The effects of stroke on driving: homonymous visual field loss

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Abstract

Introduction: Stroke often causes homonymous visual field loss, which can lead to exclusion from driving. Retention of a driving licence is sometimes possible by completing an on-road assessment, but this is not practical for all. It is important to find simple tests that can inform the assessment and rehabilitation of driving-related visual-motor function.

Method: We developed novel computerised assessments: visual search; simple reaction and decision reaction to appearing pedestrians; and pedestrian detection during simulated driving. We tested 12 patients with stroke (7 left, 5 right field loss) and 12 controls.

Results: The homonymous visual field defect group was split into Adequately Compensated or Inadequately Compensated groups based on visual search performance. The Inadequately Compensated group had problems with stimuli in their affected field: they tended to react more slowly than controls and in the driving task they failed to detect a number of pedestrians. In contrast the Adequately Compensated group were better at detecting pedestrians, though reaction times were slightly slower than controls.

Conclusion: We suggest that our search task can predict, to a limited extent, whether a person with stroke compensates for visual field loss, and may potentially identify suitability for specific rehabilitation to promote return to driving.

(i) Key findings:

1. Visual search can, to a limited extent, identify people with stroke who have compensated for visual field loss
2. Inadequate compensation leads to poor hazard detection in the affected field.
3. Adequate compensation leads to hazard detection performance similar to controls, with slightly slower reaction times.

(ii) What the study has added: This study demonstrates that after stroke, a fairly simple visual search task may be a useful way of determining the likelihood of successfully detecting hazards in a realistic driving scenario.

Key words: Stroke, Hemianopia, Driving, Visual Field, Visual Search, Hazard Detection, Reaction Times, Compensation

Introduction

Homonymous visual field loss is a common consequence of stroke. In the UK, as in most countries, people with homonymous visual field loss are usually censured from driving (Colenbrander & De Laey, 2006), although a small minority may regain their license through an 'exceptional circumstances' application and a successful on road assessment (Royal College of Ophthalmology, 2013). Here we examine whether there are computerised assessment methods that can help identify the degree to which a stroke patient has compensated for visual field loss.

Estimates of the prevalence of visual field loss among stroke survivors vary widely from 8% to 67%, which partly depends upon population factors (e.g. time since stroke) but also on the methods used to assess the presence of a visual field defect (Rowe et al., 2013). Of those who experience field loss after stroke, there is variation in the extent and pattern of visual field loss (see Figure 1), ranging from a total hemianopia extending outwards from the vertical midline, to a smaller area of field loss in a single quadrant or a paracentral scotoma (Zihl, 2000). Although homonymous field loss may improve (i.e. the extent and severity of impairment may reduce), this only occurs for a minority of patients, and for most people some degree of deficit will persist (Walsh & Hoyt, 1969; Zihl, 1995). For those with persisting visual field loss, disability is common, though this tends to be variable from person to person. For example in a convenience sample of 46 patients seen in an optometry clinic, 41% reported problems with personal care tasks, 13% with self feeding, 50% with meal preparation and 94% with shopping (Warren, 2009).

Everyday tasks involve a wide variety of visual-motor functions, but even within controlled and functionally isolated visual search tasks there seems to be variability in performance from person to person that is not predictable from the extent of visual field loss alone (Zihl, 1995). A proportion of those with a homonymous visual field defect (HVFD) can have search times that are equivalent to a control group, whilst others may have very prolonged search times (Gassel & Williams, 1963; Zihl, 1995). This dichotomy was first reported by Poppelreuter (1917) who showed that 7 out of 28 hemianopic patients exhibited search times indistinguishable from controls and seemed to be using a more effective gaze strategy to achieve this. He described the other patients as demonstrating 'characteristically clumsy' scan paths, which were 'fragmented' with low amplitude saccades and a high number of fixations (Poppelreuter, 1917 (Translation Zihl J, 1990)).

Because of the variation in function of those with a HVFD, some researchers have found it useful to categorise people with homonymous visual field loss based on their performance in a simple dot counting task. When comparing performance with a control group categories such as 'pathological hemianopia' or 'normal hemianopia' have been used (Zihl, 1995, 2000), and when comparing performance to other hemianopes, categories such as 'adequately compensated' (AC) or 'inadequately compensated' (IC) hemianopia have been applied (Hardiess, Papageorgiou, Schiefer, & Mallot, 2010). Whilst these dichotomies may be useful in predicting performance in simple tasks such as visual search, it is unclear whether such distinctions also map onto functional recovery that relate to real world tasks such as driving.

Whilst it may seem surprising, it is actually unknown whether driving with visual field loss after stroke increases crash risk—crashes are rare events and one would need a large sample size (and accurate records) to assess this reliably. Various attempts have been made to associate crash risk with peripheral visual field loss, but only one study has so far shown an increase in crash risk associated with reduced visual field (Johnson & Keltner, 1983), whilst others have shown no clear relationship (Ball, Owsley, Sloane, Roenker, & Bruni, 1993; Danielson, 1957; Decina & Staplin, 1993; Owsley et al., 1998). Of course the visual fields of these individuals could have been affected by a myriad of disorders and homonymous visual field loss due to stroke may not be well represented in these studies. Both on-road and driving simulator studies have shown evidence that at least some people with a HFVD can drive relatively safely, although some problems with maintaining lane position, gap judgement and stopping times have all been noted (Elgin et al., 2010; Racette & Casson, 2005; Schulte, Strasburger, Muller-Oehring, Kasten, & Sabel, 1999; Szlyk, Brigell, & Seiple, 1993; Wood et al., 2009, 2011). Two studies reported that the better performers seemed to be using frequent head movements towards the hemianopic field (Tant, Brouwer, Cornelissen, & Kooijman, 2002; Kasneci et al., 2014), perhaps compensating for the loss of visual information from that field.

The studies discussed so far have predominantly examined the effect of a HFVD on the ability to directly control the vehicle (i.e. steering behaviours). Driving performance can also be evaluated from the perspective of hazard detection (i.e. reacting in a timely fashion to a potential hazard on or near the road ahead), but in stroke populations this has been less frequently examined. One research group examining people with HVFDs has repeatedly demon-

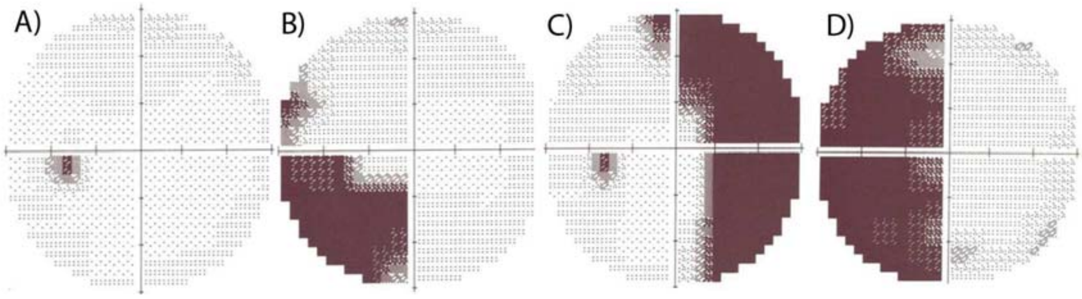

Figure 1 Left eye visual fields from example participants. Black regions show areas of the field where there is greatly reduced sensitivity to visual stimuli. Increasing intensity of grey scale indicates greater loss of sensitivity to visual stimuli. **(A)** An unimpaired field of a participant in the control group. Darker region indicated the location of the optic nerve. **(B)** The impaired lower left quadrant of a participant who was identified as adequately compensated in Experiment 1 (LHVFD2). **(C)** The impaired right field of a participant who was identified as adequately compensated in Experiment 1 (RHVFD1). **(D)** The impaired left visual field of a participant who was identified as inadequately compensated in Experiment 1 (LHVFD1).

strated slower reaction times and increased rates of failure to detect pedestrians appearing in the affected hemifield during a lengthy simulated driving course, although performance varied widely between individuals (Bowers, Mandel, Goldstein, & Peli, 2009; Alberti, Peli, & Bowers, 2014; Bowers, Ananyev, Mandel, Goldstein, & Peli, 2014). Another study has assessed patients with homonymous visual field loss and controls negotiating a simulated busy intersection at a fixed speed, using number of collisions as the primary outcome measure (Papageorgiou, Hardiess, Ackermann, et al., 2012). Again a very wide spread of ability was observed in people with hemianopia, but on average the number of collisions was increased against controls, particularly at a higher difficulty level. Whilst the extent of visual field loss and participant age was somewhat associated with performance, on their own these factors were inadequate to predict performance. Further analysis suggests that there may be a link between behaviours such as exploratory head and eye movements and performance on the task, i.e. longer saccadic amplitudes, longer scanpaths, more gaze shifts and more fixations on vehicles seemed to be associated with better task performance (Papageorgiou, Hardiess, Mallot, & Schiefer, 2012).

Current research indicates that a HFVD can impair hazard detection, but some individuals compensate to some degree. What remains unclear is the extent to which a relatively simple 'static' visual search task could provide a useful metric of compensation that also relates to hazard detection when driving. Some authors have found a relationship between visual search performance and some aspects of driving (Coeckelbergh, Brouwer, Cornelissen, Van Wolffelaar, & Kooijman, 2002; Tant et al., 2002). The present experiment set out to test the findings of Bowers et al. (2009)—namely that a group of individuals with a HVFD will exhibit impaired hazard detection when driving (relative to controls), but with wide variation between individuals and at least some individuals detecting hazards within a timescale consistent with safe driving (Bowers et al., 2009). We expected that a subgroup of people with a HVFD would have efficient scanning behaviours and perform a visual search task as quickly as visually unimpaired people. This AC group was predicted to perform similarly to controls in hazard detection tasks. In order to test these predictions we created a novel 'static' visual search task to identify AC and IC groups. We created a size discrimination task because optical size could be important for detecting approaching objects. Human sensitivity to optic expansion information (the change in optical size) is limited, so detecting the movement of small fast vehicles (e.g. motorbikes) that are far away can be difficult (Gould, Poulter, Helman, & Wann, 2012). In some cases detecting size differences could be crucial to identifying the vehicle that is approaching or receding. To capture this property we elected to use size difference as the primary feature of our search task. Pilot work with older adults showed that large size differences between the target and distracters caused target 'pop out' and so were detected quickly, whilst small size differences were difficult to detect, and active serial search seemed to be required. Both types of visual search are relevant to driving since sometimes hazards are strongly visually salient (e.g. a large hazard suddenly emerging in front of your vehicle) and sometimes hazards are subtle, peripheral, and embedded amongst similar distracter objects (e.g. one pedestrian moving out from a stationary crowd).

Once they were identified we wished to see whether those in our AC group would have sufficient visual scanning abilities to match the control's performance at a hazard perception task whilst driving in the simulator. We used a series of hazard detection tasks of increasing complexity to measure reaction times and errors detecting pedestrians appearing, either with no other task, or whilst simultaneously steering and changing lanes within a simulated driving environment. We expected that hemianopia would make hazard detection difficult, and require extremely efficient scanning behaviours to compensate sufficiently. It should be noted that although the primary deficit for our participants was visual, in line with previous research, we expected that task performance may only start to degrade as cognitive demand increased and/or when hazards appeared in the affected part of the visual field.

Method

Participants

We recruited 12 patients with homonymous visual field loss (Mean age = 63.4 years, range = 51–74 years old, all males, average time since stroke = 22 months), who had stopped driving because of their visual field loss, and 12 controls (Mean age = 61.75 years, range = 51–72 years old, 7 males and 5 females) who took part in all experiments. Patients were recruited formally through Leeds Teaching Hospitals and Leeds Community Healthcare Trust. There were 7 patients with left sided field loss and 5 with right sided field loss. None of the participants with stroke had undergone specific visual rehabilitation although all had at least accessed acute stroke rehabilitation. All participants passed Ishihara colour vision testing. This research complied with the Declaration of Helsinki. Ethical approval was obtained for testing controls via the University of Leeds Ethics panel (IPS-100070), and NHS ethics was obtained from the Bradford Research Ethics Committee following an online IRAS application, Ref: 10/H1302/3.

Apparatus

All 24 participants had their visual fields mapped using a Humphrey Field Analyser. A 30-2 standard test was used to test monocular visual fields for each eye and an Esterman test was used to test the binocular visual field. All participants had a formal optometry assessment to exclude any other ocular pathology which could have affected their driving performance. We made custom spectacles for each participant in order to optimise their vision for a distance of 1 metre—the distance from the eye to the screen on the driving simulator.

Experiment 1 (Visual Search Task) – Graphics were rendered at 75Hz via a high resolution 17 inch CRT colour monitor (Vision Master, Ilyama, Japan) with 1024 × 768 pixels spatial resolution and mean luminance of 50cd/m^2. Stimuli were generated using Experiment Builder Software (SR Research Ltd., Canada) and consisted of an array of blue squares which subtended 1.45 degrees of visual angle on the screen, and a target which differed by ±20% or ±80% in side length (Figure 2(a)). Subjects were seated 57cm from the monitor, with chin and forehead on a rest to control the visual field. The screen subtended ~37 degrees of visual angle.

Experiment 2 (Reaction Time Tasks) and Experiment 3 (Driving Task) took place in our static, fixed base driving simulator (Figure 2(d)). Graphics were rendered at 60Hz using a PC (Intel i7 950 3.07 GHz) running WorldViz Vizard 3.0.

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

Procedure

Each participant took part in three experiments: 1) the visual search task, 2) the reaction time tasks, and 3) the driving task with concurrent hazard detection task.

Table 1 Demographics for participants with a HVFD. The final row shows the demographics of the control group for comparison. **LHH** = Left homonymous hemianopia, **RHH** = Right homonymous hemianopia, **LIQ** = Left inferior quadrantanopia, **RIQ** = Right inferior quadrantanopia, **RSQ** = right superior quadrantanopia. **Av.** = mean. **Rg.** = Range. **Time** = number of months since stroke. **Miles** = Miles driven per year before stroke. **Contrast** = Binocular Pelli-Robson contrast sensitivity (log units). Degree of sparing quoted indicates the closest part of visual field defect to fovea (i.e. the absolute minimum amount of central sparing). Any areas of spared visual field in the periphery are also mentioned i.e. patchy sparing of the RSQ (Right Superior Quadrant).

Label	Visual Field Defect	Age	M/F	Impairments	Time	Miles	Contrast
LHVFD1	LHH, no sparing	73	M		3	6000	1.65
LHVFD2	LIQ, 8° sparing	63	M		10	12000	1.7
LHVFD3	LHH, no sparing	51	M	L hemiparesis	10	20000	1.75
LHVFD4	LHH to midline, patchy sparing LIQ	68	M	Mild ataxia	3	84000	1.75
LHVFD5	LHH, no sparing	66	M		42	10000	1.7
LHVFD6	LHH, 12° sparing	74	M		3	5000	1.75
LHVFD7	L paracentral scotoma, 12° sparing	57	M	Mild ataxia	72	10000	1.85
RHVFD1	RHH, 6° sparing, further sparing of RIQ	60	M		3	3000	1.7
RHVFD2	RHH, no sparing	55	M	R Hemiparesis, Aphasia	45	17500	1.8
RHVFD3	RIQ, 6° sparing	62	M		3	10000	1.7
RHVFD4	RHH, no central sparing, patchy RIQ + RSQ sparing	67	M		36	4000	1.95
RHVFD5	RSQ, no sparing	65	M		35	6000	1.95
Control	**N/A**	**Av. 61.75, Rg. 51–72**	**7M, 5F**	**N/A**	**N/A**	**Av. 12625, (2.5–30k)**	**1.6–2.1**

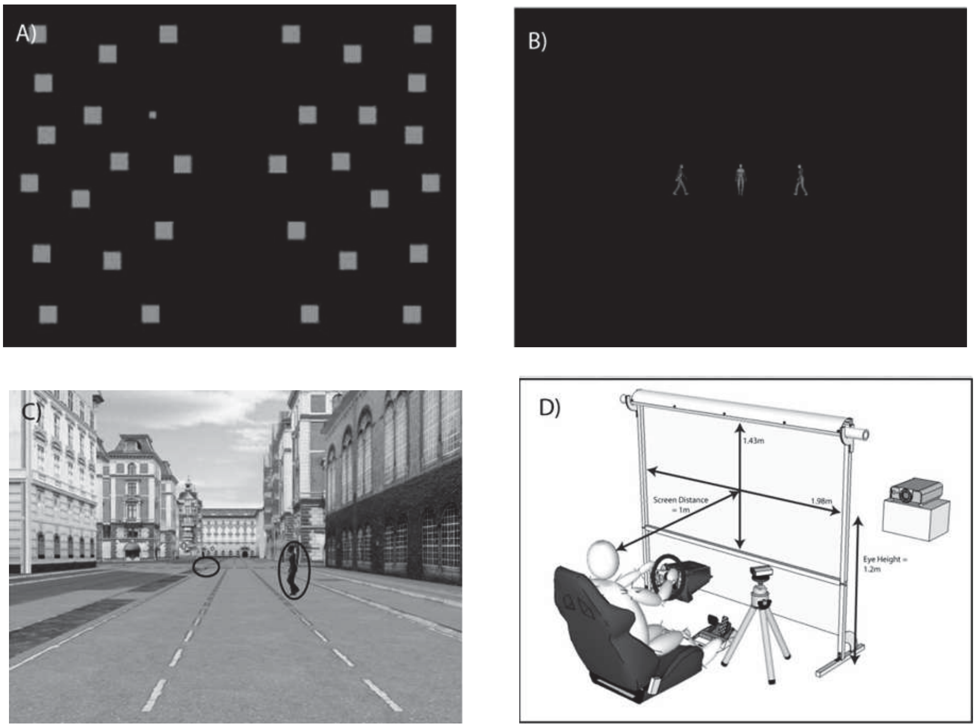

Figure 2 (a) The visual search task used in Experiment 1 showing a target square in the left hemifield with side length of 20% of the distracter squares. Older volunteers involved with pilot testing favoured a blue square on black background display as this reduced glare and eyestrain. **(b)** The reaction time task used in Experiment 2 showing the three possible target positions with the pedestrian orientated either toward or orthogonal to the observer. **(c)** The driving task used in Experiment 3 with superimposed ovals added to highlight the lane-change junction and a pedestrian walking into the road. **(d)** Driving simulator layout. Images were generated at 60Hz and were back-projected onto a screen with given dimensions in a matt-black viewing booth. Participants were seated in a height-adjustable driving seat. Total field of view 89.42°× 71.31°.

Experiment 1. For each iteration of the visual search task the participant was first presented with a central fixation cross, followed by a black screen containing 32 blue squares (Figure 2(a)). The location of the centre of each square remained constant between trials and the position of the target varied amongst some of these locations. There were 104 predefined trials, which were presented in a random order, with a comfort break midway. There were 8 catch trials that contained no target to ensure participants did not merely guess the target size. In each of the remaining 96 trials a single target square of a different size was presented in amongst the remaining 31 distracter squares. The target could be present at one of 24 locations—6 of which were located in each quadrant of the screen (there were 8 blue distracter squares whose position was never used for the target square). To vary task difficulty the target square could be 4 different sizes: much smaller (side length 20% of distracters), slightly smaller (80% side length), slightly larger (120% side length) or much larger (180% side length)—see Figure 2(a).

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

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

Experiment 3 (Driving Task). Participants were asked to drive normally down a straight 3 lane highway (free from traffic), maintaining the initial starting point in the middle lane. A grass verge separated the 3 lanes on the opposite side of the carriageway. Halfway down the highway a break appeared in the grass verge. Participants were asked to steer through the break and continue down the 3 lane carriageway on the opposite side of the road (Figure 2(c)). The vehicle moved at a constant speed of 12m/s (26.8 mph). The accelerator, brake, gears and clutch were not used.

Pedestrians (again, 1.8 metres tall) appeared on the pavement or the grass verge , 40 metres in the distance. With no steering adjustment the initial angular offset would be approximately 12.9 degrees, but this depended on the position of the driver in lane and the heading angle of the vehicle, and changed over time as the driver approached the pedestrian. The pedestrians walked and moved in space travelling at 1m/s (as opposed to Experiment 2 where they walked on the spot). Pedestrians appeared orientated as per Experiment 2, facing the observer (and walking along the pavement) or oriented orthogonally to the observer (walking into the road). As per experiment 2, the participants were required to click a wheel pad for a pedestrian walking along the pavement and to hold for a pedestrian walking out into the road. Once a wheel pad was pressed, the pedestrian disappeared from view. In each trial two pedestrians appeared before the break in the grass verge and two after, with a maximum of 16 pedestrians across the experiment. Each pedestrian had a 50/50 chance of appearing on the left or right of the road, and a 50/50 chance of walking orthogonally to the driver or towards or away from them.

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

Analysis

Our primary interest was the speed of target detection since performance on this measure will determine the earliest a driver can initiate an action (e.g. braking or swerving) to avoid collision with an obstacle. The time elapsed from presentation of the pedestrian to the participants' press of the wheel pads (reaction time in seconds) was analysed for Experiments 2 and 3. In experiment 2, there were 3 controls and 2 participants with stroke who each exhibited a single instance across the 4 tasks, of not detecting a pedestrian for over 5 seconds. Each instance of such an outlier trial occurred on the very first iteration of an experiment so were likely due to the participant not being fully prepared in some way. We were concerned that including such extreme values in a simple average would disproportionately inflate RT estimates for these individuals and therefore used medians for each individual participant's RTs. In experiment 3, a miss was recorded if no button was pressed 3.3 seconds after the pedestrian appeared (the time at which the pedestrian was passed by the driver). Missed pedestrians were not counted in reaction time calculations. We were also interested to see whether participants correctly identified the pedestrian direction when performing the decision task (Experiment 2: CRT-D, PRT-D and Experiment 3: Driving PRT-D). The orientation of a pedestrian indicated whether they are a potential hazard, for example in Experiment 3 the sidewalk pedestrians were not a risk, but the pedestrians walking into the road were a potential hazard. A measure of decision error allows a fuller interpretation of reaction time behaviour (e.g. a guessing strategy could lead to quicker RTs). Error rates are presented as the percentage of pedestrians correctly identified. Instances of complete failure to detect pedestrians in experiment 3 are reported separately.

A One-way ANOVA was conducted when comparing reaction time data and a Kruskal-Wallis test was used when comparing error rates in decision tasks (the underlying distribution was heavily skewed towards high percentage accuracy scores so a parametric test was inappropriate). If significant, planned contrasts were used to compare the Control group to the AC group, and the Control group to IC group. Adjusted degrees of freedom are presented where Levene's Test showed unequal group variances. As we did not expect to see any significant difference in error rate or reaction time between the location of targets for the control group, data was averaged across left and right fields. Effect sizes are reported as r.

Throughout the results, the Left homonymous visual field defect group (LHVFDs) and Right homonymous visual field defect group (RHVFDs) were treated as one group (HVFDs). Where possible, performance is split into stimuli falling into the affected field or the unaffected field.

Results

Experiment 1: Visual Search Task

Each participant was given a total score out of 96 (one point possible for a correct response in each trial). We also calculated the mean reaction time for the correct responses.

For the control group, the mean score was 81.19, median 80.5, standard deviation 5.96 and a range of 72–89 (equivalent to 75%–93% correct). The mean reaction time to a correct response was 3.13 seconds, median 3.05 seconds, standard deviation 0.45 seconds and range 2.54–4.23 seconds. This is appreciably longer than the 0.8 seconds it took for an older adult group (72 years) to carry out a visual search for a target at a random location amongst 18 items with some shared features (Trick & Enns, 1998). This shows that this visual task was non-trivial even for the control group—not only was performance not at ceiling but the task took longer than a simple visual search where there are marked differences in some salient property (such as colour, shape and orientation). The scores and reaction times for the HVFD participants are given in Table 2. We use the labels LHVFD and RHVFD to indicate the left or right homonymous visual field defect respectively. The participants with HVFD were categorised as adequately compensated if their total score was 72 or greater which is within the range observed in the control group (in fact each member of the AC group scored within one standard deviation of the mean score for the control group). One might worry that a more accurate score could be achieved by AC group if they simply took longer to search the array for the target, but the mean reaction times for members of the AC group were all less than 4.2 seconds (the longest mean RT exhibited by a member of the control group). We therefore categorised 5 participants as having an adequately compensated HVFD and 7 as having an inadequately compensated HVFD.

Experiment 2: Reaction Time Task

Simple Reaction Task with Central Target

A One-way ANOVA revealed no difference in reaction time between the controls (.29 secs), the AC group (.37 secs) and the IC group (.37 secs) ($F(2, 23) = 2.673, p = .092, r = .45$).

Simple Reaction Task with Peripheral Target

A One-way ANOVA revealed differences for reaction times between the groups when the target was in the affected field ($F(2, 23) = 7.961, p = .003, r = .66$) but not the unaffected field ($F(2, 23) = 3.2, p = .061, r = .46$). Planned contrasts for the affected field revealed that there were no differences between controls (.32 secs) and the AC group (.37 secs) ($t(5.820) = 1.319, p = .237, r = .48$) but the IC group (.59 secs) were significantly slower than controls ($t(6.405) = 2.831, p = .028, r = .75$). On closer inspection of this group, the difference seemed to be largely driven by two individuals in the IC group who had reaction times of .91 and .85 seconds, whereas the rest of the IC group performed similarly to the AC group (.46 seconds). This variability in performance reflects the heterogeneity of functional

Table 2 Results of the visual search task for participants with HVFD

Participant	Score (Out of 96)	Reaction Time (Seconds)	Adequately/Inadequately Compensated
LHVFD1	47	2.81	Inadequately
LHVFD2	89	3.111	Adequately
LHVFD3	48	3.32	Inadequately
LHVFD4	40	3.285	Inadequately
LHVFD5	53	3.476	Inadequately
LHVFD6	67	3.233	Inadequately
LHVFD7	76	3.977	Adequately
RHVFD1	76	4.056	Adequately
RHVFD2	62	4.468	Inadequately
RHVFD3	67	3.336	Inadequately
RHVFD4	86	3.041	Adequately
RHVFD5	84	3.138	Adequately

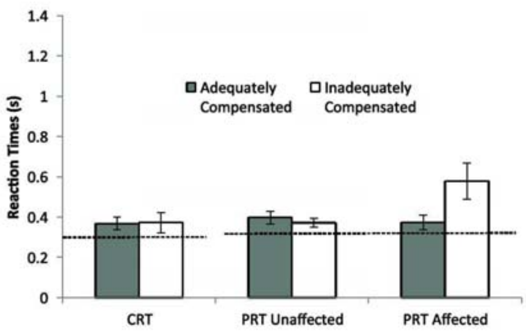

Figure 3 Mean simple reaction times (no decisions) for hazards presented either centrally (CRT) or in the periphery (PRT) during Experiment 2. Mean performance in PRT is shown for both the Unaffected and Affected fields for the Adequately Compensated (AC) or Inadequately Compensated (IC) groups as identified in Experiment 1. The dotted black line represents the mean performance of the Control group. Error bars = *SEM*.

ability even within a sub-group already categorised as inadequately compensated.

Decision Reaction Task with Central Target

When the target was presented centrally and the participants responded by indicating the orientation of the pedestrian, the groups' reaction times were significantly different ($F(2, 23) = 4.138, p = .031, r = .53$). Planned contrasts showed a significantly slower mean reaction time for the IC group in comparison to controls (.62 secs vs .48 secs; $t(8.889) = 2.314, p = .046, r = .61$). The mean reaction time for the AC group was only .07 seconds slower than that of the control group, and this difference did not quite reach significance ($t(14.985) = 2.107, p = .052, r = .48$). Error rates were not different between the three groups, as shown by the Kruskal-Wallis test (IC = 90%, AC = 92%, Ctrl = 85%; $\chi^2 = 1.56, p = .46$).

Decision Reaction Task with Peripheral Target

When the target was presented in the affected hemifield reaction times were significantly different between groups (Figure 4A; $F(2, 23) = 16.291, p < 0.001, r = .78$). Planned contrasts showed a significantly slower reaction time in the decision task for both the IC group as compared to controls (mean reaction time .80 secs vs .56 secs; $t(21) = 5.49, p < 0.001, r = .77$) and for the AC group compared to controls (.72 secs vs .56 secs; $t(21) = 3.284, p = .004, r = .58$). Error rates were not significantly different between groups (Figure 4B; IC = 91%, AC = 98%, Control = 91%; $\chi^2 = 3.389, p = .15$).

For targets presented in the unaffected side, the groups were also significantly different ($F(2, 23) = 4.281, p = .028, r = .54$). Planned contrasts for targets appearing in the unaffected hemifield revealed a slower reaction time for the IC group as compared to controls (.70 secs vs .56 secs; $t(21) = 2.89, p = .009, r = .53$). There was no significant difference between the AC group and controls (.63 secs vs

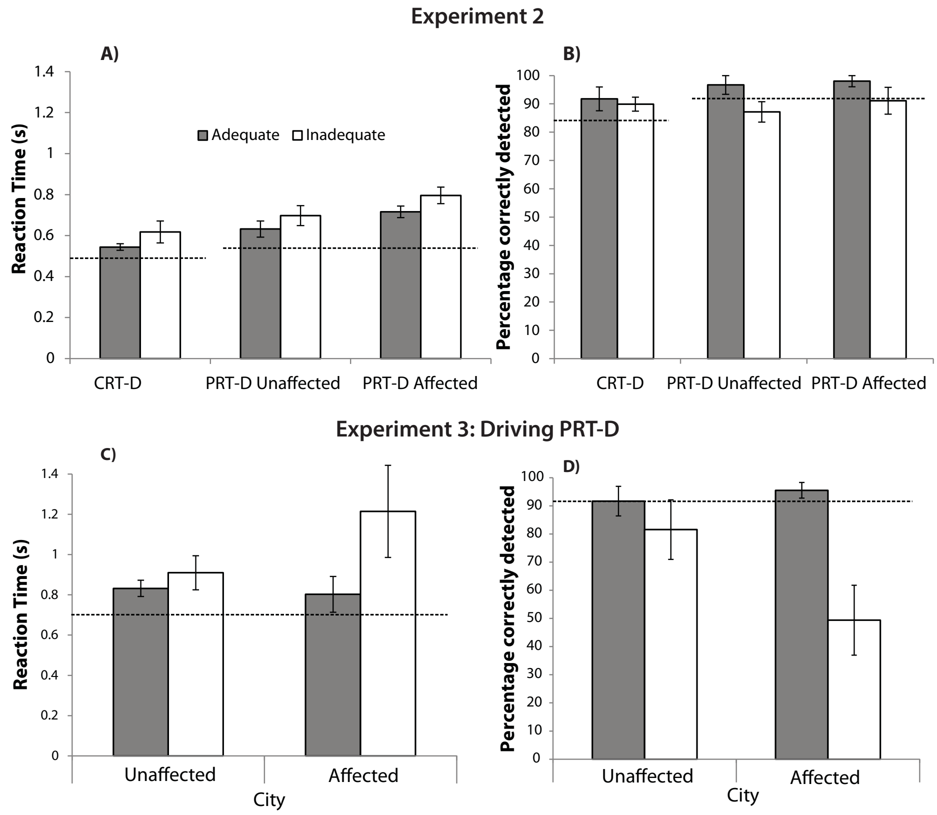

Figure 4 Mean performance in the decision reaction tasks for Adequately Compensated (AC, gray bars) and Inadequately Compensated (IC, white bars) groups in Experiments 2 and 3. **(A)** Reaction time and **(B)** Percent correct detecting hazards presented either centrally (CRT-D) or in the periphery (PRT-D) during Experiment 2. **(C)** Reaction time and **(D)** Percent correct detecting peripheral hazards when presented simultaneously with the Driving task (Driving PRT-D, Experiment 3). Mean performance in PRT is shown for both the Unaffected and Affected fields. The dotted black lines represent the mean performance of the Control group across both fields. Error bars = *SEM*.

.56 secs; $t(21) = 1.398, p = .177, r = .29$). Error rates for the unaffected side were not different between groups (IC = 87%, AC = 97%, Ctrl = 91%; $\chi^2 = 3.389, p = .15$).

Figure 4A shows the slower reaction times in the decision tasks for both HVFD groups (the dashed line represents the mean control performance), especially for peripheral targets appearing in the affected hemifield. Figure 4B highlights that the HVFD groups seem to be maintain accuracy but with the cost of performing more slowly.

Across the 4 tasks (80 targets for each of the 24 participants) there were a total of 12 false-starts (responses before the pedestrian appeared)—6 were by controls and 6 by participants with stroke.

Experiment 3: Decision Reaction Task with Peripheral Target when Driving

This final experiment added a new layer of complexity because participants had to perform a simple lane changing driving task whilst simultaneously responding to pedestrians appearing at the side of the road. When a pedestrian appeared in the affected hemifield, the ANOVA showed a significant difference between the reaction time of the groups ($F(2, 23) = 4.717, p = .02, r = .57$), however, planned contrasts showed no significant difference between the IC and Control groups (1.21 secs vs .71 secs; $t(6.452) = 2.181, p = .069, r = .65$), nor the AC and Control groups (.80 secs vs .71 secs; $t(6.080) =$

.965, p = .371, r = .36).

The Kruskal-Wallis test showed that Error rates differed significantly between groups (χ^2 = 7.561, p = .023). Pairwise comparisons showed a significant reduction in accuracy for the IC group compared to controls (49% vs 93%; p = .046) but no difference between the AC group compared to controls (95% vs 93%; n.s.). No control participant had a single failure to detect a pedestrian or made a single false-start (i.e. a button press with no pedestrian on screen). Amongst the 5 AC participants, 1 individual had a single failure to detect (to a static target in the unaffected field) and a single false-start, although their other responses were all correct. Amongst the 7 IC participants, LHVFD5 and LHVFD6 showed no false-starts or failure to detects. RHVFD3 had 1 failure and 1 false-start, LHVFD1 and LHVFD3 had 2 failures and 1 false-start, RHVFD2 had 4 failures and 9 false-starts and LHVFD4 had 5 failure to detects and no false-starts.

Whilst controls appeared to respond most quickly, an analysis of reaction time data for pedestrians appearing in the unaffected hemifield failed to reveal significant differences between groups (IC = .91 secs, AC = .83 secs, Ctrl = .71 secs; $F(2, 23)$ = 3.411, p = .052, r = .50). There were no reliable differences in error rates between groups (IC = 82%, AC = 92%, Ctrl = 93%; χ^2 = .135, p = .935).

Discussion

It has been asserted that compensatory eye or head movements may be used by some people with a HVFD to gather information from the non-sighted part of the visual field, and as a result be able to drive a vehicle relatively safely (Coeckelbergh et al., 2002; Papageorgiou, Hardiess, Mallot, & Schiefer, 2012; Wood et al., 2011). It is easy to imagine how such eye or head movements could help to orientate towards known road features i.e. the road or lane edge (Wilkie, Kountouriotis, Merat, & Wann, 2010; Kountouriotis, Floyd, Gardner, Merat, & Wilkie, 2012), or traffic emerging from a junction. Hazard perception is a different matter—if a pedestrian were to step into the road unexpectedly, someone with a HVFD may not detect the event if it happens to fall within the affected field. Such events may be rare enough that they are not observed in a real world driving examination, but the consequences of failure to spot such a hazard even once are potentially devastating. Here we examined whether those individuals that showed the capability to successfully use eye-movements to search a static visual scene to identify the 'odd one out' were also effective at detecting the sudden appearance of a pedestrian.

Using the visual search task (Experiment 1) we split our participants with HVFDs into a high performing 'Adequately Compensated' (AC) group and a lower performing 'Inadequately Compensated' (IC) group. In simple reaction time tasks (Experiment 2), reaction times to pedestrians appearing in the affected hemifield for the majority of HFVD participants were close to that of controls. When a decision about pedestrian orientation was required (Experiment 2) the reaction times to a pedestrian appearing in the affected hemifield for the participants with a HVFD were slower than controls (by ~ 0.16s for the AC group and ~ 0.24s for the IC group) but with no differences in error rate. When we asked participants to detect hazards when performing a concurrent simulated driving task (Experiment 3), the reaction times and error rates of the AC group (for either affected or unaffected fields) were very similar to controls. In contrast we observed longer reaction times and increased error rates for the affected field of many within the IC group (though the RT difference was not statistically reliable). These results would appear to confirm our two hypotheses: firstly that some people with a HVFD can successfully detect hazards whilst simultaneously driving, and secondly that we can predict those who can perform well at such hazard detection using a computer based visual search task.

These results would seem to suggest on one level that our visual search task could be a useful screening tool for identifying individuals with the capacity to successfully detect hazards whilst driving. However, there are reasons to be cautious of this interpretation of our data: We did not observe a reliable difference in reaction time between controls and the AC group in our simulated driving task, but the sample size was small and the absolute difference was ~ 0.1 secs on both the affected and unaffected side—potentially still long enough to cause problems when driving. The AC group were significantly slower at the PRT-D experiment, presumably due to a greater number of trials. Also, certain individuals did not behave as predicted—for instance LHVFD5, placed in the IC group, made 15/16 correct responses with an average reaction time of 0.82 seconds for targets on the affected side—well within the range shown by the control group. RHVFD4 was placed in the AC group, but missed one pedestrian altogether—potentially an extremely serious error. So we would make no claim that people who perform well at our visual search task should immediately have their driving licences reinstated; rather we propose that performance in this task is one indicator that could be used to inform the targeting of rehabilitation and training towards those individuals who have displayed a capacity to compensate for visual field loss. We envisage that a visual search task such as ours could provide useful feedback to patients about the severity and extent of functional loss, and even the degree of recovery (if they carry out the test at different time points post-stroke). Whilst our results are promising there is a need for further validation studies (with larger sample sizes) to establish test-retest reliability of this task before it would be suitable for use as a clinical assessment tool.

It is worth briefly considering the characteristics of the visual search task used in this research. The average search time for the target was approximately 3 seconds, which is in the order of 3 times longer than previously published visual search times for older adults (Trick & Enns, 1998). Our visual search task included target items that were very similar to the distractor items, merely 20% smaller or larger (which equates to less than $^1/_4$ degree change in edge length). When embedded as one of 32 items this makes the visual search task challenging to perform quickly and accurately, and clearly requires intact eye-movements and visual short term memory function as well as the ability for those with HVFD to sample visual information from their affected field.

When considering the relationship between the visual search task and hazard detection, it is worth considering whether the simulated driving task used in the present experiment was sufficiently representative of real world driving. The problem with attempting to simulate 'real' driving conditions is that the visual, motor and cognitive demands vary greatly depending upon the environment being driven through—consider the differences between city driving at rush hour, motorway driving at high speeds in the rain, or driving along narrow, winding country lanes at night. It is, therefore, non-trivial to precisely determine whether the task used in the present study was less demanding or more demanding than real driving. Computer simulations have been used for many years to provide well controlled visual conditions with reliable and reproducible measures of performance (Wilkie & Wann, 2002; Kountouriotis, Shire, & Mole, 2013; Raw, Kountouriotis, Mon-Williams, & Wilkie, 2012) and here the lane change driving task was used to reproduce some of the core visual-motor demands of city driving, whilst also testing the ability to detect and respond to pedestrians. The task lacked some other driving demands, such as using the pedals, dealing with traffic, and furthermore the driver knew that hazards would emerge at some point and could to some degree predict when they may appear. We are not asserting that our adequately compensated group would definitely be safe to drive in the real world—it would be necessary to carry out a longer, less constrained simulated study to examine this question further. It could also be argued that the binary button pressing motor response that we asked participants to generate is different from the usual braking or avoidance actions performed when driving. It should be noted, however, that the control group responded rapidly (~ 0.75s), detecting 100% of pedestrians (although occasionally with the wrong response). The AC group similarly detected 100% of pedestrians appearing in their affected field (with a single miss in the unaffected field), though they did respond slightly slower than controls. In contrast, 5/7 of the IC group failed to respond at all to at least two pedestrians appearing in their affected field. We would classify such misses as a major error, which does reinforce the apparent relationship between performance in a demanding visual search task and the ability to successfully detect hazards when driving.

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