-field (M=47%, SD=5.7 versus M=48%, SD=4.1, $t(58)=0.91$, $p=0.37$); or the left hemi-field (M=48%, SD=5.7 versus M=47%, SD=4.3, $t(58)=0.69$, $p=0.5$).

Searches in the left and right hemispace were then coded according to whether the search fell in a blind region or a seeing region (and for controls, in the comparable space). The controls did not demonstrate any difference in percent time spent searching each side of the visual space (49.9% on the left and 50.1% on the right). The cases (all visual field loss types) spent slightly (but not significantly) less time searching in their *blind regions,* accounting for 48% of the total search time across all stimuli. However, the search times in the blind regions were slightly different for the right and left hemianopic groups; 49% (SD=7.3) and 46% (SD=5.0) respectively, although this did not reach statistical significance $t(28)=1.37$, $p=0.18$. These results suggest that there were no systematic differences between the cases and controls on search in the blind/seeing regions.

Duration of fixations

The results described above identified that the cases made more fixations compared with the control group. To explore this further, analyses were conducted to examine whether fixations of cases differed in duration from those of the control group. The results indicated that mean fixation durations (in seconds) for cases (M=0.525, SD=0.17) and controls (M=0.534, SD=0.12) did not differ significantly, $t(57)=0.23$, $p=0.82$. No systematic differences were observed between the controls and the different visual field loss groups: quadrantanopia (M=0.500, SD=0.04) $t(32)=0.56$, $p=0.58$; right hemianopia (M=0.476, 0.09) $t(39)=1.46$, $p=0.15$; or left hemianopia (M=0.573, SD=0.23) $t(42)=0.75$, $p=0.46$. Similarly, there were no statistically significant differences in fixation duration between the three visual field loss groups $F(2,23)=0.87$, $p=0.43$. Overall, the results for fixation patterns suggest that although the cases made more fixations, the duration of the fixations did not differ from the controls.

Saccade amplitudes

The next set of analyses focused on saccade amplitudes. These analyses were conducted by comparing the mean saccade amplitudes (in degrees), pooled across all 108 stimuli. The results showed significant differences between the cases and controls, where the cases made significantly shorter saccades than controls (19.4^{o}, SD=3.2 versus 21.4^{o}, SD=2.2, $t(57)=2.79$, $p<0.01$). No significant differences were observed between the controls and the quadrantanopic group (M=20.1^{o}, SD=0.9, $t(32)=1.30$, $p=0.2$). However, significant case-control differences were found for both hemianopic groups: left hemianopia (M=19.0^{o}, SD=2.8, $t(38)=2.88$, $p<0.01$); and right hemianopia (M=19.4^{o}, SD=4.0, $t(41)=2.04$, $p<0.05$). No differences were observed across the three visual field loss groups, $F(2,27)=0.19$, $p=0.83$.

These results indicate that visual search patterns of the cases, particularly the right and left hemianopic groups, are characterised by shorter overall saccade amplitudes than those of the controls.

6.3.1.2 Target searches

The next set of analyses focused on differences between cases and controls for selected components of the visual search task: for each target (n=108), comparisons were made for the mean number of fixations *prior to the first fixation on the target* and the mean number of fixations *on the target.* These measures were of interest because they provide an indication of the effectiveness of search in locating the target and extracting the relevant information.

Mean fixations prior to the target

The cases made more fixations (M=5.4, SD=2.6) than the controls (M=4.4, SD=1.5) prior to the first fixation on target, although this difference just failed to reach statistical significance $t(58)=1.82$, $p=0.07$. No significant differences were found between the controls and the quadrantanopic group (M=5.1, SD=1.2, $t(33)=0.98$, $p=0.3$); or the controls and the right hemianopic group (M=5.2, SD=1.7, $t(39)=1.38$, $p=0.18$). However, significant differences, albeit modest, were observed for the left hemianopic group who made significantly more fixations prior to target compared with controls (M=5.6, SD=2.5, $t(42)=2.08$, $p<0.05$). No significant differences were found between the three visual field loss groups $F(2,27)=0.24$, $p=0.79$.

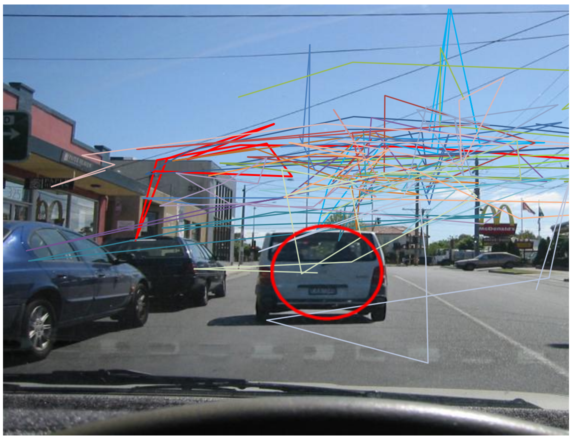
Mean fixations on the target

Overall, no group differences were found for the number of fixations on the target: cases M=2.74, SD=0.98; controls M=3.36, SD=1.51, $t(58)=1.88$, $p=0.64$. Comparisons for each hemianopic group revealed that only the left hemianopic group differed significantly from controls in number of fixations on target: (M=3.6, SD=1.7), $t(41)=2.1$, $p<0.05$. No differences were found between the controls and quadrantanopic group (M=2.9, SD=1.3, $t(33)=1.3$, $p=0.75$); or the controls and the right hemianopic group (M=3.3, SD=1.4, $t(40)=1.4$, $p=0.2$). Further, no significant differences were observed between the different visual field loss groups for number of fixations on target $t(2,27)=1.44$, $p=0.2$.

6.3.1.3 Scanpaths

Fixation patterns

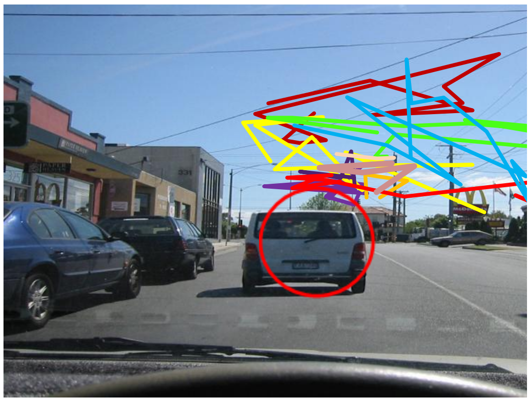
In order to explore qualitative differences in patterns of fixations between the groups, the scanpaths were plotted separately for the controls, the quadrantanopic group, the right hemianopic group and the left hemianopic group (an example is shown in Figure 26). The red circle denotes the target, and each plot includes all participants in the respective group (each participant is represented by a different coloured line). To simplify the presentation, only the first twelve fixations for each participant are shown: these represent approximately 50% of cases' fixations and 66% of controls' fixations. The fixation patterns presented in the figure show that the majority of scanpaths begin in the centre of the image. Interestingly, the search pattern in the left hemianopic group is not as broad as in the other groups and did not extend as far to the left. These patterns are explored statistically in the next section.



Scanpaths for controls

Scanpaths for quadrantanopic group

Scanpaths for right hemianopic group



Scanpaths for left hemianopic group

Figure 26 Scanpaths for selected stimulus (C5)

Each coloured line represents a different participant. The red circle denotes the target of interest.

Scanpath similarities

A more systematic comparison of the visual search patterns (scanpaths) for the cases and controls, was conducted using a Java based program developed for eye-tracking data, which computed similarity values for two scanpaths (Foulsham, 2007). The similarity values were based on a Mannan index which compares two scanpaths and returns similarity values from 0 to 100, with 100 representing an identical scanpath and 0 representing systematically different scanpaths. The similarity index is calculated by using the first sequential fixations (up to a maximum of 12) for each stimulus, and the percentage similarity is based on spatial locations. In this study, the similarity indices were calculated between each matched pair where there was sufficient data for analysis (n=29). The results are reported as an average across all stimuli (n=108).

The overall mean scanpath similarity index was 65%, suggesting a moderate level of similarity between each case-control pair. Interestingly, the quadrantanopic group had a lower similarity index with their age-matched control (*M*=58%, *SD*=7.6) than the right hemianopic (*M*=66%, *SD*=6.0) and left hemianopic groups (*M*=67%, *SD*=5.3). These differences just failed to reach statistical significance $F(2,24)=2.89$, $p=0.08$. An analysis for mean scanpath similarity across blind and seeing regions revealed no effect of region of target presentation, with 66% (*SD*=6.2) similarity in the blind regions and 65% (*SD*=6.9) in the seeing regions $t(52)=0.85$, $p=0.39$. All case-control and visual field loss group comparisons were summarised in Table 15.

6.3.2 Performance group results

The final set of analyses considered the eye movement data in the context of performance on the change blindness task. Three performance categories were identified in Chapter 5 based on accuracy: good (equal to or less than the mean errors for the control group); intermediate (equal to or within 1*SD* of the controls' performance); and poor (more than 1*SD* compared with the controls' performance). A key question of interest was whether cases who performed well employed scanning strategies that were different from those who performed poorly. It was expected that cases who performed well would demonstrate compensatory scanpaths that differed from poor performers, which enabled them to detect the target of interest. Hence, the three case-group performance categories were used to explore differences in eye movement parameters. All results are summarised in Table 17 and a summary of post-hoc comparisons, where significant overall effects were observed, is presented in Table 18.

Table 17 Eye-tracking parameters for performance categories

PARAMETER	CONTROLS	CASE-CONTROL DIFFERENCE AT *p*<0.05	CASE GROUP PERFORMANCE CATEGORY			CASES: BETWEEN GROUP DIFF. AT *p*<0.05
			GOOD	INTERMEDIATE	POOR	
Overall number of fixations Mean number across all trials	18.7 *SD*=1.0	✓	17.2 *SD*=4.9	23.4 *SD*=6.2	32.6 *SD*=11.6	✓
Search in lower left quadrant Mean number of fixations	16.7 *SD*=6.3	X	15.6 *SD*=5.3	21.7 *SD*=6.1	32.3 *SD*=13.1	✓
Search in lower right quadrant Mean number of fixations	14.8 *SD*=5.0	X	14.7 *SD*=5.3	16.8 *SD*=7.6	29.2 *SD*=15.5	✓
Search in upper left quadrant Mean number of fixations	17.9 *SD*=5.9	X	17.4 *SD*=4.3	19.1 *SD*=8.7	34.2 *SD*=16.6	✓
Search in upper right quadrant Mean number of fixations	20.7 *SD*=8.1	X	21.8 *SD*=10.3	27.9 *SD*=10.2	37.0 *SD*=13.9	✓
Duration of fixations Mean in seconds	0.534 *SD*=0.12	X	0.522 *SD*=0.13	0.517 *SD*=0.12	0.561 *SD*=0.26	X
Saccade amplitudes Mean in degrees	21.5° *SD*=2.20	✓	21.7° *SD*=2.8	19.9° *SD*=3.0	17.3° *SD*=2.5	✓
Fixations prior to target Mean number across all trials	4.4 *SD*=1.5	X	4.1 *SD*=1.7	5.2 *SD*=1.1	6.5 *SD*=3.2	X
Fixations on target Mean number across all trials	2.5 *SD*=1.0	X	2.4 *SD*=0.7	3.2 *SD*=1.2	4.2 *SD*=1.6	✓
Scanpath similarity index Percentage similarity	n/a	n/a	62% *SD*=2.9	62% *SD*=8.1	69% *SD*=5.7	✓

6.3.2.1 Oculomotor behaviour

Number of fixations

The first analysis considered the mean number of fixations overall for each performance category. The results showed that the poor performers (*M*=32.6, *SD*=11.6) made significantly more fixations than the intermediate performers (*M*=23.4, *SD*=6.2), and the good performers (*M*=17.2, *SD*=4.9) $F(2,27)=8.95$, $p<0.001$. These data are plotted in Figure 27, and show that the good group had a pattern of fixations more similar to the controls than the other case performance categories. The poor performers made almost double the number of fixations than controls, which suggests that increased fixations are a less effective scanning strategy for detecting target changes on this task.

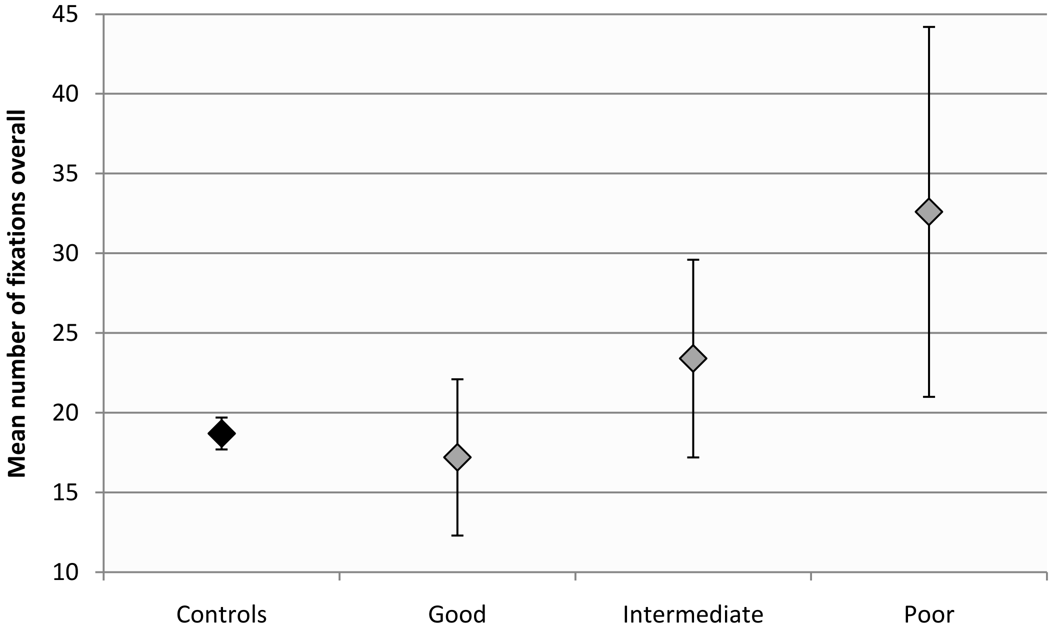


Figure 27 Overall mean fixations for performance categories

Fixations on different regions of the scene

The next analysis considered differences in the numbers of fixations between the performance groups for different regions of the scene (LL, LR, UL and UR). Significant differences were observed between the good, intermediate and poor performers for mean number of fixations in each quadrant of the scene: the *lower left quadrant* (good M=15.6, SD=5.3; intermediate M=21.7, SD=6.1; and poor M=32.3, SD=13.1, $F(2,27)$=8.68, p<0.001); the *lower right quadrant* (good M=14.7, SD=5.3; intermediate M=16.8, SD=7.6; and poor M=29.2, SD=15.5 $F(2,27)$=5.01, p<0.05); *upper left quadrant* (good M=17.4, SD=4.3; intermediate M=19.1, SD=8.7; and poor M=34.2, SD=16.6, $F(2,27)$=6.59, p<0.01); and the *upper right quadrant* (good M=21.8, SD=10.3; intermediate M=27.9, SD=10.2; and poor M=37.0, SD=13.9) $F(2,27)$=4.62, p<0.05 (shown in Figure 28).

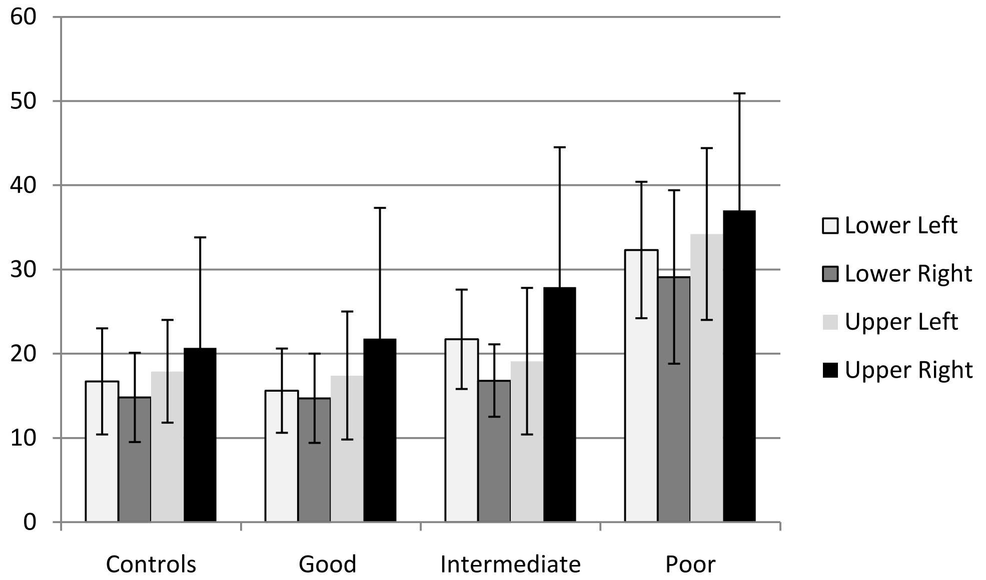


Figure 28 Mean fixations in each quadrant

Fixation durations

Fixation durations were also analysed to investigate differences between the performance categories. No systematic differences were observed for fixation duration, which were found to be highly variable within groups. The poor group had marginally, but not significantly, longer durations (*M*=0.561, *SD*=0.2) than the good (*M*=0.522, *SD*=0.13) and intermediate groups (*M*=0.517, *SD*=0.12), $F(2,25)=0.18$, $p=0.8$.

Saccade amplitudes

Saccade amplitudes were found to be significantly different across the performance categories. The good performers had the largest saccade amplitudes at 21.7° (*SD*=2.8), the intermediate were slightly smaller at 19.9° (*SD*=2.96) and the poor performers had the smallest saccade amplitudes at 17.3° (*SD*=2.53) $F(2,26)=7.26$, $p<0.01$. The saccade amplitudes of the good performers were very similar to those of the controls, with only 0.2° difference in amplitude (controls *M*=21.5°, *SD*=2.2). These data are depicted in Figure 29.

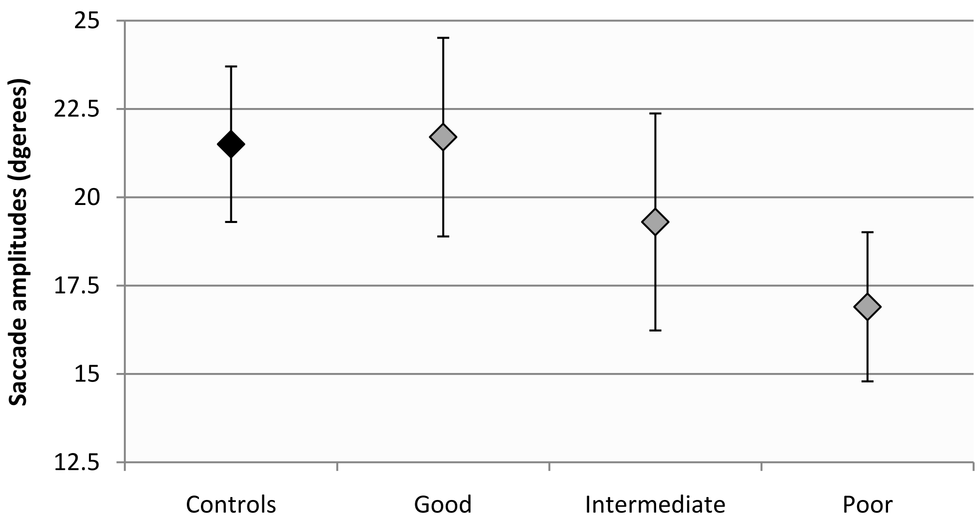


Figure 29 Mean saccade amplitudes for performance categories

6.3.2.2 Target searches

Fixations prior to target

The mean number of fixations prior to (the first fixation on) target were analysed to consider any differences between the performance categories. The results showed that the poor performers made the most fixations prior to target, however differences between the three case performance groups did not reach statistical significance (good M=4.1, SD=1.7; intermediate M=5.2, SD=1.1; and poor M=6.5, SD=3.2) $F(2,27)=2.68$, $p=0.08$.

Fixations on target

The number of fixations on target were also analysed for the three performance categories. Significant differences were found between the three case groups: the good performers made fewer fixations on target (M=2.4. SD=0.7) than either the intermediate performers (M=3.2, SD=1.2) or the poor performers (M=4.2, SD=1.6), $F(2,27)=4.70$, $p<0.05$.

6.3.2.3 Scanpaths

Finally, the scanpath similarity indices were compared for the three performance groups. The scanpaths of the poor performers were found to be the most similar to controls, with the good and intermediate performers less so (good M=62%, SD=2.9; intermediate M=62%, SD=8.1; and poor M=69%, SD=5.7) $F(2,25)=3.9$, $p=0.05$. Thus, it would appear that a higher scanpath similarity (relative to matched control) was somewhat detrimental to overall task performance.

6.3.2.4 Tukey post-hoc comparisons

Tukey post-hoc comparisons were performed across all the eye movement parameters presented where significant overall effects were observed (i.e. number of fixations, search in the different quadrants of the scene, fixations on target, saccade amplitude and scanpath similarity index). The results indicated that the majority of differences were found between the good and poor performance groups, with all parameters significant at $p<0.05$. No significant differences were found between the *good* and intermediate groups; however, with the exception of fixation duration, all differences were in the direction expected. Additionally, significant differences ($p<0.05$) were found between the intermediate and poor groups on several parameters. These differences are summarised in Table 18.

Table 18 Tukey comparisons for significant eye-tracking parameters

MEASURE	GOOD & INTERMEDIATE $p<0.05$	INTERMEDIATE & POOR $p<0.05$	GOOD & POOR $p<0.05$
Overall fixations *(mean fixations)*	X	X	✓
Search in lower left *(mean fixations)*	X	✓	✓
Search in lower right *(mean fixations)*	X	X	✓
Search in upper left *(mean fixations)*	X	✓	✓
Search in upper right *(mean fixations)*	X	✓	✓
Saccade amplitudes *(degrees)*	X	X	✓
Fixations on target *(mean fixations)*	X	X	✓
Scanpath similarity *(percent)*	X	X	✓

6.4 Discussion

In the context of hemianopic visual search, the specific patterns of eye movements observed in people with hemianopia have been shown to differ to controls, and have been reported as a proxy measure of compensation for visual field loss. However, there is limited evidence that these altered search patterns actually correspond to attentional processing in blind areas of visual space, or provide any functional benefit for the individual. Moreover, there is little discussion in the literature about heterogeneity of scanpaths in hemianopia, or specific aspects of visual search that relate to task performance. Therefore, there were two primary aims investigated in this chapter: (i) to investigate whether the visual scanning behaviours elicited during the change blindness search task were different in people with hemianopia/quadrantanopia compared with controls, and (ii) to investigate whether these visual scanning patterns were different in people who performed well on the change blindness task compared with those who performed poorly.

The results from the present study demonstrated that search patterns for the hemianopic group differed from those of the control group. More specifically, the cases made more frequent fixations with shorter amplitude saccades compared with the controls. This pattern has been previously described in the literature (Chedru et al., 1973; Pambakian & Kennard, 1997; Pambakian et al., 2000; Zihl, 1995), and has been interpreted as an unsystematic or ineffective search strategy (Kennard, 2002; Pambakian et al., 2000). The wider literature has reported that increased fixations and shorter amplitude saccades are observed when attention is directed to a stimulus of interest compared with active scanning or searching (Underwood & Radach, 1998). Thus, in the current study, it is possible that scanning patterns observed for the cases represent increased time attending to specific items of the scene, resulting in reduced efficiency at finding items within the wider array. In contrast, the control group participants appear to employ a more efficient and successful strategy, actively searching the scene for the target with wider saccades and fewer fixations.

Also noteworthy was the absence of evidence of increased searching (number and percentage of fixations) in the blind hemi-field, which, intuitively, might be expected to be an effective compensatory strategy. In contrast, previous studies have reported that while controls search the visual space relatively evenly, individuals with hemianopic field loss tend to spend more time searching the non-seeing areas (Chedru et al., 1973; Ishiai et al., 1987; Meienberg et al., 1981; Pambakian et al., 2000; Zihl, 1995). One potential explanation for this discrepancy relates to the nature of the task and complexity of the scenes. Studies that have reported increased search time in the blind spaces have generally used simple patterns (for example, dots or filtered scenes) and small scale stimuli. Moreover, reduced ecological validity of simple patterns has been shown to result in different mechanisms for perception that are likely to be driven by more visual rather than cognitive processes (Henderson & Hollingworth, 1998). Thus, the demands of the tasks using simplistic stimuli may differ considerably from more naturalistic search task across 140^0 of visual angle used in the present study.

Related to the stimulus complexity issue, another potential explanation for the search patterns and responses observed in the current study is that they were influenced by the functional nature of the stimuli: the images presented were based on the specific task of driving (traffic scenes from the perspective of a driver). Influential early research found that eye movement patterns during complex scene perception are related to the information in the scene, and by extension, perceptual and cognitive processing of the scene (Buswell, 1935). In addition, it has been observed that the information content of a component of a scene (i.e. areas of high interest or 'informativeness') tends to result in increased fixations in that area (Henderson & Hollingworth, 1998). It is therefore possible that in the present study, participants were employing a more task specific search strategy, by using the scene context (driving) to direct the search.

The use of scene context to drive search is also supported by a recent study on visual search during a functional task in hemianopia. Martin and colleagues studied a group of hemianopic cases and controls on a standardised model-building task, and found that individuals with hemianopia displayed different fixation locations and saccade amplitudes from controls during the task; however, in contrast to findings from studies using simple stimuli, no differences were observed between the blind and intact hemi-fields (Martin et al., 2007). This study highlights the possibility that search patterns during functional (goal-directed) tasks differ to those in non-goal directed tasks (such as viewing simple patterns).

An interesting observation in the present study was the difference in search strategies between the visual field loss groups (i.e. quadrantanopia, right hemianopia and left hemianopia). Overall, the results suggested that the quadrantanopic group displayed search patterns that were more similar to controls than either of the hemianopic groups; moreover, their performance on all parameters measured did not differ significantly from the controls. This finding is not surprising given that the extent of field loss in quadrantanopia (confined to one quadrant) is, by clinical definition, less than that for cases with hemianopia. The result is consistent with previous studies demonstrating that individuals with quadrantanopia tend to perform better on a range of functional tasks, including driving, than those with more extensive field loss (Racette & Casson, 2005; Wood et al., 2009).

In the present study, differences in search parameters were slightly more pronounced in the left hemianopic group than the right hemianopic group on all parameters assessed, with the exception of fixation duration. One possible explanation for these findings relates to laterality of the brain injury. As discussed in previous chapters, a right sided brain injury (left side field loss) is more likely to result in perceptual problems than left sided injuries, and attentional deficits are more frequent in this group (Arlinghaus et al., 2005). Thus, the search strategies observed in the left hemianopic group here may be the result of generalised perceptual difficulties, and this effect warrants further investigation given the small subgroup sizes in the present study. The effects of impairments on perception and attention will be considered in more detail in Chapter 7.

It is significant that previous research has identified that not all people with hemianopia display ineffective visual search patterns, or in fact display differences in visual search strategies at all (Gassel & Williams, 1963). Thus, it was important to explore evidence for differences in scanning strategies based on performance on the change blindness task. It was proposed that those who performed well, that is with a high level of accuracy on the task, would employ effective visual scanning and search patterns to detect the target changes.

The findings revealed two distinct sets of eye movement patterns associated with different task performance outcomes: (i) where cases and controls showed a similar pattern of eye movements with a good performance outcome; and (ii) where cases and controls showed a similar pattern of eye movements with a poorer performance outcome. Specifically, cases who showed similar search patterns to controls with respect to parameters including overall number of fixations, fixations on different regions of the scene, saccade amplitudes and number of fixations on the target, performed well on the change blindness task. In contrast, the closer the scanpath similarity index was to the controls, the *less* likely it was that the case performed well on the task.

These results suggest that there are specific ways in which cases search the scene that result in good functional outcomes. Poor detection of targets (poor performers) was characterised by a search pattern with increased fixations and shorter saccade amplitudes. In contrast, cases whose search patterns on these parameters more closely matched those of controls were not impaired on the target detection task (good performers).

Although it would appear that there is a functional benefit derived from searching the visual fields using *some* similar features as controls, it is unlikely that high levels of accuracy in detecting targets could be achieved without modification to some aspect of the search pattern to account for the field loss. Previous research has shown that people with hemianopia tend to make fixations in different spatial locations and with different distributions (spatial sequences) than controls (Chedru et al., 1973; Zihl & Hebel, 1997). The analysis of spatial locations, measured by the scanpath similarity index in the present study, showed that the scanpaths of the poor performers were more similar to controls than those of the good and intermediate performers. These results suggest that despite some very clear similarities to the controls on a range of eye movement parameters, one of the key aspects in functional performance is the spatial path to the target.

Duration of visual fixation was not found to be a sensitive measure in the current study. No differences in fixation times were found, either between the cases and controls or between the three case performance categories. Evidence on this measure is somewhat inconsistent in the literature, with some studies showing clear case-control differences and others showing no differences. However, where case-control differences have been observed, the cases typically make longer fixations that controls during searches of simple stimuli (Chedru et al., 1973; Pambakian & Kennard, 1997). In contrast, studies reporting no group differences in fixation duration typically use more functional tasks (Martin et al., 2007). The disparity in the methods and findings makes interpretation difficult, however it would appear that increased fixation duration is not a common strategy when engaging in functional tasks, such as the one presented in this research.

To assist with interpretation of the findings in this study, relevant theoretical constructs in cognitive neuropsychology relating to eye movements and attention are considered. Firstly, it is clear that the role of selective attention, expectations and memory are important in the programming of eye movements (Kowler, 1990). It is also likely that during search tasks, observers use peripheral visual information to guide their search (Henderson & Hollingworth, 1998), which of course people with hemianopia lack in their blind field. The location of individual fixations in a scene (including the position of the fixation after the first saccade) appear to be determined, in part, by the informativeness (relevance) of the stimulus content of the observed regions, with more fixations being directed to more informative regions (Henderson & Hollingworth, 1998). In addition, visual attention seems to be allocated through a greater number and longer duration of fixations when material that requires cognitive processing is encountered (Underwood & Radach, 1998).

These theoretical findings highlight the interplay between visual and cognitive aspects of a scene, and the goals of an observer during visual search. These concepts are captured in a theoretical model of eye movement control during scene inspection known as the 'saliency map framework' (Henderson, 1992; Henderson & Hollingworth, 1998, 1999; Henderson et al., 1999). This framework suggests that attention is always allocated to the region with the greatest saliency and fixations are then directed to these regions. The framework predicts which factors will be influential during the early stages of inspection, and describes how saliency will change as information about the scene is collected, such that the early stages of inspection will be driven by predominantly visual features, and the later stages by predominantly semantic (or informative) features (Underwood & Radach, 1998).

This framework can be used to explain some of the findings from the present study. The poor performers had a typical pattern of small amplitude saccades and a large number of fixations. Although this pattern is usually seen when an observer has identified a stimulus requiring cognitive processing, in the context observed here, this search pattern could be described as both unsystematic and ineffective since it resulted in high error rates. In contrast, the good performers made large amplitude saccades with fewer fixations, and yet responded to the targets faster than the poor performing cases. It is possible that the cases who performed well on the change blindness task employed several strategies to overcome their field deficit: commencing their search based on visually salient features rather than on the side of their visual field loss; and then employing a wide search pattern to bring more of the visual scene into the intact visual space. This is supported by the pattern of errors observed on the task: errors were more likely if the stimulus was not relevant to the task (i.e. not driving-related, such as roadside advertising) suggesting that semantic properties were important in the search strategy. This may also explain why differences have been found in blind/seeing region searches in studies using simple patterns and not in complex scenes.

6.5 Conclusions

The change blindness task performance demonstrated that a subset of people with hemianopic visual field loss performed as accurately as controls. The experimental task was proposed to measure functional compensation: to perform well, effective scanning strategies in addition to processing relevant information would need to be employed. The eye-tracking results presented in this chapter support this proposition: the cases who performed well on the task demonstrated the strongest similarity with controls on specific scanning measures, including number of fixations and saccade amplitudes; however they also searched the scene differently to controls in terms. of low scanpath similarity. This suggests that while some parameters of visual search were similar to controls and resulted in a better outcome on the task, they also employed some altered search patterns in order to effectively search visual space, and these differences most likely represent variation in spatial location and distribution of fixations. These findings are consistent with theoretical frameworks underpinning visual search (Henderson & Hollingworth, 1998; Underwood & Radach, 1998), which describe a complex interaction between eye movements, attention, visual-semantic saliency and the intentions and goals of the observer.

As discussed in previous chapters, it is likely that there is some neurocognitive basis to change blindness task performance, given that good performance is likely to represent an interaction between aspects of visual search and other clinical and cognitive variables. Therefore, the next question of interest was whether there were common characteristics shared by the cases who performed well (and similarly, by those who did not) and whether specific visual or cognitive tests can predict performance on the change blindness task.

Chapter 7 Performance correlates

7.1 Introduction

The change blindness task used in this study was designed to assess several parameters of *functional vision and compensation*: selective visual attention, information processing, scene perception and visual scanning. The effects of hemianopic visual field loss and the role of visual scanning on change blindness task performance were considered in the previous two chapters. It is recognised that a number of capacities are required for effective performance on complex functional tasks, including the oculomotor ability to scan the environment, the sensory ability to detect this information, perceptual and attentional capacities to attend and process multiple pieces of information simultaneously, cognitive abilities to use the information to make appropriate decisions, and the motor ability to execute these decisions in a timely fashion (Wilkinson, 1999). Thus, effective engagement in functional tasks requires a complex combination of both sensory *visual function* (such as acuity and contrast sensitivity in order to physically perceive the stimuli) and *functional vision* (scanning and cognitive processing of the information).

Previous research has suggested that some individuals with hemianopic visual field loss have the potential to develop compensatory scanning skills that allow them to access visual information appearing in the impaired field (Coeckelbergh, Brouwer, Cornelissen & Koojiman, 2001; Kasten et al., 1999; Kasten, Poggel & Sabel, 2000; Koojiman et al., 2004; Mazer et al., 2003; Modi, Woo, Anderson, Strowmatt & Perez, 2005; Nelles et al., 2001; Pambakian & Kennard, 1997; Pambakian et al., 2004). Additional evidence from the current study supports this hypothesis. While the majority of cases did not perform as well as the controls on the change blindness task, a subset of cases performed at similar (accuracy) levels to the controls. The visual scanning measures reported in Chapter 6 go some way to explaining these findings; certain visual parameters appeared to be associated with increased accuracy on the functional task. However, there are a number of other factors which may help to explain the individual performance differences in hemianopic field loss; including age, aetiology, and visual and cognitive deficits associated with the neurological condition underpinning the hemianopia.

The aim of this component of the research was to examine the association between performance on the functional vision (change blindness) task, and the demographic, cognitive and vision functions that may help to explain the ability to compensate for field loss. It was hypothesised that performance on the change blindness task would be more highly correlated with performance on tasks requiring cognitive processing than those measures which test visual function parameters. A related secondary aim was to identify the cognitive and visual characteristics of cases which predicted high levels of performance on the change blindness task.

7.2 Method

The study methods are described in Chapter 3. The full sample of 62 participants was included in the analyses described here, and their clinical characteristics were presented in detail in Chapter 4.

7.2.1 Predictor variables

Details of the predictor variables for the analyses of this component of the research are presented in Chapter 3 and are summarised here to facilitate interpretation of the findings. Three sets of measures were used: (i) demographic information (including medical history, age, aetiology and time since onset of visual field loss (in years), derived from the participant questionnaire; (ii) vision assessments (visual acuity, contrast sensitivity and binocular functional fields); and (iii) cognitive assessments (D2, MVPT, Trails B and the UFOV). Details of the measures and scoring techniques are summarised in Table 19.

Table 19 Summary of vision and cognitive assessments

MEASURE	DESCRIPTION
VISION ASSESSMENTS	
Esterman *Humphrey Field Analyzer*	Automated static perimetry test performed binocularly with normal vision correction. Scores were recorded as the number of detection errors from a possible total of 120 (Esterman, 1982).
24-2 *Humphrey Field Analyzer*	Automated static threshold perimetry test (HFA) performed monocularly and merged using the average eye method (Nelson-Quigg et al., 2000). Scores are expressed as binocular mean decibel deviation.
Contrast Sensitivity (CS) *Pelli-Robson*	An optotype wall chart to measure the ability to detect differences in contrast between objects. Scores were expressed as binocular contrast sensitivity (Faye, 2005; Pelli et al., 1988).
Visual Acuity (VA) *LogMAR distance acuity*	An optotype wall chart used to measure the eye's ability to discriminate high contrast, fine detail at distance. The scores were expressed as binocular logMAR (Bailey & Lovie, 1974).
COGNITIVE ASSESSMENTS	
D2 *Concentration Endurance Test*	Paper and pencil cancellation task designed to assess sustained attention and visual scanning accuracy and speed. Scores were recorded as the number of items correctly processed (Bates & Lemay, 2004; Brickenkamp & Zillmer, 1998).
MVPT-VCS *Motor Free Visual Perception Test Visual Closure Subtest*	Visual closure subtest, designed to assess visual perception without reliance on motor skills. Scores were expressed as the number of incorrect responses (max 12) (Colarusso & Hammill, 2003).
Trails B *Trail-making Test Part B*	Paper and pencil test which measures high-level information processing and working memory ability. Scores were expressed as the time to complete the test in seconds (Bowie & Harvey, 2006).
UFOV *Useful Field of View Test*	Computer-based task designed to assess decline in visual sensory function, slowed visual processing speeds and impaired visual attention skills (Ball et al., 1988). Scores were expressed as percentage reduction from perfect (Ball et al., 1993).

As identified in the table, there were four vision tests that assessed different aspects of vision (acuity, contrast sensitivity and visual fields), and four cognitive tests assessing different aspects of visual search and attention. In addition to the tests presented in the table, other factors identified in previous chapters that were considered to be potential influences on task performance were included as variables in this chapter. These factors included age, aetiology and time since onset of visual field loss (in years).

7.2.2 Analyses

The primary focus in this chapter was to determine which variables were associated with performance on the change blindness task. Thus, the initial analyses focused on the hemianopic case group performance categories identified in Chapter 5 (good, intermediate and poor) to identify whether there were between-groups differences on the vision and cognitive variables.

More sophisticated regression modelling was also conducted to determine which individual variables were good predictors of change blindness task performance, and whether the sensitivity and specificity of the model could be improved using a combination of variables. Prior to performing these analyses, the data were assessed to determine which variables were suitable for inclusion in the model using correlation analyses. These analyses focused on the relationships (Pearson correlations) between the individual variables and performance on the change blindness task, and the relationships among the variables themselves (intercorrelations). Based on these data, univariate and multivariate logistic regression analyses were performed to determine the best predictors of performance on the change blindness task.

7.3 Results

7.3.1 Between-groups performance

One aim of this chapter was to identify the characteristics of the cases who performed well on the change blindness task. Thus, the first set of analyses considered whether there were differences between the cases and controls, and the performance-based groups, on the vision and cognitive variables. Firstly, the case-control differences were considered for each of the variables (Table 20). These data were presented in Chapter 4, and are summarised here for comparative purposes to facilitate interpretation of the case performance category analyses.

As previously reported, the cases had significantly smaller visual field extents than the controls, but the visual acuity and contrast sensitivity levels of both cases and controls were at normal age-based levels and did not differ. However, the cases did present with impairment (relative to the control group) on several measures of cognitive functioning, which suggests there was some level of cognitive impairment among the cases in addition to their visual field defect.

Table 20 Case-control between-group differences

MEASURE	CASES		CONTROLS		*t*	Sig. *p*<0.05
	MEAN	*SD*	*MEAN*	*SD*		
VA *(logMAR units)*	0.00	0.10	-0.10	0.10	0.71	X
CS *(Pelli-Robson units)*	1.50	0.13	1.50	0.13	-2.61	X
Esterman *(missed points)*	34.3	19.9	0.6	1.8	9.88	✓
24-2 *(mean deviation)*	-12.4	4.68	-0.72	1.09	13.5	✓
UFOV *(% reduction)*	54.1	17.8	21.7	13.8	-8.00	✓
D2 *(correctly processed)*	333	106	428	74	4.08	✓
MVPT *(number of errors)*	1.8	1.6	1.0	1.0	-2.38	X
Trails B *(time to complete)*	100.5	57.1	57.1	18.9	-4.02	✓

To explore these differences further, visual and cognitive function was compared on the basis of the performance categories identified in Chapter 5 (good, intermediate and poor relative to error rates for the control group). The results are presented in Table 21.

Table 21 Performance category differences

PARAMETER	CASE-CONTROL DIFF. *p*<0.05	PERFORMANCE CATEGORY GOOD	INTER.	POOR	PERF. GROUP DIFF. *p*<0.05
DEMOGRAPHIC VARIABLES					
Age Years (n)	X	37.7 *SD*=12	49.5 *SD*=21	61.0 *SD*=12	✓
Time since onset Years (n)	n/a	8.6 *SD*=5.6	6.0 *SD*=5.3	8.7 *SD*=8.0	X
VISION VARIABLES					
Contrast sensitivity Binocular Pelli-Robson	X	1.53 *SD*=0.1	1.56 *SD*=0.2	1.45 *SD*=0.1	X
Visual acuity Binocular LogMAR	X	-0.05 *SD*=0.1	0.01 *SD*=0.1	0.1 *SD*=0.2	X
HFA Esterman Binocular points missed (n)	✓	34.2 *SD*=21.5	23.3 *SD*=19.1	41.3 *SD*=14.1	X
HFA 24-2 Binocular mean deviation	X	-11.4 *SD*=4.5	-9.9 *SD*=5.5	-14.7 *SD*=3.4	X
COGNITIVE VARIABLES					
D2 Items correctly processed (n)	✓	399 *SD*=74	338 *SD*=115	280 *SD*=98	✓
MVPT-VCS Errors (n)	X	1.7 *SD*=1.6	1.3 *SD*=1.3	2.2 *SD*=2.0	X
Trails B Time to complete (seconds)	✓	57 *SD*=17	100 *SD*=42	133 *SD*=64	✓
UFOV Reduction (%)	✓	40 *SD*=20	57 *SD*=15	63 *SD*=10	✓

Significant differences were found between the three performance categories for participant age, with the good performers being younger than the poor performers, $F(2,29)=5.81$, $p<0.01$. Time since onset of the lesion which resulted in the visual field loss was not significantly different across the three groups.

A potential explanatory variable of interest was aetiology of visual field loss. The small dataset for performance subgroups precluded statistical analysis, however crosstabs highlighted the following observations: the cases who sustained their field loss through surgery (or neurosurgery) were predominantly in the intermediate or poor performance categories, with only one (of a possible 11) in the good category; and all the cases who sustained their field loss through traumatic brain injury (n=1) or congenital defect (n=3) were in the good performance category.

Visual acuity and contrast sensitivity did not differ between the cases and controls, and similarly no differences were observed among the good, intermediate and poor case group performance categories. Interestingly, despite strong case-control differences in the number of points missed on the Esterman (34 points for the cases versus one point for the controls), differences were not observed between the three performance groups on this measure. Similarly, no differences were observed for 24-2 scores, which suggests that extent of field loss was not significantly different among the three case group performance categories.

Analyses of the cognitive tests revealed that the good performers had significantly better scores than the other two groups on the three remaining measures: they processed around 30% more stimuli on the D2 than the poor performers, $F(2,29)=6.63$, $p<0.01$; they took less than half the time to complete the Trails B than the poor performers, $F(2,29)=11.70$, $p<0.01$; and scored almost 25% better than the poor performers on the UFOV, $F(2,29)=6.43$, $p<0.01$. The MVPT-VCS was the only task which failed to distinguish between cases and controls. Moreover, this test was not sensitive to differences among the case group performance categories, possibly because the range of performance (error scores 1-7) on this task was very small.

Tukey post-hoc analyses revealed significant differences between the good and poor performance groups for: age $F(2,29)=6.72$, $p<0.01$; D2 test correct responses $F(2,29)=4.33$, $p<0.05$; time to complete the Trails B $F(2,29)=7.17$, $p<0.01$; and percentage reduction in UFOV $F(2,29)=6.30$, $p<0.01$. No significant differences were observed between the good and intermediate or between the poor and intermediate performers for any of the parameters studied.

Overall, these results suggest that in addition to the differences observed on a case-control basis for a number of demographic, vision and cognitive variables, there were also clear differences among the cases on a performance basis, particularly for age and cognitive task performance: those who performed well on the change blindness task were younger and tended to perform well on all of the cognitive measures. In the following section, these effects were explored in more detail to determine the relative importance of the demographic, vision and cognitive variables (or a combination of these variables) in explaining performance on the change blindness task.

7.3.2 Correlation analyses

Correlations were performed in order to determine the suitability of the data for regression modelling. The first set of correlations considered the relationships between the predictor variables (intercorrelations), and the second set of correlations were intended to investigate relationships between performance on the change blindness task (accuracy) and each of the cognitive and vision measures. A full description of the correlation analyses and determining suitability for regression modelling can be found in Appendix 12. A brief summary of relevant results is presented here.

Intercorrelations among predictor variables are important to consider prior to conducting multivariate regression modelling as interactions among the different variables have the potential to complicate the interpretation of a model without reliably improving it. Specifically, high correlations among the variables can lead to multicollinearity (Tabachnick & Fidell, 2001). Prior to performing the correlations, analyses of outliers and normality were conducted. A Shapiro-Wilk normality analysis revealed that all variables were normally distributed, and analysis of skewness and kurtosis determined that all values were less than two. Therefore, it was considered appropriate to use Pearson's correlation method for all variables. The correlations were performed with data pooled across all participants (cases and controls, n=62). The results of the correlation matrix are presented in Table 22.

Table 22 Correlations matrix for vision and cognitive measures

R-VALUES								
	VA	CS	24-2	ESTERMAN	UFOV	D2	MVPT-VCS	TRAILS B
VA	**1**							
CS	-0.36*	**1**						
24-2	0.40*	0.16	**1**					
ESTERMAN	0.26*	-0.34*	0.88*	**1**				
UFOV	0.41*	-0.13*	0.70*	0.65*	**1**			
D2	-0.37*	0.16*	0.38*	-0.41*	-0.59*	**1**		
MVPT-VCS	0.15*	-0.02*	0.36*	0.39*	0.19*	-0.32*	**1**	
TRAILS B	0.39*	-0.15*	0.48*	0.39*	0.57*	-0.71*	0.28*	**1**

*significant at <0.05

Some level of correlation would be expected among the variables, given that several are measuring similar constructs. The results (shown in the table) indicate that although all of the measures were significantly correlated, they generally did not explain much of the variance between the variables. There were three notable exceptions; Trails B and D2 were moderately highly correlated (*R*=-0.71, p<0.01), and the UFOV and Esterman were moderately correlated (*R*=0.65, p<0.01). Furthermore, the HFA 24-2 measure of visual field loss was highly correlated with both the Esterman (*R*=0.88, $p<0.05$) and UFOV (*R*=0.70, $p<0.05$). Given these high levels of intercorrelation, it was proposed that one of each of the variables with high shared variance should be excluded from the multivariate regression models.

A second set of correlations were conducted to investigate the indicative relationships between change blindness performance accuracy and each of the individual predictor variables. These correlations were performed for the full sample (cases and controls), and separately for the hemianopic group to determine whether the relationships were differentially affected by field loss. The results indicate differences in the strength of relationships between several of the performance measures and the change blindness task for the hemianopic group compared with the full sample (Table 23). For example, the UFOV explained almost double the variance in the full sample compared with cases only (R^2=0.40 in the full sample; R^2=0.21 in the hemianopic group). Based on these findings, it was considered appropriate that subsequent analyses should be performed for cases and controls separately.

Preliminary analyses also showed that performance of the two outliers in the case group (reported in Chapters 5 and 6) affected the variance for several of the measures (details can be found in Appendix 11). Based on these data, it was concluded that although the two outliers did not have significant leverage on all of the variables, they altered the variance enough in selected variables to be removed from the *multivariate* regression analyses.

Table 23 Correlations after removing outliers

MEASURE	ALL PARTICIPANTS		HEMIANOPIC GROUP	
	R^2 (including outliers)	R^2 (excluding outliers)	R^2 (including outliers)	R^2 (excluding outliers)
VA binocular	0.04	0.17	0.02	0.18
CS binocular	0.04	0.04	0.05	0.04
24-2	0.09	0.06	0.06	0.06
Esterman	0.13	0.20	0.08	0.07
UFOV	0.19	0.40	0.07	0.21
D2	0.28	0.31	0.26	0.25
MVPT	0.18	0.04	0.20	0.04
Trails B	0.48	0.37	0.46	0.34

Among the variables that showed evidence of multicollinearity, the UFOV, Trails B and the Esterman were most highly correlated with change blindness performance. On this basis, these variables were selected for inclusion in the multivariate regression modelling, and accordingly, the D2 and HFA 24-2 measures were excluded.

7.3.3 Logistic regression

7.3.3.1 Univariate analysis

The correlation analyses presented thus far were concerned with assessing the indicative relationship strength between the individual variables and performance on the change blindness task, and the relationships among the variables themselves (intercorrelations). These analyses were performed as a precursor to the regression modelling, and the findings identified (i) the two outliers should be removed, and (ii) the analyses should be performed for the cases and controls separately.

Next, univariate regressions were conducted to examine the strength of association between each of the individual variables and performance on the change blindness task. These analyses were performed using binary logistic regression models, with an outcome measure of *correct response on the change blindness task*. Separate models were constructed for the cases and controls (as recommended by the findings in the correlation analyses). The odds ratios and 95% confidence intervals for each model are presented in Table 24.

Table 24 Odds ratios predicting blindness correct responses

PREDICTOR	CASES ONLY				CONTROLS ONLY			
	ODDS RATIO	95% LCL	95% UCL	*p*<0.05	ODDS RATIO	95% LCL	95% UCL	*p*<0.05
Change blindness	**1.000**				**1.000**			
Visual acuity	0.217	0.124	0.380	✓	1.680	0.497	5.683	X
Contrast sensitivity	2.654	1.198	5.883	✓	1.440	0.472	4.393	X
Esterman	0.991	0.985	0.996	✓	1.153	0.917	1.448	X
24-2	1.051	1.025	1.076	✓	1.145	0.996	1.316	X
UFOV	0.981	0.974	0.987	✓	0.972	0.963	0.981	✓
D2	1.004	1.002	1.005	✓	1.003	1.001	1.005	✓
MVPT-VCS	0.908	0.843	0.978	✓	1.104	0.955	1.276	X
Trails B	0.991	0.989	0.994	✓	0.996	0.989	1.004	X
Age	0.984	0.978	0.991	✓	0.979	0.970	0.987	✓
Time since onset	1.002	0.986	1.018	X	n/a	n/a	n/a	n/a

The results revealed that the individual variables appeared to be better predictors of change blindness performance in the case group compared with the control group. This was not unexpected, given the greater within-group variance for the cases.

Among the cases, all of the individual predictor variables were individually significantly associated with correct responses on the change blindness task. For example, for each year increase in age, the odds of responding correctly reduced by 2%, a better contrast sensitivity and less extensive field loss (24-2) were associated with better performance on the change blindness task, and for each missed point on the Esterman, the odds of responding correctly on the change blindness task reduced by 1%.

Notably, the models showed that the relationships were generally in the direction expected, with the exception of visual acuity (OR=0.217), where better acuity was associated with *poorer* performance on the change blindness task. This counterintuitive finding probably reflects the very low variability and range of scores (log units) for this measure, rather than any finding of significant functional relevance. Alternatively, this may reflect macular sparing rather than being a true measurement of acuity, as macular splitting can present as reduced visual acuity (Lorenz & Borruat, 2008).

The cognitive tasks were also found to be significant predictors of change blindness performance among the cases. For example, for each 10 point increase on the D2, the odds of responding correctly on the change blindness task increased by 4%, and for each additional second to complete the Trails B, the odds of responding correctly reduced by 1%. More errors on the MVPT-VCS and higher percentage reduction on the UFOV were associated with more errors on the change blindness task.

Results for the controls indicated that only the UFOV, the D2 and age were individually associated with performance on the change blindness task. For example, the odds of responding correctly on the change blindness task reduced for: each year increase in age by 2%; every 10 point increase on the D2 by 3%; and each percent increase on the UFOV by 3%. Although these values were quite low, it was noteworthy that many of the parameters that significantly predicted correct responses in the case group were not significant in the control group. As noted above, this finding is likely to reflect greater variability on these measures amongst the cases compared with the controls. The exception to this was age, however it was possible that the combination of age and field loss had a greater impact on performance than age alone.

Having established differences between cases and controls with respect to the strength of the relationships between variables of interest and performance on the change blindness task, subsequent analyses were conducted with the case group only to identify those variables which best predicted good performance.

In addition to the odds ratios, it was also of interest to determine the level of sensitivity and specificity for each predictor variable for the cases. In the context of this study, sensitivity refers to correctly predicting those who made no error on the task (i.e. true positives), and specificity refers to correctly identifying those that made errors on the task (i.e. true negatives). The cut-off value to dichotomise the predicted outcome based on the predicted correct response probability from the logistic model was set to 88.5%, which resulted in the highest combined sensitivity and specificity. The results for predicting performance on the change blindness task (errors) for the cases are reported in Table 25.

Table 25 Sensitivity and specificity for cases

PREDICTOR	SPECIFICITY	SENSITIVITY	OVERALL PREDICTIVE VALUE
VA binocular	69.1%	33.8%	64.9%
CS binocular	35.2%	74.3%	39.9%
Esterman	49.8%	60.5%	51.1%
24-2	43.0%	68.4%	46.0%
UFOV	35.4%	75.9%	40.3%
D2	53.4%	63.2%	54.6%
MVPT-VCS	59.8%	52.2%	58.9%
Trails B	67.0%	47.6%	64.7%
Age	45.3%	61.6%	47.3%
Time since onset	3.4%	95.9%	14.4%

The results showed that each of the individual tests had reasonably poor overall predictive power for the cases, with the best predictive value at 64.9% for visual acuity. The poorest predictive power was for time since onset of lesion resulting in visual field loss (which had a non-significant odds ratio as well). The best predictors in the cases were visual acuity and Trails B. However, although modest specificity values were observed for these measures, in the case of visual acuity, sensitivity was very low. Thus, the individual tests appear better at predicting good (compensatory) performance on the change blindness task (sensitivity) than predicting poor performance on the change blindness task (specificity).

Sensitivity and specificity consider binary outcomes (pass or fail), however a triage approach has been used throughout this thesis classifying cases into one of three categories: good, intermediate and poor. The univariate analyses found that none of the predictor variables were particularly good at classifying cases based on their performance using a single cut-point (88.5%), thus to explore whether these findings were consistent with the triage approach, the data were plotted for several variables. To illustrate, Figure 30 depicts a hypothetical measure whereby there is distinct separation between the classification of the cases. The red lines in the figure demonstrate no overlap between the cumulative performance distributions for the good, intermediate and poor cases.

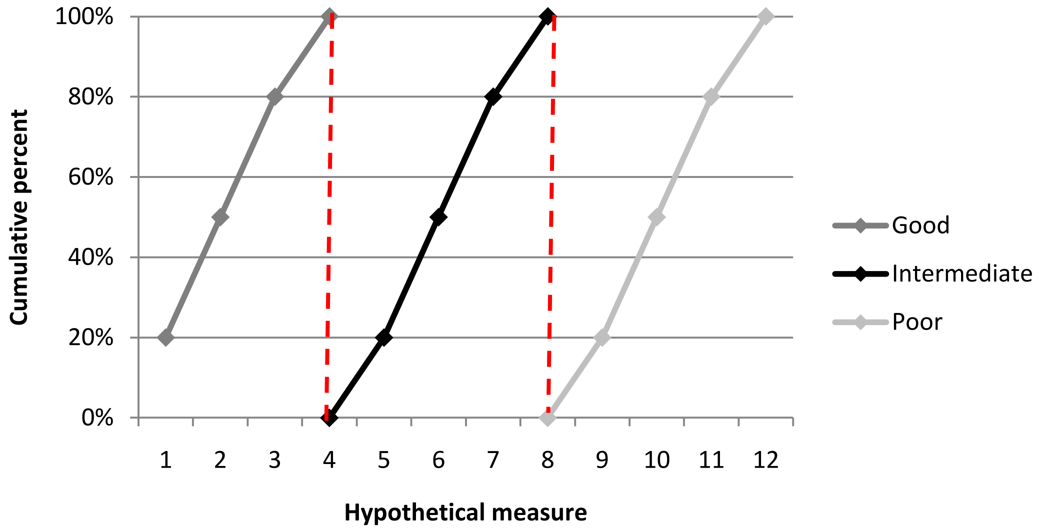


Figure 30 Hypothetical performance classification of cases

Figure 31 depicts the cumulative distribution within the performance classifications (good, intermediate and poor) for age. As can be seen in the figure, there is a significant amount of overlap between the performance categories, particularly the intermediate and poor groups. This is consistent with the results of the univariate analysis for this variable which showed that despite being a significant predictor, the overall predictive value for age was relatively low.

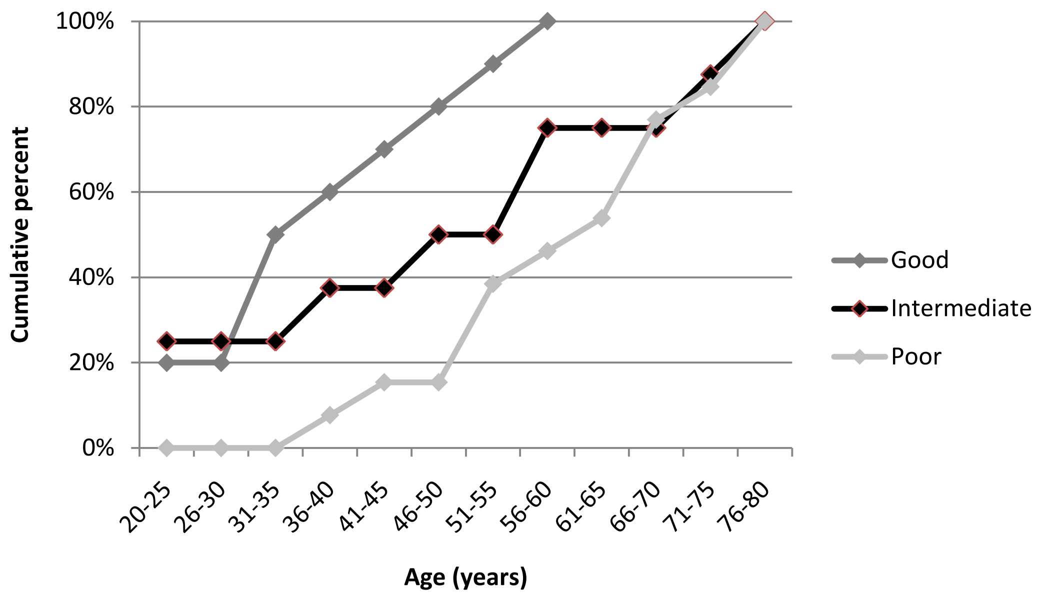


Figure 31 Performance classification for age

Figure 32 depicts the cumulative distribution within the performance classifications for Trails B, and Figure 33 depicts the Esterman. Consistent with previous analyses, Trails B appears to have better separation for the good performers, but there is still significant overlap between the intermediate and poor groups. This suggests that there is significant heterogeneity of performance on Trails B, particularly among the intermediate and poor change blindness performance categories.

In contrast, there does not appear to be any separation among the categories for the number of points missed on the Esterman, which suggests that the Esterman scores significantly overlap among the change blindness performance categories. This confirms previous analyses where it was found that the Esterman was a poor predictor of performance on the change blindness task.

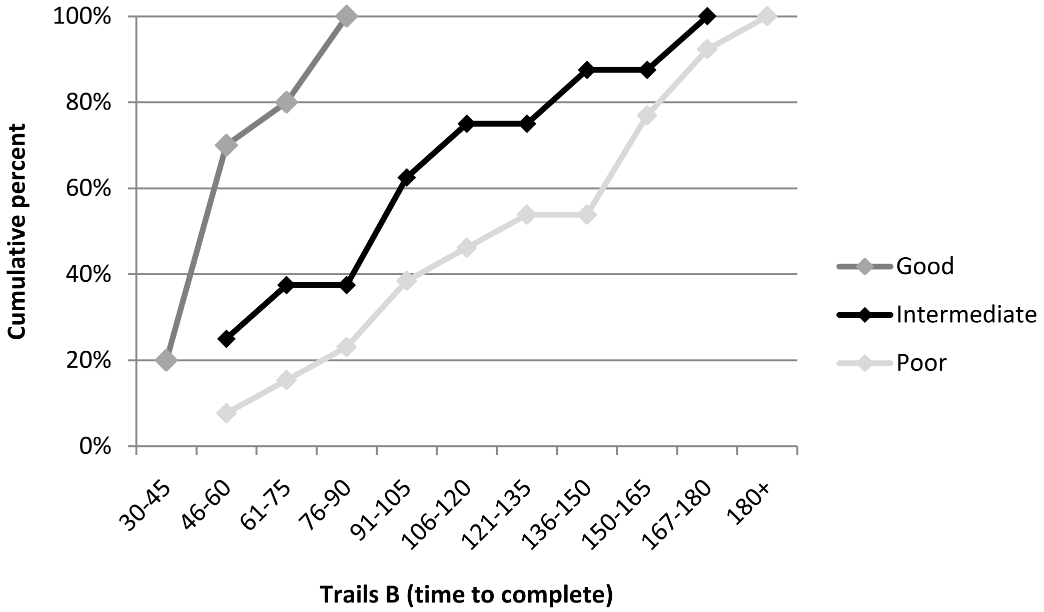


Figure 32 Performance classification for Trails B

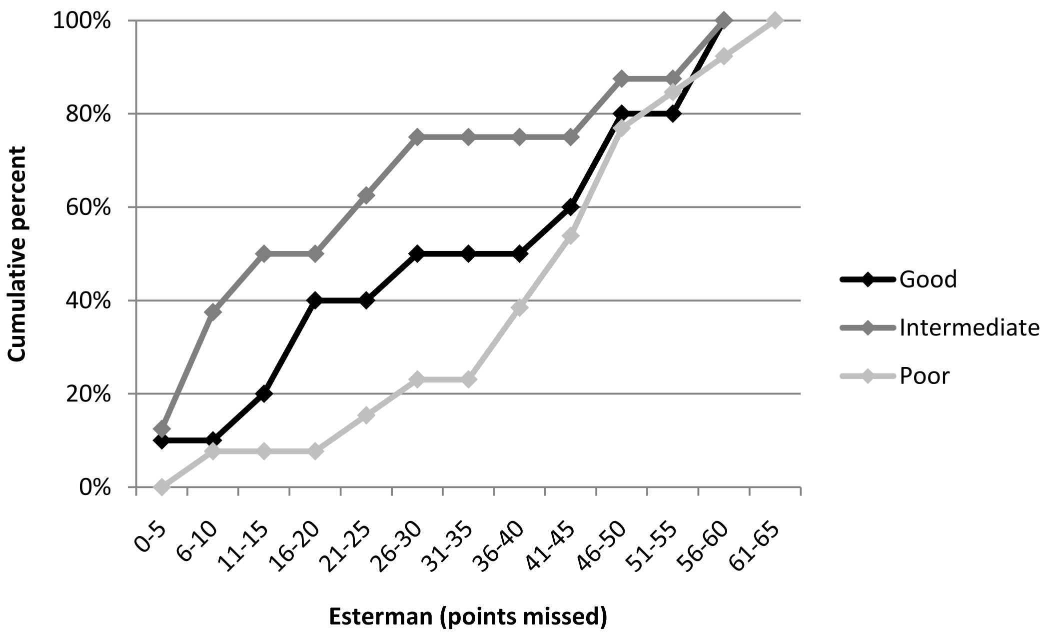


Figure 33 Performance classification for the Esterman

In summary, the key results from the univariate analyses revealed that all of the cognitive and vision variables were independently significantly associated with errors on the change blindness task in the case group. However, despite the significant associations between the individual variables and change blindness errors, the predictive power of each test was relatively low using a binary outcome (sensitivity and specificity) and a triage (performance classification) approach. Thus, in isolation the individual variables were not strong predictors of performance, and it was deemed appropriate to perform multivariate analysis to explore whether a combination of variables could better predict performance on the change blindness task.

7.3.4 Multivariate analysis

7.3.4.1 Multivariate model for error data

The multivariate model was applied to the case data to further explore the combined role of demographic, cognitive and vision measures in predicting change blindness performance (compensation) in the case group. As the correlation and univariate analyses indicated that several variables had different predictive power between the case and control groups, the analyses were performed for the case group only. A separate analysis for controls was not performed as this was not expected to contribute to an understanding of compensation for field loss.

A backwards step-wise logistic regression model was employed to construct the best predictive model. This method represents an iterative variable-selection procedure where the inclusion and exclusion of predictors from the equation is based solely on statistical criteria: poor predictors of performance are removed from the model during the step-wise process (Tabachnick & Fidell, 2001). The variables included in the model were: age, time since onset of lesion, visual acuity, contrast sensitivity, Esterman UFOV, MVPT-VCS and Trails B, with correct responses on the change blindness task as the outcome variable. The HFA 24-2 and the D2 were not included in this analysis due to the high level of intercorrelation with other variables. The odds ratios and confidence intervals for the predictors that remained in the final model are presented in Table 26.

Table 26 Multivariate regression for error data

PREDICTOR	ODDS RATIO	LOWER CI (95%)	UPPER CI (95%)	*p*<0.05
CHANGE BLINDNESS	**1.00**			
AGE	0.990	0.984	0.995	✓
UFOV	0.987	0.983	0.992	✓
MVPT-VCS	0.893	0.834	0.956	✓
TRAILS B	0.995	0.993	0.998	✓

These results indicated that the best combination of predictor variables were age, UFOV, MVPT-VCS and Trails B, all of which had significant partial effects when employing a 95% criterion of statistical significance. Contrast sensitivity, visual acuity, Esterman and time since onset of lesion were removed from the model during the stepwise process. This was not a surprising result: the vision variables (visual acuity, contrast sensitivity and the Esterman) had very low variability and their explanatory power for performance was found to be relatively low in the univariate modelling. In addition, time since onset of brain injury was not a significant predictor of performance in the univariate analyses and the findings in this analysis confirm this result.

The relationships between the significant variables in the model and change blindness task performance were all in the direction expected, although the explanatory power of each variable was quite low. The odds ratios indicated that the odds of responding correctly on the change blindness task (among the cases) reduced for: every year increase in age by 1% (OR=0.990); every percent reduction in the UFOV by 1% (OR=0.987); each error on the MVPT-VCS by 11% (OR=0.893); and each second on the Trails B by 0.5% (OR=0.995). The multivariate model correctly predicted only 52.3% of the response outcomes (50.2% sensitivity and 68.4% specificity, using an 88.5% cut-off). Thus, these results suggest that combining the variables did not result in a highly predictive model for change blindness performance, which suggest there are still factors influencing the outcome that have not been accounted for.

To summarise the multivariate model, the best combination of variables for predicting error performance on the change blindness task were age, the UFOV, Trails B and the MVPT-VCS, predicting just over 50% of the correct responses. None of the vision assessments were found to be good predictors of performance in this model, nor was time since onset of field loss. The cognitive variables predicted performance on the change blindness task better than the vision tasks, and there remained a significant portion of performance outcomes (47.7%) that were not well predicted by any of the demographic, neuropsychological or vision variables used in this study.

7.3.4.2 Multivariate model for errors and response time

In order to assimilate all the data presented in this thesis, an additional multivariate regression model was performed to investigate the effects of both errors and response times together. A new variable was created to reflect whether the response was correct *and* occurred within an appropriate time frame. This variable was defined as a 'successful' response (i.e. *a response that correctly identified the stimulus within one standard deviation of the mean response time of the controls*). All incorrect responses and responses occurring outside the defined time period were coded as 'unsuccessful responses'. A binary logistic regression model was applied to the data, using the step-wise process presented previously. The outcome measure was 'successful response', and the variables entered into the model were: age, time since onset, visual acuity, contrast sensitivity, Esterman, UFOV, MVPT-VCS and Trails B. The odds ratios and confidence intervals for the variables remaining in the model after the step-wise process are presented in Table 27.

Table 27 Multivariate regression for errors and response time data

PREDICTOR	ODDS RATIO	LOWER CI	UPPER CI	$p<0.05$
'Successful' CB response	**1.00**			
Age	0.986	0.981	0.991	✓
UFOV	0.992	0.987	0.998	✓
MVPT-VCS	0.811	0.767	0.858	✓
Trails B	0.990	0.990	0.994	✓

Employing a 95% criterion of statistical significance, age, the UFOV, MVPT-VCS and Trails B all showed significant partial effects. Interestingly, these were the same variables that were significant in the model using error data only. Similarly, time since onset, visual acuity, contrast sensitivity and the Esterman were not found to be significant predictors. The odds ratios for the significant variables were also very similar to the error only model. The odds of responding 'successfully' (i.e. correctly and within 1*SD* of the controls' response times) were decreased for: each one year increase in age by 0.9%; each one percent increase in UFOV by 0.2%; each error on the MVPT by 14.2%; and each one second increase on the Trails B by 0.6%.

Using a 50% cut-off (which represented the best sensitivity and specificity for this model), the overall predictive value was 65.1%. This represented very good sensitivity (87.7%), but poor specificity (26.0%). Adding the response time to the outcome improved the overall predictive value of the tests somewhat (from 52% for errors only, up to 65%), however, the specificity of the combination of variables remained relatively low.

Overall, the results of this analysis indicated that the cognitive variables were better predictors of successful performance (errors and response time) on the change blindness task than the vision tasks, none of which remained in the step-wise model. Adding the response time improved the overall predictive value of the model, however, a large portion of performance (34.9%) remained that was not well predicted by any of the cognitive or vision tasks employed. Moreover, the model better predicted those who performed well than those who performed poorly on the change blindness task.

7.4 Discussion

The overall aim of this chapter was to examine the association between the change blindness task and selected cognitive and vision measures commonly used in clinical and driving assessment settings. The change blindness task was considered a measure of *functional vision* (i.e. a tool for measuring compensatory ability) in people with hemianopia, and was designed to measure visual search, visual scanning and selective attention across 140° of horizontal visual field. It was proposed that if visual attention was effectively employed in the blind regions (defined as responding correctly to a changing target) it implies that the participant engaged in effective visual search (locating the target), visual scanning (identifying the stimulus even when it appeared in the blind region) and visual attention (processing the stimulus). This in turn suggests that the strategies the individual employed had *functional benefit*, and thus indicates a compensatory mechanism.

In Chapter 5, a subset of participants were identified who performed as well as the controls on the change blindness task, while others had great difficulty in completing the task accurately. The eye movement data presented in Chapter 6 explained this phenomenon to some extent; cases who performed well on the task engaged in visual search strategies that were different to those who performed poorly. However, it was also of interest to determine whether the vision or cognitive abilities of the participants, as measured by tests in common clinical practice, could add to the explanatory power in predicting performance on the change blindness task.

The analyses revealed a number of interesting findings regarding the demographic, vision and cognitive correlates of change blindness performance. As expected, there were a number of differences between the hemianopic cases and controls on the different variables, and in order to explore this further, the data were first considered in the context of the performance categories identified in Chapter 5 (good, intermediate and poor, relative to the control group performance). The between-group differences were then studied more closely using correlations and regression analyses to consider specific associations between individual variables (and combinations of variables), and predictions of change blindness task performance.

On the performance category level, several characteristics emerged. The 'good' performers (i.e. those who performed as well as the controls) tended to be younger and did not display impairment (relative to the other performance categories) on several of the cognitive tests: D2, Trails B and UFOV. Interestingly, participants in the three performance categories did not differ on the vision measures (contrast sensitivity, visual acuity or the Esterman), suggesting that these measures were not good predictors of performance on the functional task. The two measures of visual field extent, 24-2 and Esterman, were highly intercorrelated and while the 24-2 was excluded from the final regression models for this reason, it is unlikely that this measure would have been more predictive of performance.

Age was significantly different among the performance categories, with the good performers being younger than the poor performers. This finding was confirmed in the final regression analyses; age emerged as a good predictor in both models: for errors only and errors and response time together. This relationship was in the direction that would be expected: as age increased, change blindness task performance decreased. A number of experimental studies have indicated that older people tend to respond more slowly to targets than younger ones, and the effect of age is more pronounced for complex reaction time tasks (Bertsch et al., 2009; Deiber et al., 2010; Lavie, 2005; Madden, 2007; Madden & Whiting, 2004; Parkin & Walter, 1992; Parkin et al., 1995; Salthouse & Czaja, 2000; Salthouse et al., 1998), which arguably the change blindness task represents.

Time since onset of visual field loss was not found to be different among the performance categories, and similarly was not found to be a good predictor in any of the models constructed (univariate or multivariate). This is a somewhat surprising result, because presumably adaptation for visual field loss would occur over time, and thus it could be expected that the longer the time since onset, the greater the opportunity for adaptation and improvement in performance. However, it is possible that the interaction between age, time since onset, and the presence of more general cognitive impairment is more important in adaptation than time since onset alone.

Few associations were found between the three tests of visual function used in this study and errors/response time on the change blindness task. Neither visual acuity nor contrast sensitivity were found to be significantly associated with change blindness performance in the correlation analyses, and this was confirmed by the multivariate regression where both variables were found to be poor predictors. However, all participants in this study (cases and controls) presented with visual acuity and contrast sensitivity that were within normal limits which is likely to explain the low explanatory power of these variables.

The Esterman was associated with task performance in the full sample (i.e. cases and controls) which would be expected given the heterogeneity of field loss (ranging from none to extensive). However, it was not associated with task performance in the case group, and the univariate analysis found low predictive power for this measure (51%). These data suggest that change blindness task performance and visual function measures are relatively independent of one another. This was not entirely unexpected; visual search represents a complex activity that requires the integration of visual attention (to select the stimulus of interest), effective eye movements (to focus on the stimulus of interest) and memory (to apply stored knowledge to the stimulus) (Styles, 2005). Thus, to effectively search the visual environment, the eyes must be directed to relevant areas of the visual field, and active scanning is necessary to build an accurate representation of the scene. Given that the vision tests reported in this study represent static measurements of visual function, interpreting the results in the context of complex scenes that require the integration of attention, eye movements and memory is challenging.

The UFOV combined both visual and cognitive functions, and was found to be a significant predictor in the cases: it was significantly associated with accuracy (number of errors) on the change blindness task, and was also found to be a reasonable predictor of performance in the multivariate modelling. However, the univariate analyses found that the UFOV was a better predictor of good change blindness performance (sensitivity 76%) than poor performance (specificity 35%), leading to a low overall predictive value (40%). This suggests that good performance on the UFOV correctly identified a large proportion of the sample that performed well (compensated) on the change blindness task, however it was a relatively weak predictor for those that did not compensate well.

Considering the aspects of vision and cognition the UFOV is designed to capture, the finding of a low overall predictive value for performance on the change blindness task is not surprising. The UFOV is designed to determine the visual space over which visual information can be rapidly processed, and the 'useful field of view' is defined as the total visual field area in which one can extract useful visual information in a single glance without eye or head movement (Ball et al., 1993). As a test, it measures processing speed, selective attention, and divided attention (Ball et al., 1993). As the UFOV measures both visual function (sensory skills) and functional vision (cognitive skills), it arguably provides a more global measure of visual functional status than either sensory or cognitive tests alone (Wilkinson, 1999). However, the problem with using the UFOV in the case of hemianopia is that it measures the capacity to perform a central discrimination task at fixation while *simultaneously* localising a presented target presented in the periphery. This requires adequate vision and visual fields, and thus is an unrealistic expectation in hemianopia (American Academy of Ophthalmology, 2009). So, although UFOV has been shown to be a sensitive task for assessing older drivers and some clinical conditions (Ball & Owsley, 1991), the findings of the current study suggest its utility in hemianopic field loss is more limited and scores are likely to reflect the level of visual field loss.

Among the cases, the multivariate modelling found that the cognitive assessments had more predictive power than the visual tests for performance on the change blindness task; all three of the four cognitive tests entered in the model were found to be good predictors of performance. In contrast, none of the vision tests were useful predictors of change blindness performance. Based on the univariate and multivariate analyses, the best predictors were the Trails B and the MVPT-VCS.

This finding is consistent with the functional nature of Trails B, which is a measure of visual search and sequencing, information processing speed, divided attention and set flexibility (Bowie & Harvey, 2006; Hester et al., 2005; Misdraji & Gass, 2009; Shultheis, DeLuca & Chute, 2009; Steinberg et al., 2005; Tombaugh, 2004). Trails B has good face validity because its cognitive demands include visual scanning, visuomotor coordination and visual-spatial ability which are similar constructs to those being measured by the change blindness task (i.e. the integration between visual and cognitive aspects of visual search and processing). However, despite the good overall predictive value of the Trails B, it was also found to have better specificity than sensitivity in the cases. This indicates that while Trails B predicted poor change blindness performance well, it did not correctly identify a large proportion of the sample that performed well (compensated) on the change blindness task. This suggests that whilst there is some significant overlap in performance between the two tasks, there is some aspect of functional performance that the two do not share.

The MVPT-VCS was also found to be a good predictor of change blindness performance. This test captures perceptual-cognitive performance and visuo-motor integration, and provides a measure of the understanding of spatial relationships which is important for identifying partially obscured objects (Ball et al., 2006; Fildes et al., 2004; Modi et al., 2005). In the present study, the MVPT-VCS explained a small but significant portion of the variance in errors on the change blindness task. Among the cases, the sensitivity and specificity were fairly similar (52% and 60% respectively), however, a large part of the variance was not well explained by this variable when considered as a univariate predictor of change blindness performance. This in turn suggests that the change blindness task measured an aspect of performance that the MVPT-VCS did not.

The D2 Test of Sustained Attention was not included in the overall regression modelling due to the high level of intercorrelation with Trails B. The D2 is a cancellation task designed to measure selective attention, inhibition, processing speed, rule compliance, sustained attention and quality of performance (Bates & Lemay, 2004; Brickenkamp & Zillmer, 1998), and thus the intercorrelation with Trails B was not entirely unexpected as both tasks measure similar constructs. However, significant correlations were found between the D2 and the change blindness task, and the performance category analyses found that the good performers processed around 30% more stimuli than the poor performing cases. Thus it would appear that there was some degree of overlap between constructs measured in the change blindness task and those measured by the D2.

Overall, the analyses of performance correlates on the change blindness task revealed two significant findings. Firstly, a combination of age and cognitive test performance (specifically Trails B, MVPT-VCS and UFOV) were more predictive of change blindness task performance than vision tests. This suggests that performance on the change blindness task was driven by attentional and cognitive mechanisms more than visual function (i.e. static measures of acuity or contrast sensitivity). Secondly, even using a combination of variables, there remained a portion of the variance that was not well explained by any of the assessments used in this study.

Thus, these findings suggest that the change blindness task measured a construct *in addition* to those measured by the standard clinical and vision tasks that were used here. The original hypotheses of the research proposed that in order for cases to perform well on the task, it would be important to engage in effective and compensatory scanning strategies *in addition* to processing the relevant information. Findings reported in Chapter 5 revealed that despite the presence of visual field loss, a subset of cases did not display impairment relative to the controls on the change blindness task. Visual scanning during the task was explored in Chapter 6, and indeed the findings revealed differences in search strategies between cases who performed well on the change blindness task and those who did not. Together, these findings suggest that *functional compensation*, as evidenced by good performance on the change blindness task, is associated with both distinctive patterns of visual search as well as attentional and cognitive performance.

7.5 Conclusions

Results from the correlation and regression analyses presented in this chapter provided a number of insights regarding functional assessment in this group. The cognitive assessments were found to be more predictive of performance on the change blindness task than the assessments of visual function. In addition, the cognitive measures shared common variance, indicating that people with hemianopia were likely to score poorly on multiple measures of cognitive function.

Trails B and the MVPT-VCS were found to be the most sensitive of the performance-based measures for predicting performance on the change blindness task. Those who were able to compensate well for their hemianopia, as measured by better performance on the change blindness task, were those who also performed well on Trails B and MVPT-VCS.

These results have good face validity, in that selective attention, visual scanning, working memory and an understanding of spatial relationships, as assessed using Trails B and the MVPT-VCS, are cognitive functions integral to performance on the change blindness task. The applicability of these findings to the driving domain is discussed in Chapter 8.

Chapter 8 General discussion and conclusions

This PhD research represents a novel approach in the investigation of selective attention and compensation in hemianopia. This final chapter is intended to summarise and integrate the main themes of the research. An overview of the purpose of the research is presented, followed by a detailed discussion of the key findings. The implications and practical application to driving are discussed and consideration is given to the study limitations and recommendations for future research.

8.1 Overview

Hemianopia and quadrantanopia are visual field defects that result from neurological damage to the visual pathways at the optic chiasm or post-chiasmal pathways. Given the neurological component in hemianopic field loss, there are often compounding cognitive and attentional problems. Thus, these field defects have the potential to affect a wide range of activities of everyday living, including reading, writing, general mobility and driving. Currently people with hemianopic field loss are precluded from holding a driving licence in many jurisdictions around the world. However, the research suggests that hemianopic field loss does not necessarily result in impairment of everyday activities, and may not impair driving performance enough to warrant licence refusal. Further, driving cessation impacts on quality of life, with consequences for mental health and social inclusion, thus it is important that people with hemianopic field loss are not excluded from driving unnecessarily.

The absence of functional impairment observed in a subset of individuals with hemianopia has been explained by compensation: it is thought that some individuals are able to adapt their visual search to overcome their field defect. However, compensation is also thought to involve a complex interaction between visual and cognitive processing. To date, most studies have considered compensation in the context of eye movements and have paid little regard to the integration of low level visual processing and higher order cognitive processing. Further, the role of cognitive, visual and visual search capacities has not been considered previously, in the context of naturalistic driving-related scenes.

Thus, the overarching aim of this PhD was to investigate functional compensation in hemianopia. This was conducted using the change blindness paradigm to investigate attentional processing and eye movements across the visual field in naturalistic driving scenes. It was proposed that this method would assess several parameters simultaneously: visual scanning, scene perception, selective visual attention and information processing. Specific objectives of this research were to investigate the extent to which individuals with hemianopic field loss adequately compensate for their field loss through altered scanpaths; and to investigate the relationship between performance on the change blindness task and cognitive/vision tests commonly used in driving research and assessment.

The evidence reviewed in Chapter 1 suggested that although peripheral vision plays an important role in safe driving, some people with hemianopic field loss perform as well as people with normal vision during on-road or simulated driving assessments (Szlyk et al., 1993; Tant et al., 2002; Wood et al., 2009). The general consensus in the literature is that these differences exist because some individuals employ compensatory or adaptive strategies to a greater extent than others. However, the definition, measurement and mechanisms underpinning compensation are still largely a matter of debate. The research indicates that despite actively searching a visual scene and fixating on targets, adequate processing does not necessarily occur (i.e. the 'look without seeing' phenomenon) (Galpin et al., 2009). Thus, it is clear that compensation represents a complex interaction between a number of factors, such as visual search, visual perception, information processing and attentional processes, and cannot be inferred from eye movements alone.

The change blindness task used in this research represented a measure of functional vision, and was designed to assess visual search, visual scanning and selective attention across 140 degrees of the horizontal field of view. The theoretical framework underpinning the change blindness paradigm argues that the key factor in producing the change blindness effect is attention: visual perception of change in any given scene occurs only when the change is being selectively attended (Rensink et al., 1997). Thus, successful performance on this task purportedly required the effective *integration* of visual scanning, visual attention and visual processing.

It was proposed that the processes that mediate compensation include: visual scanning and search to locate the target, visual perception and object recognition to identify the stimulus, and selective visual attention to process the stimulus. Based on this assumption, it was hypothesised that if visual attention was effectively employed in the blind regions (correctly responding to a target), the participant was in some way compensating for their field loss given that there was no visual function in that area. Thus, the first experimental component of the current study focussed on task performance, particularly with respect to accuracy.

8.2 Key findings

Overall, the change blindness paradigm was useful in discriminating functions relevant to hemianopia. A key finding was that across 140 degrees of visual field, the cases performed worse than the controls on both accuracy and response times, and the differences in error rates and response times were more pronounced in the blind regions. Cases were 77% less likely to respond correctly, and around 45% slower than controls to respond to targets in their blind regions. In contrast, they were 54% less likely to respond correctly and 25% slower than controls in their seeing regions. This finding suggests a general processing deficit which was evident across the entire field, including the seeing regions.

Notwithstanding the clear findings showing performance decrements in hemianopia, there is also well documented evidence that a subset of individuals, even with extensive field loss, live entirely normal and active lives without impairment in activities of daily living (Gassel & Williams, 1963) including driving (Tant et al., 2002; Wood et al., 2009). The present study provided further evidence for this, demonstrating that the hemianopic cases represented an extremely heterogeneous group of individuals, with considerable variation in visual and cognitive characteristics. This is consistent with the varied clinical picture in hemianopia and quadrantanopia, and not surprising given the wide range of aetiologies and levels of impairment associated with the condition (Arlinghaus et al., 2005; Arumugam et al., 2010). Thus, it was considered important to examine the pattern of variation in functional performance amongst cases with hemianopia.

To explore these individual differences in greater detail, a key component of Chapter 5 was the development of a framework for classifying the cases based on their change blindness performance. This performance classification framework facilitated meaningful comparisons between those who performed well and those who did not, and allowed inferences to be made regarding characteristics based on performance.

A three-level outcome was selected for this study, based on a body of psychometric and cognitive literature (Anastasi, 1998; Baiyewu et al., 2007; Galanis et al., 1999; Verdoux et al., 2000). This approach has also been adopted by the American Academy of Ophthalmology in a set of recommendations for assessing driving performance, proposing that individuals with hemianopia should be considered on one of three levels: good, intermediate, and poor (American Academy of Ophthalmology, 2009). In a similar triage approach, the classification system developed for this study used the control group data as a baseline to determine categories of performance among the hemianopic participants.

A number of interesting findings emerged from the performance classifications. Importantly, it was found that around one-third of the cases performed at least as well as controls. This was a critical finding, and confirmed that a subgroup were able to accurately respond to targets, despite the absence of visual function in that region, thus indicating some level of compensation. It is interesting to note that a similar proportion of hemianopic cases have been reported to show no sign of impairment on a range of everyday or functional tasks (Gassel & Williams, 1963).

The response time data also highlighted some interesting findings. Firstly, although cases as a group were slower to respond to targets than controls, when considering the data on a performance category basis, the good performers were not significantly different to the controls, and the poor performers took on average more than three times as long to respond correctly to targets. These data suggest that the poor performers had difficulty identifying (or processing) the targets, and for the few targets they were able to accurately identify, response times were considerably slower. This in turn suggests a global processing deficit in the poor performers for both accuracy and time, which was not evident among the good performers. Collectively, these findings also provide support for the use of a triage approach for understanding performance differences among the cases.

One explanation for these findings is that individuals with hemianopia have an inability to develop a brief and comprehensive overview of the visual space available (Tant et al., 2002). This is a function of working memory, and it is possible that this explanation could account for the general inefficiency in search and localisation of targets of the poor performers in the current study. Visual working memory is considered a transient store of visual information on which selective attention can operate to transfer information to a more durable, reportable form, for example long term memory (Styles, 2005). The premise behind change blindness is that the visual perception of change occurs only when selective attention is employed, and in the absence of selective attention, the contents of visual working memory are overwritten by subsequent stimuli and therefore cannot be used to make a comparison.

Another fundamental premise of the change blindness paradigm is that perception of change is mediated through an attentional bottleneck, with attention attracted to parts of the scene based on high-level interest (Rensink et al., 1997). Further, the flicker paradigm allows stimuli to be presented for long durations, providing the best opportunity for an observer to build scene representations which suggests a role for working memory. Thus, poor performance observed in the present study may reflect difficulty in the use of visual working memory to develop an overview of the visual space available.

In summary, the findings for the change blindness component of the research showed that the cases as a group performed more poorly than the controls, making more errors and taking longer to identify targets. However, a subset of the cases performed as well as the controls, despite the presence of visual field loss. This suggests that some individuals with hemianopia compensated effectively during the task. Based on these results it is argued that the change blindness task appears to be a sensitive tool for investigating compensation in hemianopia.

To effectively search the visual environment, the eyes must be directed to relevant areas of the visual field using two key eye movement parameters, saccades and fixations. Previous research suggests that the quality and patterns of eye movements in hemianopia differ to those of controls, and that people with hemianopia may explore the left and right hemi-spaces differently (Chedru et al., 1973; Pambakian & Kennard, 1997; Zihl & Hebel, 1997). However, effective visual search requires more than a response to sensory input: it also requires a range of cognitive processing skills such as attention, object recognition, and application of stored knowledge from memory. Thus, even in the presence of active visual scanning and fixation on parts of a scene, attentional processing may not necessarily occur. Evidence for an association between eye movement parameters and attentional processing of a target is required in order to demonstrate that the visual search strategies are truly compensatory, holding functional benefit for the individual.

Evidence presented in Chapter 2 indicated that some parameters of visual search in hemianopia differ to those of normally sighted individuals (referred to as hemianopic scanpaths). These scanpaths are described as having small amplitude staircase saccades toward the blind hemi-field, and frequent repetitions of fixations during visual search and inspection (Pambakian et al., 2000; Zihl, 1995). However, it is unclear whether these scanning patterns are primarily generated by the visual field defect, by other higher-order brain damage, or whether they reflect compensatory eye-movement strategies (Machner et al., 2009).

Furthermore, there are a number of factors that are known to affect eye movements and visual search. The pattern and duration of fixations are affected by low level visual factors including contrast and luminance (Liversedge & Findlay, 2000), and high level semantic properties, such as task complexity, instructions provided to the observer and scene familiarity (Rayner, 1998). The specific parameters that represent 'hemianopic scanpaths' have been shown to vary based on stimulus type (naturalistic scenes or simple patterns) and task demands. Thus, it is still a matter of debate as to whether these scanpaths provide functional benefit for task performance, which aspects might contribute to compensation, and whether all people with hemianopia use the scanning patterns to the same extent.

To address the ambiguity in the literature regarding the role of eye movements, a specific objective of the present research was to investigate the extent to which individuals with hemianopia compensated for their visual field loss using altered scanpaths on the change blindness task. A recent study investigating functional compensation in hemianopia highlighted the need to use large field stimulus displays with varying processing demands to fully investigate compensatory gaze in hemianopia (Hardiess, Papageourgio, Schiefer & Mallot, 2010). The present study employed a search task using naturalistic (complex) driving scenes, and forced responses across the visual field using a large field stimulus display (subtending 140^{0} of horizontal visual angle). Furthermore, eye movements were permitted to allow the measurement of responses at peripheral locations in both the blind and seeing regions of the visual field.

Examination of search patterns in the present study revealed that the hemianopic group differed from those of the control group, supporting the notion of some type of 'hemianopic scanpath'. Consistent with previous research, the cases made more fixations with shorter amplitude saccades on average, compared with the controls (Chedru et al., 1973; Pambakian & Kennard, 1997; Pambakian et al., 2000; Zihl, 1995). Typically, this search pattern has been interpreted as an unsystematic or ineffective search strategy (Kennard, 2002; Pambakian et al., 2000). However, it is clear from the accuracy and response time data reported here, that a subset of cases performed as well as the cases in the change blindness task, with few errors and relatively fast response times, suggesting an efficient and effective search strategy. Thus, additional analyses were conducted to investigate further, the specific parameters of search that were related to task performance and to determine which aspects of 'hemianopic scanpaths' were of functional benefit, or compensatory.

Indeed, the analyses of scanpath similarity revealed that the search strategies of the hemianopic cases who performed well in the present study were distinctive, and differed significantly to the poor performers. The search strategy for the good performers was characterised by fewer fixations and longer saccade amplitudes, similar to controls, however they differed markedly from the poor performers in spatial locations (scanpath similarity). Thus, an effective search strategy in this study represented normal fixations and saccades, with an atypical spatial path to reach the target. In contrast, the poor performers adopted an ineffective pattern comprising increased fixations, short saccades, and a similar spatial path to the controls. These findings suggest that the key aspect of compensatory visual search in the present study was spatial scanpath to the target.

To explain these findings, consideration is given to the role of working memory. Tant and colleagues proposed that hemianopic scanpaths are the result of an inability to use working memory to develop a brief and comprehensive overview of the visual space available, which infers that those who compensate for their loss are better able to use working memory to create an overview of the visual scene in order to direct further search (Tant et al., 2002). Martin and colleagues provide further evidence to support this explanation in a study of visual search during a naturalistic model-building task. The authors suggested that individuals with hemianopia may compensate in naturalistic situations by relying on visuo-spatial memory to a greater extent than those with normal vision (Martin et al., 2007). Good performance on the model-building task was characterised by increased memory-guided saccades and straight ahead fixations, which are thought to reflect increased updating of spatial information in visual working memory. Thus, individuals with hemianopia may rely on visual working memory to a greater degree than those with normal vision, given that the peripheral visual information that usually guides saccade targeting is missing. This highlights the possibility that some individuals with hemianopia use more memory-guided saccades and look-ahead fixations to complete naturalistic tasks effectively (Martin et al., 2007).

Similarly, a recent study considering visual search patterns in a cognitively demanding task postulated an important role for working memory in compensation for hemianopia (Hardiess et al., 2010). These authors found that on a simple dot-counting task, a subset of the hemianopic group performed a search task with similar performance levels to controls without using gaze movements to compensate. It has been suggested that this phenomenon may be attributed to increased working memory involvement: cases did not need to use additional eye movements as the stimulus was stored in working memory (Hardiess et al., 2010). However, in the same study, differences were found when the visual search task was more complex. The cases who performed poorly on this task developed a novel but ineffective scanning pattern, and in contrast, the cases who performed well on the task appeared to use compensatory scanning gaze movements in order to achieve normal performance levels. The authors suggest that these findings could be attributed to a working memory deficit. Compensation using eye movements involves *both* visual scanning and object recognition. Thus, the individuals who performed poorly attempted to compensate for both scanning and recognition deficits simultaneously, resulting in an inefficient and ineffective search (Hardiess et al., 2010). In contrast, the good performers did not try to do both at once as they relied more heavily on working memory (Hardiess et al., 2010).

Considering the task demands in the present study more closely, the theoretical framework underpinning the change blindness phenomenon proposes a central role for selective visual attention (Rensink et al., 1997). A number of studies have postulated a close link between working memory capacity and selective attention of environmental cues (Fukuda & Vogel, 2009). This process facilitates voluntary shifting to spatial locations or objects based on the goals of the observer rather than sensory saliency (Fukuda & Vogel, 2009). Furthermore, the ability to override the capture of attention based on sensory saliency differs significantly between individuals. This difference has been closely linked to working memory capacity, with a larger working memory capacity associated with greater ability to resist attentional capture based on saliency (Fukuda & Vogel, 2009). These authors hypothesise that when the ability to override attentional capture is poor, it is likely to result in unnecessary storage of information in working memory. This in turn suggests that a poor working memory capacity does not only affect attention, but it can actually further limit the capacity of working memory (Fukuda & Vogel, 2009).

This hypothesis of a working memory deficit could also be used to explain the results in the present study. Firstly, those who performed well on the task used very similar gaze parameters (saccade amplitude and number of fixations) to the controls. However, their spatial locations (scanpaths) differed markedly to controls, suggesting that adaptation for field loss was effectively employed by changing the spatial path of search. In contrast, the poor performers had deficits on task performance, and displayed novel search patterns characterised by wide saccades and increased fixations that differed to both the good performers and controls. Furthermore, their scanpaths did not differ to controls in spatial locations, thus they did not appear to adapt their spatial search path to overcome their field loss. This could indicate that the poor performers attempted to compensate for both scanning and recognition deficits at the same time, inducing working memory deficits and thus performance inefficiencies.

There is a compounding issue for working memory involvement in the case of hemianopia given the neural pathways that have been implicated in attention. The type and location of brain damage sustained can interfere with spatial organisation and integration of visual scanning during visual search, which leads to disorganised and time consuming searches (Chedru et al., 1973). Furthermore, the capture of attention based on goals and sensory saliency have been shown to be associated with different areas of the brain. Goal direction of attention is driven by top-down signals from the prefrontal cortex that bias processing in posterior cortical areas (Desimone & Duncan, 1995). In contrast, saliency capture is driven by bottom-up control from subcortical structures and the primary sensory cortices (Yantis & Jonides, 1990). Given the heterogeneity of brain injuries found in hemianopia, it is possible that in some individuals, the pattern of neural damage may influence working memory capacity.

Evidence for localised effects of brain damage are reported in a recent study investigating eye-movements in an acute hemianopic group (Machner et al., 2009). Findings showed that mesio-ventral areas of the temporal lobe were more likely to be affected in those who demonstrated severe impairment on the visual search task and spared in those who were mildly impaired on the task. Temporal regions are associated with the ventral processing stream, involved in the visual recognition of objects (Ungerlieder & Mishkin, 1982) and have also been implicated in the control of attention (Goodale & Milner, 2004). Thus, although the site of lesion was not specifically considered in the present research, it is possible that some of the findings could be explained by the location of the brain injury underlying the hemianopia. Further research is warranted to investigate the effects of lesion location on visual search patterns in functional tasks.

Overall, the results from the eye-tracking data collected in this study found significant differences in the search strategies of the hemianopic cases who compensated compared with those who did not, and these findings could be explained in the context of working memory capacity influencing task performance.

In Chapter 7, the relationship between change blindness task performance and clinical, demographic, vision and cognitive variables commonly used in driving research and assessment was explored. Several cognitive measures were selected for the analyses, including the UFOV, Trails B, the MVPT-VCS and the D2 test of sustained attention. The vision assessments included visual acuity, contrast sensitivity and visual fields (HFA 24-2 and Esterman). Additionally, based on the existing theoretical and functional performance literature, several demographic and clinical variables were selected: age, side of field loss and aetiology of underlying brain injury.

The review of literature presented in Chapters 1 and 2 highlighted the strong clinical distinction between visual function (physical functioning of the eye) and functional vision (visual skills and performance in activities of daily living). Thus, it was hypothesised that the cognitive measures selected for this study would be more highly correlated with performance on the change blindness task than the measures of visual function, given that the cognitive tasks were more likely to assess general cognitive functioning and higher-order perceptual problems. However, the change blindness task was intended to measure an additional construct representing compensation for field loss, and so it was also hypothesised that the cognitive variables would not fully explain performance on the change blindness task.

All of the findings in this study indicate that tests of visual function were poor predictors of performance on the change blindness task: no significant differences were found between those who performed well and those who performed poorly on any of the vision measures. The absence of effects for visual acuity and contrast sensitivity can be explained by the relative homogeneity among cases and controls; a criterion for inclusion was normal (or corrected to normal) visual acuity and there was no evidence of impairment for either groups. Thus, it is difficult to comment on the role of these two tests for the change blindness task. It is likely, however, that impaired contrast sensitivity would have affected performance given that more errors were made (in both cases and controls) when the target had low contrast relative to the background.

A finding of considerable interest was that the Esterman test, which measures binocular visual fields, did not predict performance on the change blindness task, and no differences were found between the performance categories in terms of the number of points missed. This was an important finding given that the underlying premise of this research was that static measures of visual function do not necessarily translate into functional impairment. For example, while it is clear that people with hemianopia and quadrantanopia have impairment of visual function to varying extents, they are not necessarily impaired on everyday tasks (Gassel & Williams, 1963). As discussed previously, a plausible explanation for these differences is that some individuals are able to compensate for their field loss, and the findings from the current study provide further support for this notion.

Considering the purpose of tests such as the Esterman (and the HFA 24-2), it is clear that they are not intended to provide information about functional performance during dynamic and cognitively demanding tasks such as driving. Thus, although the Esterman gives a good overview of how an individual responds to peripheral targets during steady gaze, it does not consider the role of cognition or compensatory eye-movements. For example, the Esterman has generally been found to be a poor predictor of functional performance and patient-reported assessments of vision (Jampel, Friedman, Quigley & Miller, 2002). Similarly, there is limited evidence linking Esterman scores with driving performance (Ball & Owsley, 1991), and previous research has found that performance on functional tasks such as driving are not necessarily dependent on visual field extent (Ball & Owsley, 1991).

In the present study, it was found that the individual clinical, demographic and cognitive measures were better predictors of performance on the change blindness task than the vision measures. A key finding was that age may influence task performance overall, and compensation may be more likely in younger cases than older. Support for this result can be found in earlier research on driving. In a simulated driving task, hemianopic cases did not perform as well as a group of younger healthy adults, however their performance was comparable to group of older adults (Szlyk et al., 1993). A substantial body of literature describing general cognitive changes associated with age adds weight to the contention that older adults are slower to assimilate information (Leclercq et al., 2002; Luchies et al., 2002; Salthouse & Czaja, 2000). Further, Batchelder and colleagues considered the effects of age on task performance using a change blindness paradigm with static driving-related images (Batchelder et al., 2003). The results confirmed the expectation that the older drivers were slower and less accurate on the task, and the authors suggest that this could be attributed to decreased visual processing speed and reduced visual attention in older drivers (Batchelder et al., 2003).

A noteworthy finding in the present study was that although age and cognitive variables predicted change blindness task performance better than tests of visual function, the predictive power of the individual variables was fairly low, and there remained a portion of the variance that was not well explained by any of the variables measured. However, the multivariate modelling identified that the best *combination* of predictor variables for change blindness performance was age, Trails B, the MVPT-VCS and the UFOV.

These findings were not unexpected given that all of the hemianopic cases had an underlying brain injury. The wider literature suggests that the most common deficits in cognitive functions produced by brain injury are in the domains of working memory, attention and information-processing speed (VanZomeren & Brouwer, 1994). Furthermore, the literature also suggests that reaction times are slowed to different degrees on a range of tasks (Bashore & Ridderinkhof, 2002). As discussed earlier in the thesis, selective attention is described as the capacity to focus on a small number of important stimuli while suppressing competing distractions (VanZomeren & Brouwer, 1994), and the related construct of vigilance (or sustained attention) refers to the capacity to maintain an engaging activity over a period of time (Brickenkamp & Zillmer, 1998).

Some studies have argued that working memory capacity reflects the efficiency of executive functions, particularly the ability to maintain a few task-relevant representations in the presence of competing distractors (selective attention), and there appear to be large individual differences in the ability to use focused and sustained attention, particularly when other events are competing for attention (Engle, Tuholski, Laughlin & Conway, 1999). Where attentional problems are found, the frontal areas of the brain are frequently implicated (Kane & Engle, 2002). A fundamental assumption in the change blindness paradigm used in the present study is that successful performance requires both selective attention, and to some degree, focused attention.

The pattern of cognitive changes associated with successful performance in the present study is consistent with the literature on functional impairment following brain injury. Poor change blindness performance was associated with slower Trails B performance, suggesting executive dysfunction; poor D2 performance, indicating sustained attention impairment; increased errors on the MVPT-VCS, suggestive of visual closure difficulties; and poorer UFOV performance, indicating selective and divided attention problems.

Research suggests that working memory capacity is closely linked to the ability to the use attentional processes to control information from the environment (Fukuda & Vogel, 2009). Thus, the findings in the present study support the theory of a reduced working memory capacity playing a role in change blindness task performance: Trails B has been found to primarily reflect working memory ability (a component of executive function) (Sanchez-Cubillo et al., 2009), the D2 assesses sustained attention in the presence of distractors, the MVPT-VCS identifies difficulty with visual discrimination, and the UFOV is a measure of selective/divided attention. Furthermore, the most commonly observed deficits in cognitive function associated with brain injuries (e.g. in the domains of working memory, attention and information-processing speed) are likely to be compounded by advancing age: older adults have the problem of generalised cognitive slowing in addition to the effects of their brain injury. These findings support the theory that the good performers (compensators) had better visuospatial abilities and a larger working memory capacity than the poor performers.

Overall, results from the correlation and regression analyses provided a number of insights of relevance to functional assessment in hemianopia. It was clear that some people with hemianopic visual field loss in this study developed compensatory skills resulting in functional access to visual information appearing in the impaired field. Age was found to be a strong predictor of performance on the change blindness task, which suggests that older individuals may have more difficulty in developing compensatory skills than younger individuals. Interestingly, this was not related to time since onset of the brain injury. In addition, cognitive measures of visual working memory and visual attentional capacities were found to be more predictive of performance on the change blindness task than the assessments of visual function. Further, these cognitive measures shared common variance, indicating that people with hemianopia were likely to score poorly on multiple measures of cognitive function. These results have good face validity, in that selective attention, visual scanning and an understanding of spatial relationships, as assessed using Trails B and the MVPT-VCS, are cognitive functions integral to performance on the change blindness task.

8.3 Implications for driving performance

The fundamental aim of this research was to explore a functional paradigm for investigating compensation in hemianopia. An important motivation for this research was to understand the role of compensation in everyday tasks such as driving. This was particularly relevant because current tests of visual function are not good predictors of driving performance in this group (Owsley & McGwin, 1999). The research presented in this thesis did not attempt to directly link the change blindness task with driving performance, however the intention was to investigate the potential theoretical application of the paradigm for driving assessment. Thus, some extrapolations based on the current findings are made here.

There are a number of skills required to effectively engage in the driving task; the oculomotor ability to scan a rapidly changing environment, the sensory ability to perceive this information, attentional ability in order to process multiple items of information simultaneously, the cognitive ability to judge this information and to make appropriate decisions, and the motor ability to execute these decisions in a timely fashion (Wilkinson, 1999). Furthermore, research suggests that safe driving is largely dependent on the ability to integrate and respond to complex visual-perception information rather than being dependent on measures of visual function (Simms, 1985).

Although visual field loss is intuitively the primary limiting factor in hemianopia, a complicating factor for driving is the neurological origin of the condition and associated cognitive impairments. Studies have found significant group differences in people with brain injuries (including stroke) on tests of perception, cognition, and attention between those who passed and those who failed a driving test (Engum, Lambert & Scott, 1990). Research by Sivak and colleagues compared the performance of people with stroke, head injury, spinal injury and controls on perceptual and cognitive tests, and also provides evidence for significant associations between *cognitive test performance* and driving ability, measured by an on-road driving evaluation (Sivak et al., 1981). Thus, it is likely that the most appropriate assessments for investigating driving performance in hemianopia would be ones that measure *functional vision,* including visual search, attention, memory and perception.

The role of compensation for field loss is also of critical importance, and needs to be considered when assessing driving performance. For example, it has been suggested that a driver with a restricted visual field but excellent visual scanning ability may be a safer driver than an individual with an intact visual field but no neck rotation ability; and individuals with some degree of peripheral visual field loss who have an awareness of the parameters of their visual field may learn (or engage in) compensatory scanning techniques sufficient to drive safely (American Academy of Ophthalmology, 2009). Other authors have argued that if a quick screening test of visual perception or compensation could be shown to accurately identify those who are not ready to resume driving, healthcare professionals might be more willing to initiate screening in their daily practice (Korner-Bitensky et al., 2000; Modi et al., 2005).

However, there remains the problem of how to objectively screen for compensation for visual field impairment (American Academy of Ophthalmology, 2009). The UFOV test is, to date, the best predictor of driving performance for people with normal visual acuity but cognitive impairment (Duchek, Hunt, Ball, Buckles & Morris, 1998). The UFOV has also been shown to be more useful than age for identifying drivers at risk for crashes, with a sensitivity of 89% and specificity of 81% (Ball et al., 1993). Furthermore, a reduction in the UFOV has been associated with a four-fold increase in future crash involvement (in older drivers), in contrast to moderate reductions in visual acuity, contrast sensitivity, and visual field which are not associated with future crash involvement (Owsley et al., 1998).

However, the UFOV relies on simultaneously locating a central and peripheral target, which is unachievable in those with hemianopia (Wilkinson, 1999). There is also a restricted capacity to move the eyes during the task as a result of the simultaneous stimulus presentation, thus affecting the potential for the hemianopic cases to compensate. The difficulties those with hemianopic field loss encounter with the UFOV are evident in the current study. Although the good performers performed very well on a wide range of neuropsychological tasks, and had better UFOV scores than the poor performers, the majority still failed based on the 40% reduction cut-off required for driving. Although the UFOV was found to be a weak predictor in the multivariate modelling, this is likely to reflect the extent of field loss given there was high intercorrelation with the Esterman and the HFA 24-2. Thus, although the UFOV is very useful in the appropriate clinical context, for hemianopia it is less useful.

A recent report by the International Council of Ophthalmology noted that tests of functional vision should determine sustainable performance in a real-life environment where multiple uncontrolled parameters may vary simultaneously and in unpredictable combinations (International Council of Ophthalmology, 2007). More specifically, in hemianopia, compensation represents a complex interaction between a number of factors, and therefore an appropriate screening tool in this group needs to include cognitive and motor abilities as well as visual sensory ability (American Academy of Ophthalmology, 2009).

Consideration has also been given to the way in which screening tests are applied to determine fitness to drive. A prime authority on vision standards for safe driving in the United States proposes that performance on screening tests in hemianopia should be considered in three basic ranges rather than a binary pass/fail approach:

excellent, intermediate and poor (American Academy of Ophthalmology, 2009). Excellent performance represents driving ability assumed to be normal unless the individual's driving record suggests otherwise, intermediate performance highlights the need for further evaluation and possibly conditional licenses, and poor performance suggests a combination of abilities too limited for licensure, unless exceptional circumstances warrant further consideration.

The capacity for compensation following hemianopic visual field loss is fundamentally important for safe driving. Despite its importance, the evidence reviewed here suggests that current tests fail to adequately measure compensation in hemianopia. The present study proposed a novel approach for investigating compensation, and provided some baseline information regarding the theoretical potential for using the change blindness paradigm to develop a clinical screening tool. The change blindness task shows considerable promise for studying functional vision (incorporating both visual and cognitive factors) in hemianopia. Further research is warranted to investigate its clinical utility for screening drivers to determine their suitability for an on-road driving test.

8.4 Limitations

The sample employed this study was relatively small (31 cases and 31 matched controls) and therefore the results may be of restricted range. Furthermore, the sample represents a very heterogeneous group in terms of clinical history and visual field loss. However, the diversity of the sample is not dissimilar to other research on hemianopia and driving, cognitive assessment and eye movements. Sampling bias can be an issue when considering hemianopia, particularly studies investigating driving performance where there is often a tendency toward higher functioning individuals. Thus, a strength of the current study is the wide spectrum of functional capacity the sample represented, and significant effects were found even with wide variation in clinical characteristics.

An obvious extension of the research presented here is to validate the outcomes on the change blindness task with performance in real world driving using an on-road driving assessment, naturalistic driving methods and/or prospective crash records. In Australia, this is challenging legally and ethically, given that individuals with hemianopia are precluded from holding an unconditional driving licence. However, this could be alleviated by adapting the task for the international context as some jurisdictions around the world do not have the same restrictions. Alternatively, although real-world driving performance remains the gold standard, it would be useful to examine the validity of the task against performance in a high-fidelity driving simulator.

A further limitation of this study was that an indirect response time measure was employed (verbal response to experimenter) to reduce bias introduced by functional limitations in the case group. To make this as controlled as possible, the same experimenter conducted all of the trials. This experimenter was not blinded to participant condition, but this task was completed prior to any further assessments, to ensure the experimenter was not aware of the extent of impairment. Ideally, a more direct reaction time measure would have been adopted, and alternative methods for measuring reaction time without relying on motor responses would be useful in this group.

8.5 Future research

There is significant scope for further research in this area. The sample needs to be extended to investigate the characteristics identified in this PhD in more detail, and it is important that the findings are related to on-road driving performance and crash records. This would provide some evidence of how compensatory scanning ability translates to real-world driving performance and crash risk.

Furthermore, it would be useful in future studies to collect MRI or CT scans of the brain injury in order to try and map compensatory behaviours to specific brain regions and to determine whether task performance and scanning strategies are influenced by hemisphere or location of brain injury.

The importance of goal-driven versus sensory saliency also emerged as an important feature of task performance, and this could be investigated in more detail by balancing the specific visual features of task-relevant and non-task relevant stimuli, for example by contrast, location, size and scene complexity. More detailed testing of working memory capacity and functioning would also be useful to explore the role of working memory in task performance.

Finally, it would also be useful to replicate the study allowing the use of head-movements to determine whether the combination of eye and head movements play a role in task performance and compensatory scanning.

8.6 Conclusions

Hemianopic visual field loss precludes individuals from holding an unconditional driving licence in many jurisdictions around the world. However, the literature suggests that not all individuals with hemianopic field loss are functionally impaired as a result of their visual field defect. There is limited evidence regarding the ability to drive safely with hemianopia, however some studies have suggested that hemianopic field loss may not impair driving ability enough to warrant licence refusal.

Research suggests that individuals with hemianopic field loss appear to compensate for their deficit to varying degrees, and it has been proposed that the mechanism underpinning this compensation is through altered visual search patterns. However, the location of visual fixation does not necessarily imply attentional processing, and it remains unclear as to whether search patterns evident in hemianopia actually have functional benefit for the individual. Therefore, it was proposed that in order to adequately demonstrate compensation, it would be critical to identify whether individuals with hemianopia can accurately respond to targets across the blind and seeing regions of visual space, and whether their visual search patterns correspond to successful attentional processing.

This thesis proposed a novel approach for investigating compensation in hemianopia, using a change blindness paradigm to investigate whether individuals with hemianopia could respond to targets across the blind and seeing areas of visual space. Further objectives of the research were to investigate the extent to which individuals with hemianopic field loss used altered visual search patterns to mediate compensation, and to investigate the relationship between compensation and cognitive/vision tests commonly used in driving research and assessment.

This research provided several important insights into compensation in hemianopia. Firstly, the change blindness task appeared to be a useful tool for measuring compensation in hemianopia. Although the cases as a group were found to perform more poorly than controls overall, importantly, a subset of the hemianopic group were able to accurately respond to changing targets in both their blind and seeing regions. The finding that some individuals with hemianopia were able to respond accurately to targets *in areas with no visual function* suggests they were able to compensate for their visual field defect on this task.

Secondly, this study provided important insights into the specific characteristics of the visual search patterns associated with successful performance on a functional task: those who compensated for their visual field loss made fewer fixations and wider saccades (comparable to controls), however the spatial scanpaths employed to reach the visual targets were markedly different. In contrast, the cases who performed poorly on the task made more fixations and shorter saccades relative to controls, but searched the scenes using similar spatial paths, suggesting that spatial scanpath is a key mechanism underpinning compensation on this task.

Finally, the cognitive and visual correlates of change blindness task performance (compensation) were explored. Of interest was whether measures commonly used in driving research and assessment and other individual characteristics were predictive of successful compensation. The measures that best predicted performance were age and cognitive assessments. Interestingly, measures of visual function, including extent of field loss, did not predict performance well. These results suggest that individuals with hemianopia who were able to compensate for their field loss were more likely to be younger and less cognitively impaired, particularly on measures of selective/divided attention, visual discrimination and sustained attention. Working memory capacity is closely linked to the ability to the use attentional processes to control the information from the environment (Fukuda & Vogel, 2009), and thus the pattern of performance observed in the present study suggests that compensation may be influenced by working memory capacity.

This research represents the first attempt to link attentional processing with eye movements and compensation for hemianopic field loss in naturalistic driving scenes. Outcomes of this research provide new evidence describing the characteristics of scanpaths associated with successful compensatory performance in hemianopia. The findings highlight the usefulness of the change blindness task for discriminating those individuals who were able to successfully compensate for their visual field loss. Further research is recommended to explore the utility of the driving-related change blindness task as a suitable screening assessment for visual fitness-to-drive with hemianopic field loss.

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Appendix 1 Explanatory statement

Vision Impairment and Fitness to Drive
PhD Study: Hemianopia and Driving
Participant Information Sheet

The Monash University Accident Research Centre is currently conducting a new research project studying driving performance in individuals with conditions affecting their vision. By identifying any differences between those with vision impairments and those without, we will be able to develop safety strategies to assist drivers on the roads, especially drivers with vision conditions.

As part of this study, a PhD project is being conducted by Carlyn Muir. This is being supervised by Dr Judith Charlton and Professor Brian Fildes from Monash University, and Professor Joanne Wood from Queensland University of Technology. This study is looking at performance on a range of vision, attention and driving tasks in people with hemianopia, quadrantanopia and no vision impairment.

What is involved?

This study is being undertaken at the Accident Research Centre, which is based on the Clayton Campus of Monash University.

The study involves a few different tasks. These are:

- A short questionnaire concerned with information such as age, driving experience and health factors related to driving. All of the responses to the questionnaire are confidential.
- A few tasks to assess vision, memory and attention. Some of these are paper and pencil, and others are computer based. These take approximately one hour to complete.
- A change detection task, which involves viewing images on a large computer screen and looking for changes.

The study will require participants to come into the Accident Research Centre. A friend or family member is welcome to attend the session should a participant wish to be accompanied. The session will include some vision, memory, and attention tasks, and a change detection task. This should take approximately two hours.

Your participation

If you agree to participate in the project, we will provide you with a parking permit for Monash University, or cab vouchers to transport you from your home to Monash University and back home again if required.

Participation in this research is voluntary, and even if you agree to participate, you may withdraw your consent within 4 weeks of your agreement to participate. Withdrawal beyond 4 weeks will not be possible as there will be no means of linking the unique identifier assigned to your personal details, which will be permanently destroyed. If you do withdraw from the study, your records will be destroyed. Withdrawing from the study or not answering some of the questions asked during the discussion will have no consequences for you.

If you decide that you do not wish to participate, this will in no way affect your ability to receive treatment at the Royal Victorian Eye and Ear Hospital.

If you would like to participate in this study, please read and sign the Consent Form.

Confidentiality

The information we will collect is for research purposes only and will be treated in the strictest confidence. However, we are concerned about the safety and welfare of all who participate in this project and we feel that it would be irresponsible of us not to inform you if we had any concerns regarding your safety. In this event we would encourage you to discuss this with your family doctor.

Only members directly involved in the research will have access to the data, which will be stored securely for a minimum period of seven years in accordance with Monash University regulations.

Findings

It will not be possible to inform you of the outcomes of the study on an individual basis. However, at the conclusion of the study, you may obtain group findings from Monash University Accident Research Centre website. The findings will be made available to the sponsors of the project in the form of a report, and conference papers and journal articles may also arise from this research project.

Contacts

If you agree to participate you will be contacted by **Carlyn Muir** (PhD Candidate) from Monash University Accident Research Centre to arrange a suitable time to take part.

If you have any queries or would like to be informed of the findings of the study, please contact **Carlyn Muir** at Monash University

Carlyn Muir

Tel: (03) 9905 1903

Fax: (03) 9905 4363

Email: carlyn.muir@muarc.monash.edu.au

Should you have any complaint concerning the manner in which this research is conducted, please do not hesitate to contact The Standing Committee on Ethics in Research on Humans at the following address:

Project: Vision Impairment and Fitness to Drive (Phase 2)

The Secretary

The Standing Committee on Ethics in Research on Humans

P.O. Box 3A, Monash University, Victoria 3800

Telephone: (03) 9905 2052 Fax: (03) 9905 1420

Appendix 2 Recruitment brochure

Would you like to take part in exciting new research studying visual field loss and driving?

MONASH University
Accident Research Centre

Contacts

For more information, please contact:

Carlyn Muir
PhD Candidate

Accident Research Centre
Monash University
Clayton Campus
VIC 3800

Tel: (03) 9905 3899
Mob: 0414 304 433

carlyn.muir@muarc.monash.edu.au

MONASH University
Accident Research Centre

HEMIANOPIA AND DRIVING STUDY

What is it all about?

The Accident Research Centre at Monash University is conducting exciting new research on visual field loss and driving.

This research is a PhD study investigating hemianopia and quadrantanopia and driving.

The aim of this research is to help develop safety strategies to assist drivers on the roads, especially drivers with vision conditions

Who can take part?

We are looking for people with **hemianopia** or **quadrantanopia** to take part in this study.

Field loss must have been present for **6 months or longer**.

We are also looking for people with **no vision conditions** to participate.

Participants must have held a **driving licence**, either now or in the past.

What do I have to do?

We will be asking participants to come to the Accident Research Centre at Monash University on to take part. Sessions can be arranged at most times during or after business hours.

Transport will be provided to and from the centre where necessary.

You will be asked to:

- Complete a **questionnaire** (on medical and driving history)
- Do some **vision, memory and attention** tasks
- Look at some images on a computer

All of the information collected is kept confidential.

Appendix 3 Correspondence

MONASH University Accident Research Centre

The Royal Victorian Eye & Ear Hospital

Centre for Eye Research Australia

Dear PARTICIPANT,

Research Study: Vision and Driving (Hemianopia and Quadrantanopia)

Thank you for agreeing to participate in my study. I would like to confirm our time of TIME on DATE. I will arrange for a cab to pick you up at TIME from your home address. I anticipate that the session will last up to 3 hours.

I have attached a map of the Clayton campus of Monash University, and where the Accident Research Centre is located. Please advise your cab driver to bring you to the front door where I will pay for your cab.

Please bring any glasses you wear for driving or reading, and a copy of your current prescription.

If you have any further queries, please do not hesitate to contact me on PHONE NUMBER.

Kind regards,

Carlyn Muir

PhD Candidate

Appendix 4 Consent form

MONASH University Accident Research Centre

The Royal Victorian Eye & Ear Hospital

Centre for Eye Research Australia

Vision Impairment and Fitness to Drive
PhD Study: Hemianopia and Driving
Consent Form

I agree to take part the Monash University research project "vision impairment and fitness to drive". The project has been explained to me and I have read the Participant Information Sheet, a copy of which I will keep for my records. I understand that agreeing to take part means that I am willing to:

- ❑ Complete questionnaires asking me about my driving history, medical history and crash and infringement history
- ❑ Complete some vision, attention and memory assessments
- ❑ Participate in a change detection task while eye movements are tracked
- ❑ Allow a designated researcher access to my medical (vision) records (if applicable)

I understand that any information I provide is confidential and that no information that could lead to the identification of any individual will be disclosed in any reports on the project or to any other party.

I also understand that my participation is voluntary, that I can choose not to participate in part or all of the project, and that I can withdraw within 4 weeks of my participation, without being penalised or disadvantaged in any way. Withdrawal beyond 4 weeks will not be possible as there will be no means of linking the unique identifier assigned to my details. If I choose to withdraw, my details will be destroyed.

I have been informed that it is not possible to have access to individual feedback about my performance on the functional performance assessment or regarding the survey, but that group results will be available from the Monash University Accident Research Centre upon request, once the study has been completed.

I have also been informed that the information collected will be stored in a secure location at the Monash University Accident Research Centre for a minimum of seven years, as required by Monash University regulations.

Participant's Name: ____

Signature: ______________________________ **Date:** ____________________

Witness signature: ______________________________ **Date:** ____________________

Appendix 5 Testing checklist

APPOINTMENT	
Send confirmation letter and map	
Ask for lens prescription	
Arrange a time for taxi pick-up / car arrival	
TESTING DAY	
Call cab for pickup	
Arrange cab vouchers x 2 or parking permit	
Turn on and test HFA	
Turn on and test UFOV	
Setup screen	
Setup Facelab and calibrate	
Synch computers	
Run practice trial	
TEST SESSION	
DEMOGRAPHICS/SCREENING	
Consent form	
Demographics questionnaire	
MMSE	
VISION TESTS	
HFA 24-2 right eye	
HFA 24-2 left eye	
HFA esterman fixed eye	
LogMAR distance acuity	
Reading cards near acuity	
Pelli-Robson contrast sensitivity	
COGNITIVE TESTS	
Balloons test	
D2 test	
MVPT	
Trails A	
Trails B	
UFOV	
CHANGE BLINDNESS TASK	
Change blindness task	
Eye-tracking data	
FOLLOW-UP	
Call the following day for questions	
Thank you letter	

Appendix 6 Questionnaire

ID	CXX – CONTROL (ID) NUMBER Pxx – CASE (ID) NUMBER
DOB	DD/MM/YYYY
Gender	MALE FEMALE
Marital Status	NEVER MARRIED MARRIED/DEFACTO DIVORCED/SEPARATED WIDOWED
Education	PRIMARY SCHOOL 4-6 YEARS HIGH SCHOOL/TRADE SCHOOL TERTIARY (COLLEGE/UNIVERSITY)
Year of first full licence	YYYY
Current licence?	YES NO – DETAILS
Km driven per week	APPROXIMATE NUMBER
Hemi or quad	HEMIANOPIA QUADRANTANOPIA
Circumstances	DETAILS OF BRAIN INJURY
Date of brain injury	DD/MM/YYYY
Co-morbidities (medical)	ADDITIONAL MEDICAL CONDITIONS
Co-morbidities (visual)	ADDITIONAL VISUAL CONDITIONS
Medications	CURRENT MEDICATION REGIME
Visual training programme	PARTICIPATED IN PRIOR VISUAL TRAINING OR RESTITUTION PROGRAM – YES/NO
Doctor details	DETAILS OF TREATING DOCTOR FOR MEDICAL FILE REVIEW
Crash history	CRASH HISTORY – PRE/POST FIELD LOSS, NUMBER, FAULT.
Circumstances of crash	CIRCUMSTANCES (CAUSING INJURY, CAR DAMAGE ETC).
Traffic infringements	NUMBER AND TYPE, DATES.
Metro or rural	PARTICIPANT RESIDES IN METROPOLITAN, RURAL OR COUNTRY TOWN AREA.
Glasses?	CURRENT PRESCRIPTION GLASSES – YES/NO
Prescription	PRESCRIPTION FOR AUTO PROGRAMMING IN HFA.

Appendix 7 Odds ratios for matched pair errors

RELATIVE ODDS OF RESPONDING CORRECTLY: MATCHED-PAIRS				
PAIR ID	**EXP (B)**	**LOWER CI**	**UPPER CI**	**SIG. $p<0.05$**
Pair 4	2.5	0.323	1.141	
Pair 8	1.312	0.01	0.024	
Pair 10	0.88	0.204	0.487	
Pair 18	1.122	1.463	3.528	
Pair 19	1	0.43	1.177	
Pair 1	0.451	0.021	0.045	
Pair 2	0.017	0.106	0.272	
Pair 5	0.679	0.842	2.347	
Pair 9	0.654	0.475	1.732	
Pair 12	1.346	0.554	1.493	
Pair 17	1	0.366	0.809	
Pair 23	0.338	1.052	4.817	
Pair 25	0.206	0.341	1.166	
Pair 27	2.055	0.136	0.296	
Pair 28	0.447	0.361	1.115	✓
Pair 29	0.43	0.397	1.399	
Pair 30	0.301	0.756	3.105	
Pair 3	0.352	0.685	1.76	
Pair 6	0.041	0.756	3.105	
Pair 7	0.176	0.184	0.678	
Pair 11	0.669	0.088	0.236	
Pair 13	0.481	0.152	0.34	
Pair 14	0.253	0.211	0.563	✓
Pair 15	0.534	0.719	2.558	
Pair 16	0.555	0.139	0.428	
Pair 20	0.252	0.485	1.579	
Pair 21	0.139	1.182	2.785	✓
Pair 22	0.273	0.227	0.462	✓
Pair 24	1	0.232	0.67	
Pair 26	0.7	0.196	0.559	
Pair 31	1	0.662	1.955	

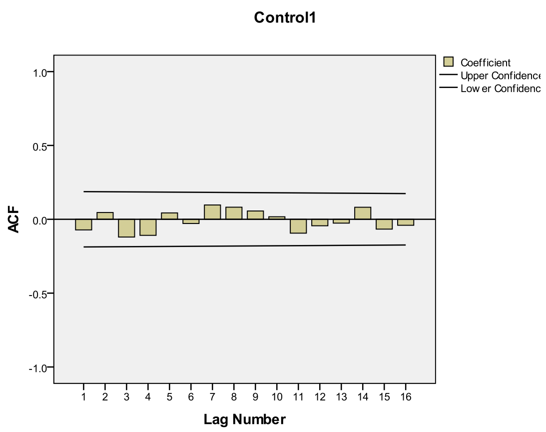
Appendix 8 Odds ratios for blind regions

RELATIVE ODDS OF RESPONDING CORRECTLY IN THE BLIND REGIONS				
PAIR ID	**EXP (B)**	**LOWER CI**	**UPPER CI**	**SIG. $p<0.05$**
Pair 1	0.354	0.61	2.045	
Pair 2	0.16	0.004	0.062	✓
Pair 3	0.335	0.083	1.346	
Pair 4	2.875	0.502	16.477	
Pair 5	0.638	0.168	2.413	
Pair 6	0.002	0.000	0.20	✓
Pair 7	0.182	0.048	.0685	
Pair 8	1.000	0.059	16.928	
Pair 9	1.000	0.192	5.210	
Pair 10	1.000	0.130	7.717	
Pair 11	0.167	0.034	0.805	✓
Pair 12	1.532	0.245	9.587	
Pair 13	0.375	0.069	2.031	
Pair 14	0.081	0.018	0.374	✓
Pair 15	0.479	0.084	2.743	
Pair 16	0.320	0.032	3.184	
Pair 17	0.653	0.104	4.085	
Pair 18	2.087	0.177	24.615	
Pair 19	1.000	0.059	16.928	
Pair 20	0.184	0.021	1.633	
Pair 21	0.089	0.019	0.411	✓
Pair 22	0.203	0.062	0.655	✓
Pair 23	0.308	0.091	1.046	
Pair 24	0.653	0.104	4.085	
Pair 25	0.190	0.039	0.929	
Pair 26	0.574	0.130	2.545	
Pair 27	1.465	0.432	4.969	
Pair 28	0.318	0.112	0.905	✓
Pair 29	0.638	0.168	2.413	
Pair 30	0.335	0.83	1.346	
Pair 31	1.000	0.192	5.210	

Appendix 9 Odds ratios for seeing regions

RELATIVE ODDS OF RESPONDING CORRECTLY IN THE SEEING REGIONS				
PAIR ID	**EXP (B)**	**LOWER CI**	**UPPER CI**	**SIG. p<0.05**
Pair 1	0.571	0.092	3.563	
Pair 2	0.017	0.005	0.062	✓
Pair 3	0.362	0.119	1.103	
Pair 4	2.383	0.859	6.610	
Pair 5	0.736	0.157	3.446	
Pair 6	0.113	0.045	0.281	✓
Pair 7	0.171	0.046	0.634	✓
Pair 8	1.369	0.453	4.134	
Pair 9	0.322	0.032	3.187	
Pair 10	0.846	0.272	2.634	
Pair 11	1.518	0.535	4.308	
Pair 12	1.000	0.061	16.379	
Pair 13	0.655	0.105	4.071	
Pair 14	0.503	0.193	1.311	
Pair 15	0.578	0.132	2.541	
Pair 16	0.736	0.157	3.446	
Pair 17	2.036	0.179	23.091	
Pair 18	1.000	0.357	2.804	
Pair 19	1.000	0.196	5.104	
Pair 20	0.310	0.060	1.602	
Pair 21	0.209	0.056	0.786	✓
Pair 22	0.362	0.119	1.103	
Pair 23	0.379	0.070	2.036	
Pair 24	1.527	0.246	9.497	
Pair 25	0.223	0.045	1.101	
Pair 26	1.000	0.136	7.350	
Pair 27	2.813	0.828	9.555	
Pair 28	0.613	0.230	1.634	
Pair 29	0.297	0.076	1.160	
Pair 30	0.260	0.052	1.310	
Pair 31	1.000	0.238	4.205	

Appendix 10 Autocorrelations for the control group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Coefficient
Upper Confidenc
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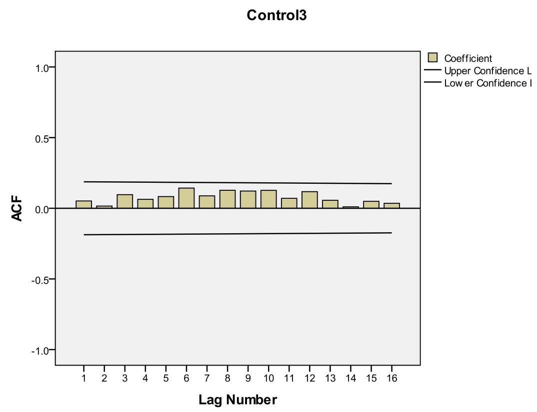
Lag Number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Coefficient
Upper Confidence L
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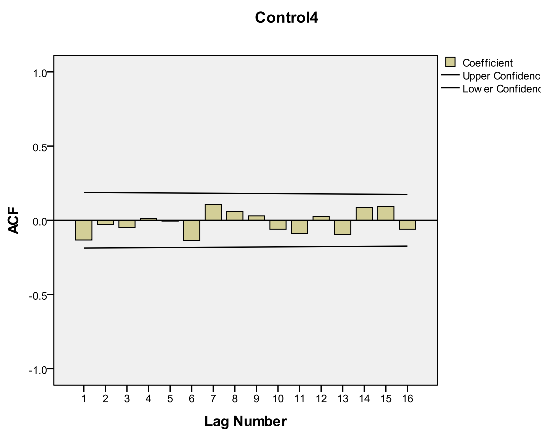
Lag Number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Upper Confidenc
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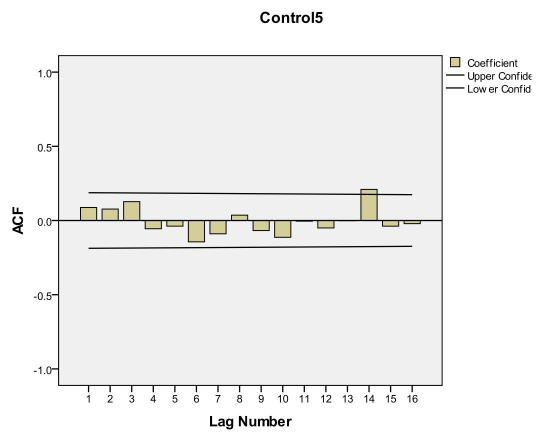
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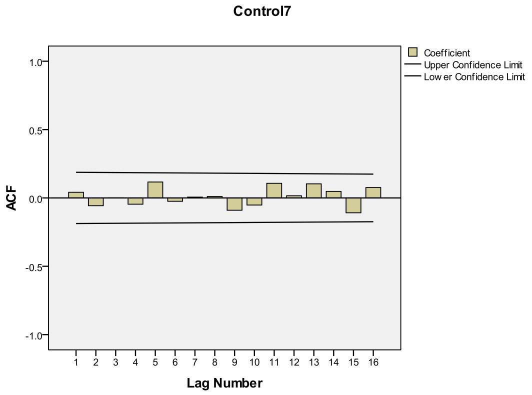
Lag Number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Coefficient
Upper Confidence Limit
Low er Confidence Limit
ACF
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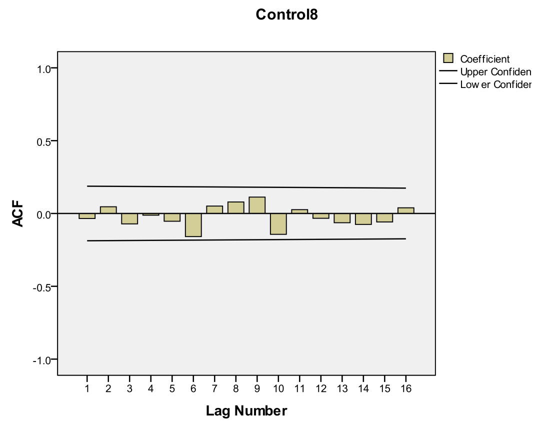
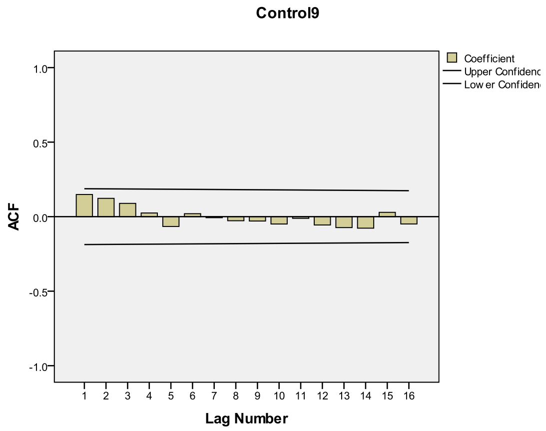
-0.5
-1.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Lag Number


Control8
Coefficient
Upper Confiden
Low er Confider
ACF
1.0
0.5
0.0
-0.5
-1.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Lag Number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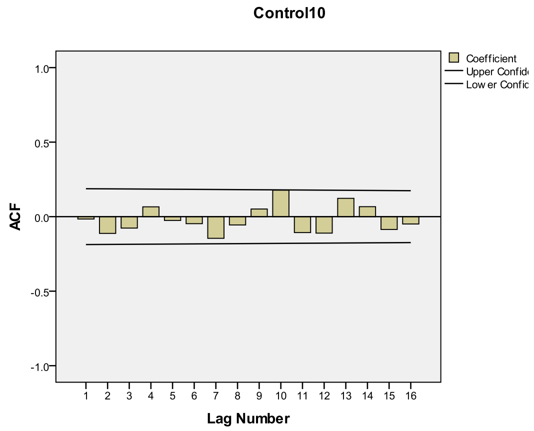
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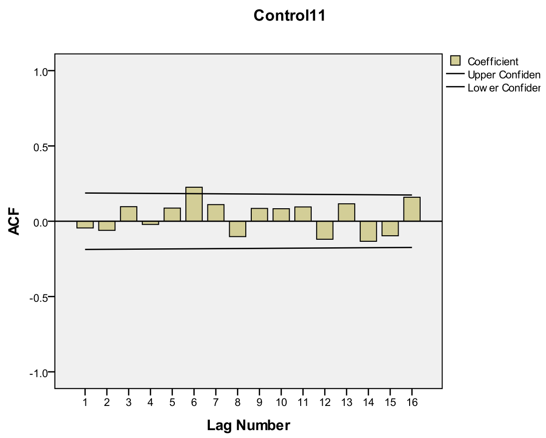
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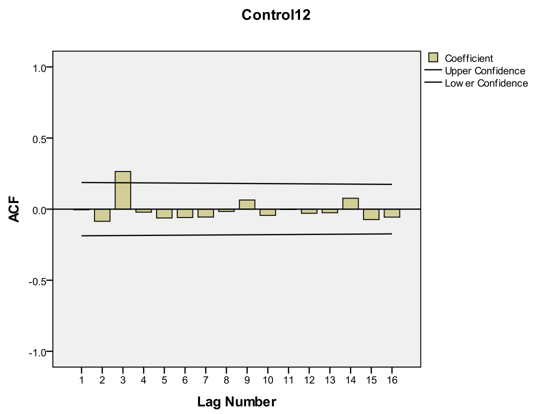
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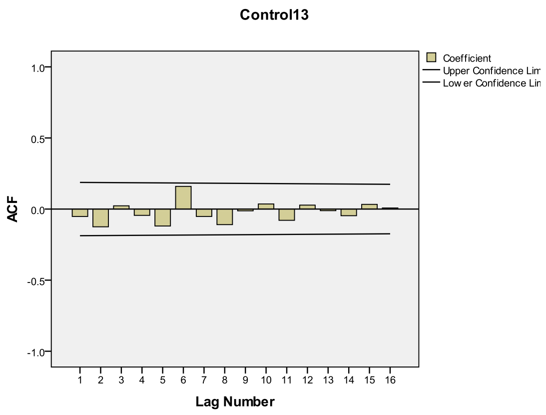
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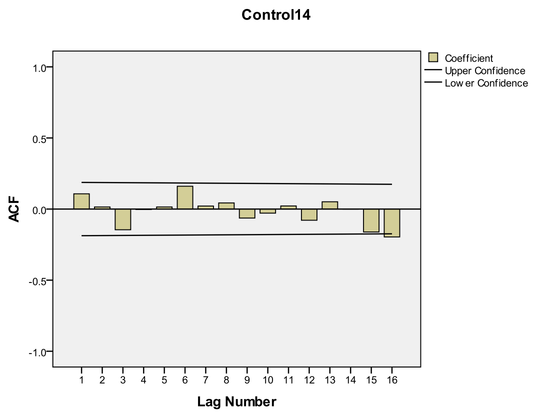
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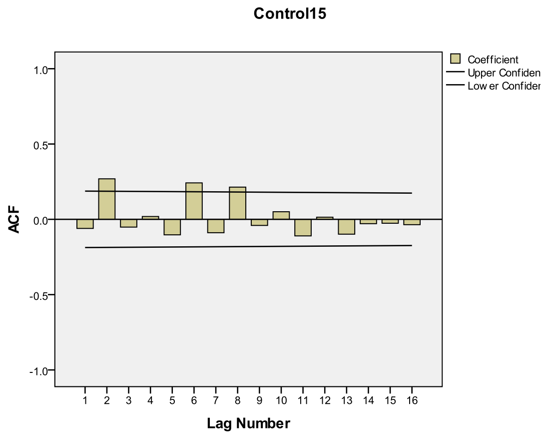
Lag Number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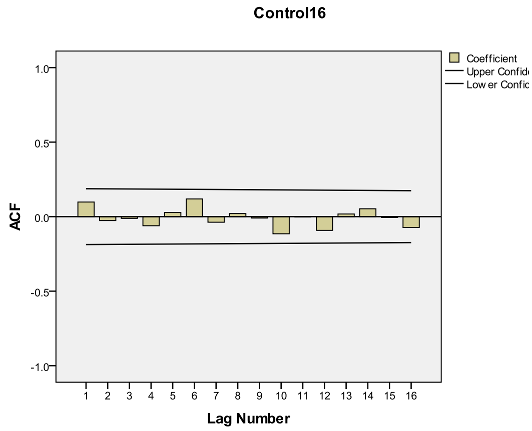
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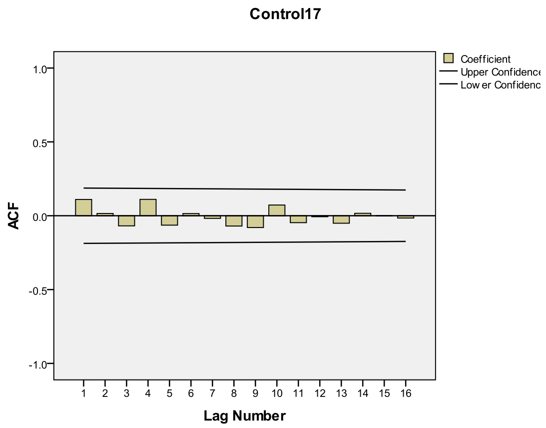
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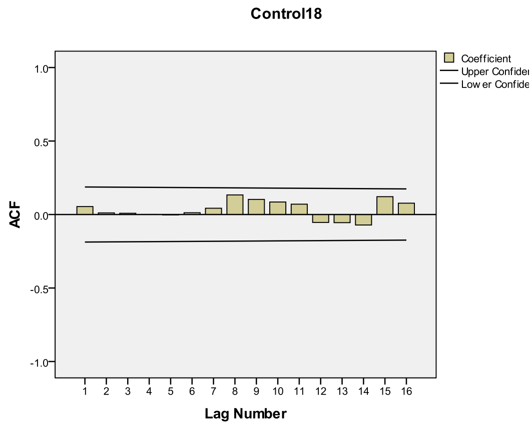
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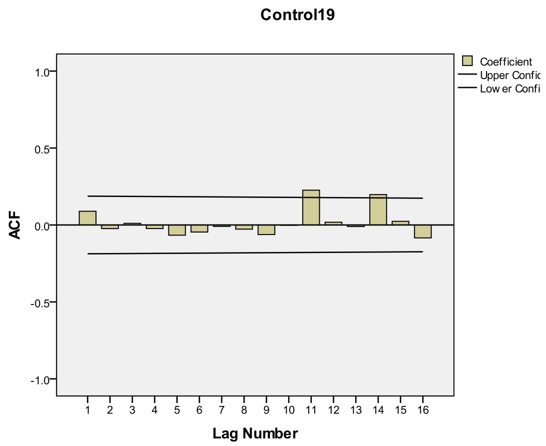
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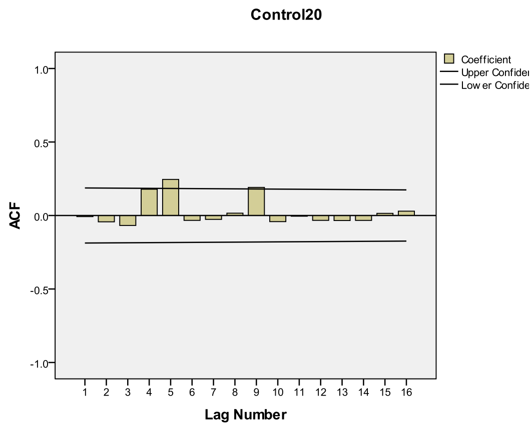
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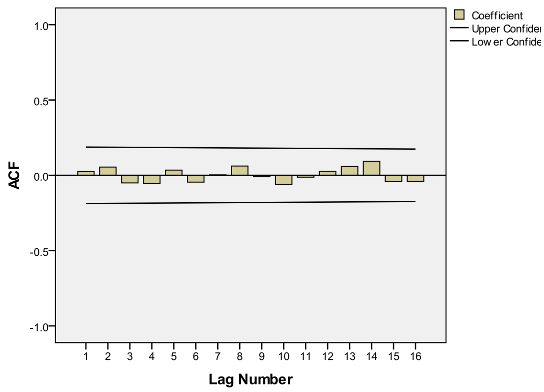

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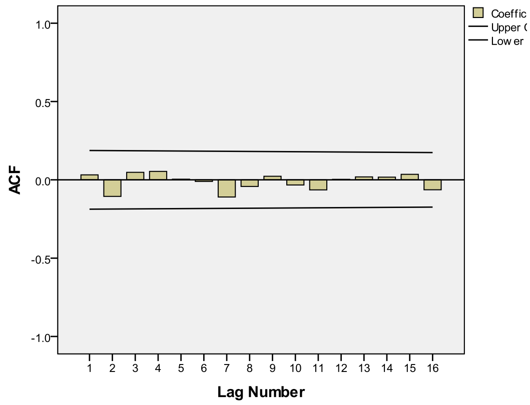

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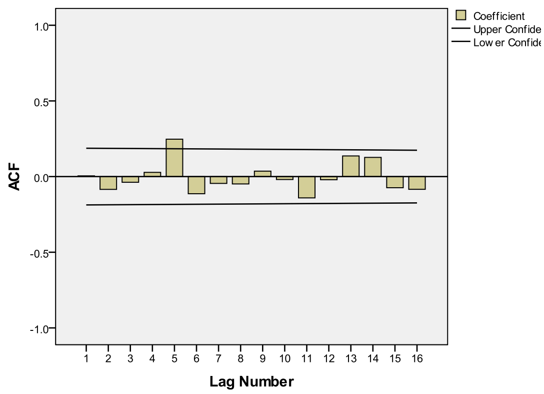

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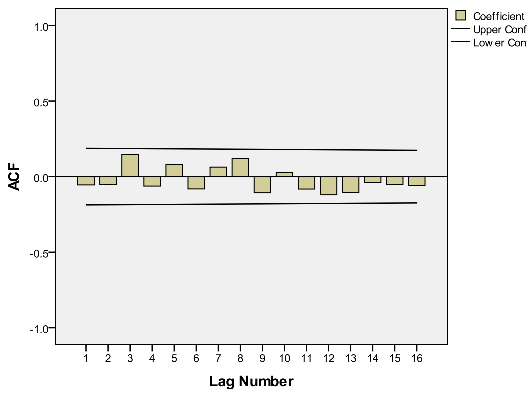

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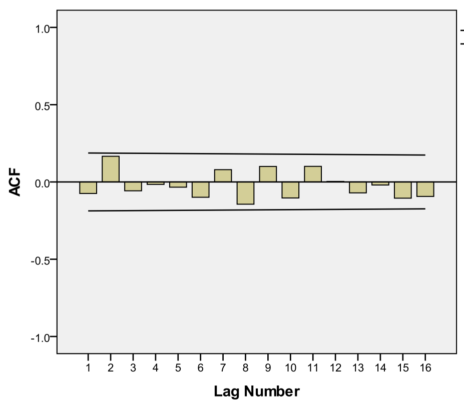

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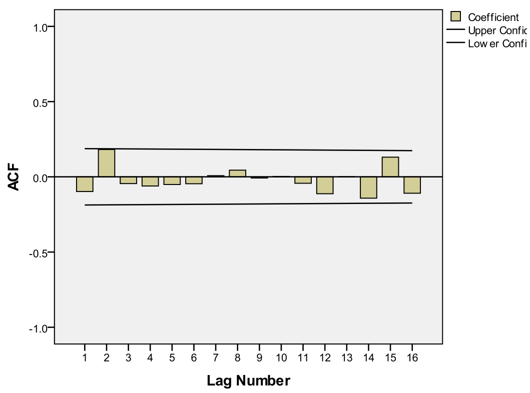

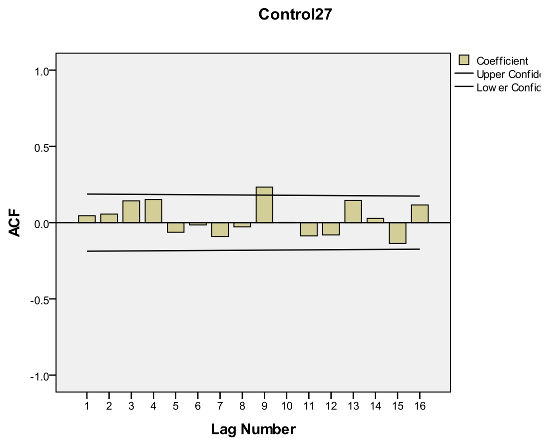
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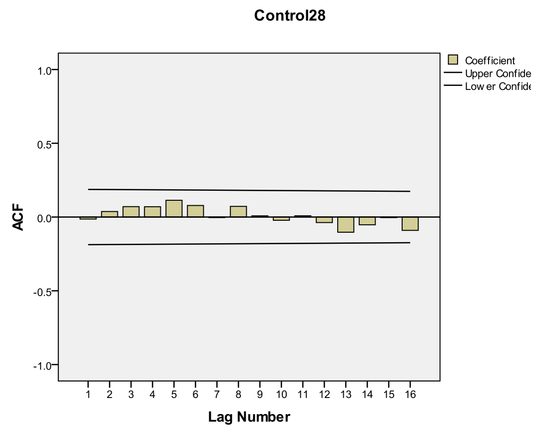
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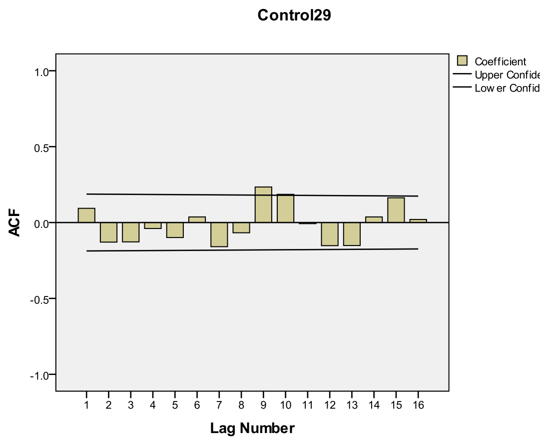
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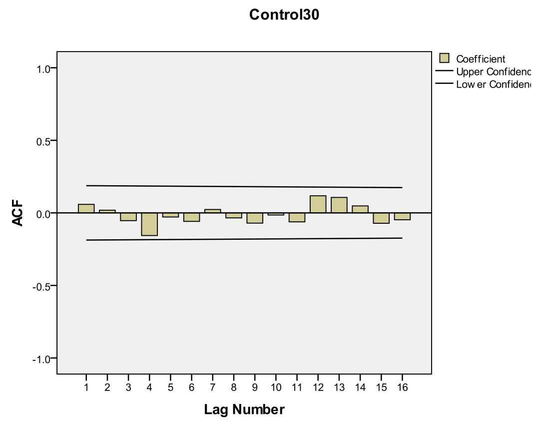
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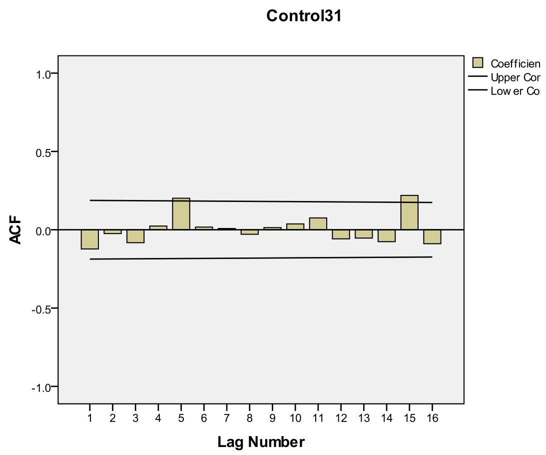
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Appendix 11 Correlation analyses

Correlation analyses were performed in order to determine the suitability of the data for regression modelling. The first correlations were intended to investigate relationships between performance on the change blindness task (correct responses and response times) and each of the individual cognitive and vision measures. Prior to performing the correlations, analyses of outliers and normality were conducted. A Shapiro-Wilk normality analysis revealed that all variables were normally distributed, and analysis of skewness and kurtosis determined that all values were less than two. Therefore, it was considered appropriate to use Pearson's correlation method for all variables. The correlations were performed, with data pooled across all participants (cases and controls, n=62). Table 28 summarises the results of the correlation matrix.

Table 28 Correlation matrix for all participants

MEASURE	TOTAL ERRORS		RESPONSE TIME	
	PEARSON CORRELATION	SIGNIFICANT AT $p<0.05$	PEARSON CORRELATION	SIGNIFICANT AT $p<0.05$
VA binocular	0.20	X	-0.35	✓
CS binocular	-0.20	X	-0.24	X
Esterman	0.37	✓	0.50	✓
UFOV	0.44	✓	-0.67	✓
D2	-0.53	✓	-0.61	✓
MVPT	0.43	✓	0.31	X
Trails B	-0.96	✓	0.66	✓

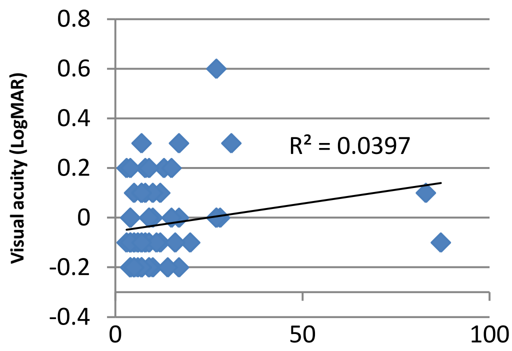
The results for the vision variables found that contrast sensitivity was not correlated with either accuracy of responses (number of errors) or response times on the change blindness task. Binocular visual acuity was not correlated with the number of correct responses on the change blindness task, however, it was significantly correlated with response time (i.e. a better visual acuity was associated with a faster response time). Esterman scores for field loss were significantly related to change blindness accuracy and response times: increased visual field loss (i.e. number of missed points on the Esterman) was associated with more errors and longer response times.

Performance on all four of the cognitive tasks was significantly correlated with response accuracy (number of errors) on the change blindness task: i.e. a better performance on the cognitive tests was associated with fewer errors on the change blindness task. The strongest correlation was observed for time to complete the Trails B. In terms of response times, poorer performance on the UFOV, D2 and Trails B were all correlated with longer response times on the change blindness task, with the strongest effects observed for the D2 and Trails B. The number of errors on the MVPT was not correlated with response time.

It was also important to determine whether correlations between the variables were differentially affected by visual field loss, so the Pearson correlations were repeated using data for the hemianopic group only (n=31). The data are summarised in Table 29 and the relationships observed are depicted in Figure 34. The plots on the left represent all participants, and the plots on the right represent the hemianopic group only. The correlations were plotted as the scores for each variable (y-axis) against the total number of errors for the task (x-axis).

Table 29 Correlation matrix for hemianopic group

PARAMETER	TOTAL ERRORS		RESPONSE TIME	
	PEARSON CORRELATION	*p*<0.05	PEARSON CORRELATION	*p*<0.05
VA binocular	0.13	X	0.27	X
CS binocular	-0.22	X	-0.28	X
Esterman	0.16	X	0.21	X
UFOV	0.27	X	0.45	✓
D2	-0.51	✓	-0.50	✓
MVPT	0.45	✓	0.25	X
Trails B	0.68	✓	0.61	✓



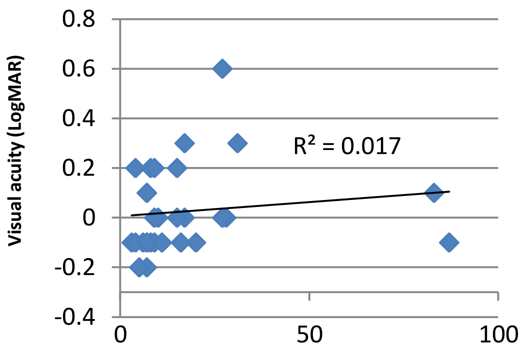


Figure 34 (A) Correlations between VA and CB errors

All participants on left and hemianopic group only on right

Figure 34 Correlations between cognitive/vision variables & CB errors

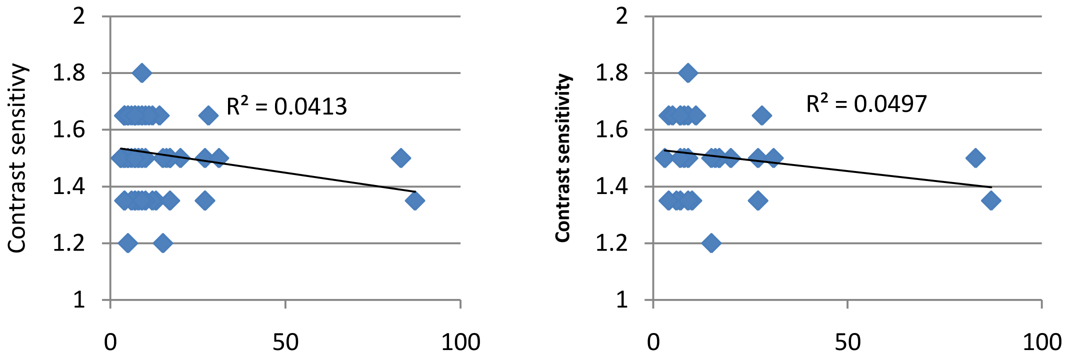


Figure 34 (B) Correlations between CS and CB errors

All participants on left and hemianopic group only on right

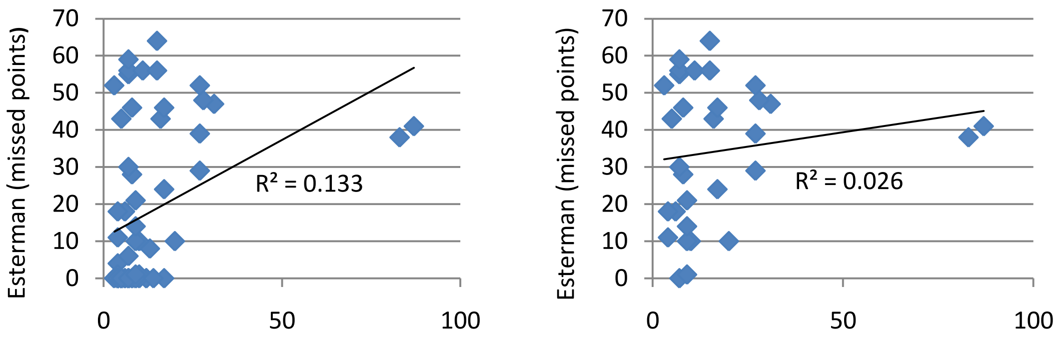


Figure 34 (C) Correlations between Esterman errors and CB errors

All participants on left and hemianopic group only on right

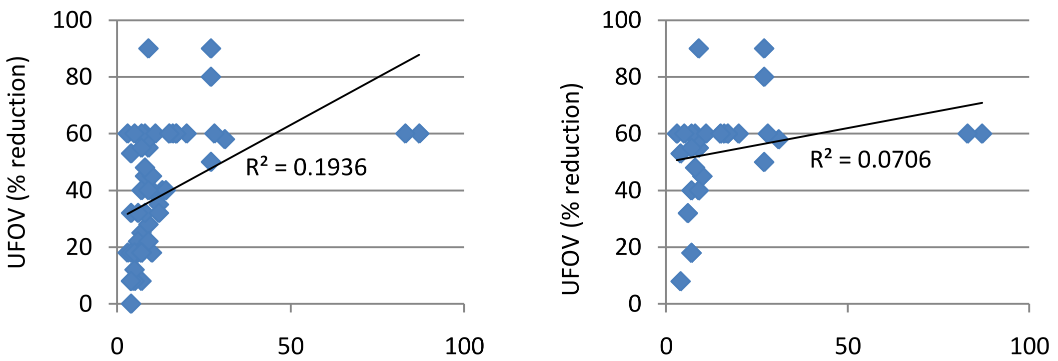


Figure 34 (D) Correlations between UFOV and CB errors

All participants on left and hemianopic group only on right

Figure 34 (cont'd) Correlations between cognitive/vision variables & CB errors

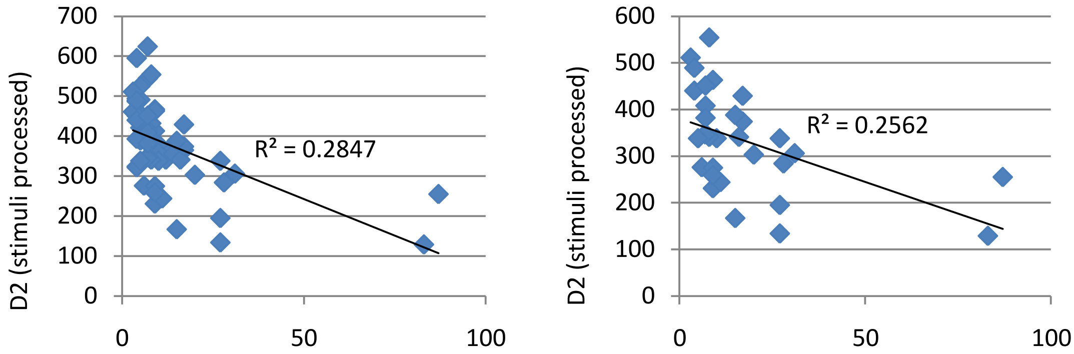


Figure 34 (E) Correlations between D2 and CB errors

All participants on left and hemianopic group only on right

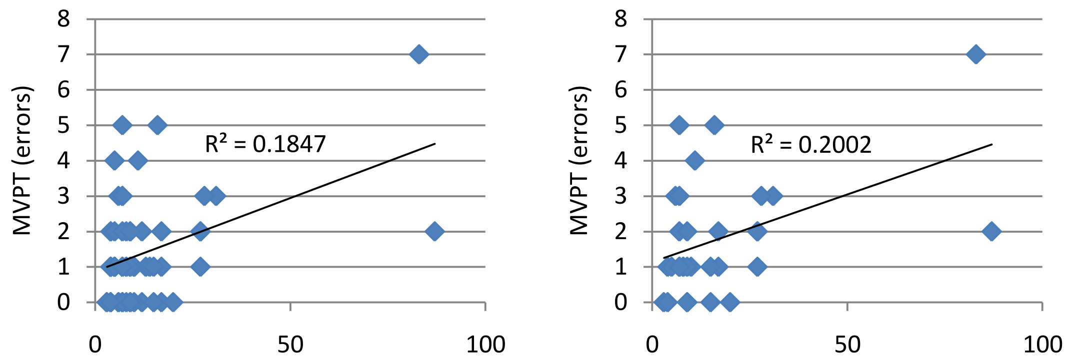


Figure 34 (F) Correlations between MVPT errors and CB errors

All participants on left and hemianopic group only on right

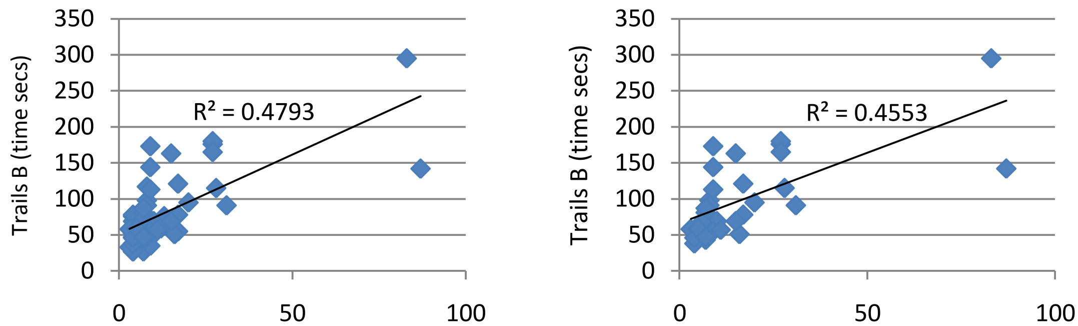


Figure 34 (G) Correlations between Trails B and CB errors

All participants on left and hemianopic group only on right

Figure 34 (cont'd) Correlations between cognitive/vision variables & CB errors

The results from this analysis indicate that some relationships between the performance measures and change blindness task were moderately different when comparing the hemianopic group and the full sample (cases and controls). These results suggest that subsequent analyses (i.e. regression modelling) should be performed for cases and controls separately.