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Driving with central field loss III: vehicle control

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Background: Visual impairment associated with central field loss may make vehicle control more difficult due to the degraded view of the road. We evaluated how central field loss affects vehicle control in a driving simulator.

Methods: Nineteen participants with binocular central field loss (acuity 6/9 to 6/60) and 15 controls with normal vision drove 10 scenarios, each about eight to 12 minutes. Speed, lane offset and steering wheel reversal rate were measured on straights, left and right curves, along city (approximately 50 km/h) and rural highway (approximately 100 km/h) routes. Following distance was measured on two city straight segments.

Results: Subjects with central field loss had higher steering wheel reversal rates (0.55 versus 0.45 reversals per second, $p = 0.015$), suggesting that the steering task was more demanding for them, requiring more steering corrections; however, they did not differ in other performance measures. Nearly all maintained a safe following distance, although they were more likely than controls with normal vision to lose sight of the lead car in scenarios that required following a car.

Conclusions: Most measures of vehicle control did not significantly differ between participants with central field loss and those with normal vision; however, the higher steering wheel reversal rates suggest that, in compensating for their vision impairment, drivers with central field loss had to allocate extra steering effort to maintain their lane position, which in turn could reduce attentional resources for other driving tasks.

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Central field loss (CFL) is often caused by age-related macular degeneration (AMD), an ocular disease that affects up to one million Australians[1] and eight million Americans.[2] Other less common causes include Stargardt's disease, optic nerve atrophy or degeneration and ocular histoplasmosis. Although the highest-resolution area of the retina is damaged in macular disease, patients may still have visual acuity sufficient to qualify for a conditional driver's licence in Australia[3] (visual acuity between 6/12 and 6/24) or a restricted drivers' license in many jurisdictions in the USA,[4] where visual acuity can be as low as 6/60 for a restricted licence to drive with a bioptic telescope.

Central field loss could affect a range of driving skills through impairments in visual acuity and contrast sensitivity, as well as the effect of the scotoma itself. Surprisingly, there have been relatively few studies of the effects of CFL on driving.[5] Prior simulator studies have reported that individuals with CFL tend to drive more slowly than normally sighted drivers,[6] respond less quickly to traffic signs[6,7] or changes in speed of a lead car[8] and crash more often than normally sighted drivers[6] (but not more often than drivers with peripheral field loss[8]). In a series of recent driving simulator studies, we consistently found that individuals with para-central and CFL had delayed reactions to potential hazards (pedestrians) appearing within their binocular scotoma.[9–11] More often than normally sighted controls, they did not respond in time to avoid a collision, if the pedestrian had continued on the same trajectory.[9–11]

Vehicle control skills, such as keeping the vehicle within the travel lane boundaries and maintaining a safe following distance, are considered an important aspect of safe driving. The effects of CFL on lane position and lane boundary crossings are not well established. Based on a model of steering,[12,13] Coeckelbergh and colleagues[8] hypothesised that drivers with CFL might have relatively good lane positioning (that involves monitoring of near road areas in peripheral vision) but might be less able to anticipate and follow changes in road curvature (which involves extraction of visual information from more distant parts of the road that they might have more difficulty seeing). Coeckelbergh and colleagues[8] concluded that the results of their driving simulator study provided support for both hypotheses. Drivers with CFL made few lane boundary crossings and their lane position was less affected by road curvature than drivers with peripheral field loss and good visual acuity, that is, they did not move as far to the left on left curves or to the right on right curves. A comparison to normally sighted control drivers was not included in that study and curve following was only evaluated when driving at 80 km/h. Furthermore, Coeckelbergh and colleagues[8] reported only the overall age of their sample and did not separately report ages for the CFL and peripheral field loss groups. Therefore, it is unknown whether the between-group differences in lane position were solely related to differences in the type of visual impairment or whether between-group age differences might also have been a factor. A recent driving simulator study of participants with normal vision (NV) reported that older drivers (over 60 years) stayed more in the middle of the lane, when driving round curves than younger drivers (aged under 40 years), who cut the curves to a greater extent.[14]

To address these potentially conflicting tendencies and the paucity of data on vehicle-control skills of drivers with CFL, we used a driving simulator to evaluate the lane positioning and steering of drivers with CFL on straight and curved road segments in urban and rural driving and compared their performance to age-similar normally sighted drivers. We hypothesised that drivers with CFL would be more likely to adopt a central position on curves. We also hypothesised that maintaining lane position would be more difficult than for normally sighted drivers, resulting in a greater number of steering reversals per minute[19] and possibly greater variation in lane position. In addition, we evaluated the ability to maintain a safe following distance, which we expected to be more difficult for drivers with CFL.[8] We hypothesised that drivers with CFL would have a greater variation in following distance than normally sighted drivers, with a higher proportion of time being too close to the lead car to stop in time to avoid a collision.

METHODS

We followed the tenets of the Declaration of Helsinki in the planning and conduct of the research. The research protocols were approved by Institutional Review Boards at both the Veteran's Administration Boston Healthcare System and at Schepens Eye Research Institute.

Participants

Nineteen participants with bilateral CFL and 15 participants with NV were enrolled in the study. Peripheral visual field extent was measured with Goldmann perimetry (V4e target) to ensure each participant had a minimum 120 degrees horizontal binocular field (the visual field extent requirement for driving in Massachusetts). In addition, for participants with CFL, central scotomata were mapped using a custom digital light projector system at one metre from a screen that subtended 60 degrees of visual angle. The participant fixated a bright cross (size 1.23 degrees, 74 candela/m^2) using his or her preferred retinal locus (PRL), over a 24 cd/m^2 grey background, to map the scotomata under monocular and binocular viewing. Participants with CFL had 6/60 single letter acuity or better with correction measured binocularly (controls 6/7.5 or better). Participants completed the Short Portable Mental Status Questionnaire[15] and a short computerised test of letter contrast sensitivity that gives results similar to the Pelli-Robson chart (Dr R Woods, personal communication, May 24, 2012).

Driving simulator

We used a high-fidelity FAAC PP-1000X-5 driving simulator, which has five CRT displays covering 225 degrees horizontal by 32 degrees vertical field of view. The 29-inch (diagonal) monitors viewed at one metre had a resolution of 2.2 minutes of arc per pixel, corresponding to acuity of approximately 6/12. The cab has a three-degrees-of-freedom motion seat and all controls were typical for a car with automatic transmission.

Each participant drove four rural highway and six city scenarios, each designed to be completed in eight to 12 minutes. Half were administered during the first session and the other half one week later. Five participants with CFL and two with NV required three sessions to complete all drives. Before starting the test scenarios, participants completed a series of acclimatisation and practise drives. They were allowed as much time as needed to become comfortable driving in the simulator (average 39.5 minutes for participants with CFL across the two sessions and 30.4 minutes for participants with NV). Each simulator session lasted 3.0 to 3.5 hours with breaks. Data were continually recorded at 30 Hz, including speed, control usage and locations of all entities in the virtual world. Scenarios were programmed to include oncoming traffic on all drives, as well as infrequent passing traffic on city drives.

Participants were asked to follow all the normal rules that apply when driving on the right of the road (as in the USA) and to drive close to 30 mph (48 km/h) in the city and 60 mph (97 km/h) on highway drives on straight segments. Participants had full control of vehicle speed and steering. They were guided along the routes by audio cues (for example, 'turn left at next intersection') similar to an in-car GPS navigation system. Two of the city drives included a section, where participants were instructed to follow a police car, while maintaining a safe following distance. During drives, participants were also asked to press the horn button, as soon as they saw a pedestrian to test their hazard detection abilities. The detection results were previously published.[11,16,17]

Analyses

We measured driving performance on a number of predetermined road segments including: two straight segments, two left and two right curves for each city scenario and two straight segments and three right and three left curves for each highway scenario. The average total distance of the scored segments was approximately 15 per cent of the total distance driven.[18] The segments were selected to be free of any events, including pedestrians, which might affect steering or vehicle control (such as the need to press the horn).

For each segment, we measured:

1. Average speed;
2. Lateral lane offset, the difference between lane and car centres;
3. Variability (standard deviation) of lateral lane offset (a measure of steering stability);
4. Number of steering wheel reversals per second (a measure of steering task demand or difficulty[19]); and
5. Percentage time out of lane.

More details are available in an earlier paper by Bowers and colleagues.[18] As simulator data were recorded at 30 Hz, a straight segment 200 metres long driven at 48 km/h (13.4 m/s) would have 447 samples from which each of the measures was computed.

We calculated medians for each subject's performance on each segment type and used repeated measures analyses of variance to analyse the data with vision group (CFL or NV) as the between-subjects factor and segment type (straight, left curve or right curve) and drive type (highway or city) as within-subjects factors.

For the scenarios in which participants were asked to follow a lead car, we analysed performance on one straight segment, about 155 metres long, from each scenario, during which the lead car was driving at a constant speed (about 48 km/h). We calculated the distance from the participant's car to the lead car, at each time point, and determined the proportion of times during which they would have been able to stop in time to avoid a crash had the lead car begun braking (assuming 5.0 m/s^2 deceleration[20] for both vehicles).

The formula used was:

$$\begin{aligned}&(\text{braking distance at current speed}\\&+\text{minimum reaction time}\\&\times\text{current speed})\;>\\&(\text{distance to lead car}\\&+\text{lead car stopping distance}).\end{aligned}$$

The minimum reaction time was calculated individually for each participant from their reaction time to pedestrian hazards (this assumes that they initiate braking at a time equivalent to the fastest time they could detect a pedestrian hazard and press the horn, average 0.74 ± 0.22 seconds, range 0.53 to 1.40 seconds). This permitted an analysis of relative risk between participants with CFL and with NV; the proportion of time participants maintained safe following distances. As each participant performed two drives in which they followed a lead car, an average was used to represent each participant and non-parametric statistical tests were used to determine significance.

RESULTS

Participant characteristics

Participant characteristics are summarised in Table 1. The NV and CFL groups were not different for age, sex and driving experience; however, as expected, the participants with CFL had significantly worse visual acuity and contrast sensitivity. Average scotoma width was 12.6 ± 5.9 degrees (range 5.0 to 22.5 degrees), measured along four cardinal directions. Most scotomata were to the right (nine of 19) or above (six of 19) the PRL, with a minority to the left (three of 19) or below (one of 19).

Ten of the participants with CFL were current drivers, driving a median 57 kilometres per week (inter-quartile range [IQR] = 22 to 100 kilometres per week). The remaining nine participants with CFL had stopped driving a median of six (IQR = one to seven) years previously. Former and current drivers with CFL did not significantly differ for sex (six of nine male former, six of 10 male current, not significant), age (former mean 70 years, current 61 years; Mann–Whitney $U = 32.5$, $p = 0.32$), visual acuity (former mean 0.71, current 0.62 logMAR; Mann–Whitney $U = 35.5$, $p = 0.45$) or contrast sensitivity (former mean 1.15, current 1.33 log units; Mann–Whitney $U = 30$, $p = 0.24$).

Vehicle handling: speed

On average participants with CFL drove slightly slower than controls with NV (52.1 km/h versus 55.5 km/h), ($F[1, 32] = 3.68$, $p = 0.06$). This was true for most segments, except city curves, and was most notable for highway straight segments (79 km/h versus 85 km/h, 95 per cent CI of difference 0.6 km/h to 12.2 km/h, $p = 0.03$). As expected, participants drove more quickly on straight segments than curves ($F[2, 31] = 139.5$, $p < 0.001$) and of course, faster on highway than city routes ($F[1, 32] = 820.1$, $p < 0.001$).

Vehicle stability: average lane offset, steering wheel reversals and time out of lane

Overall, there were no significant differences in lateral lane offset between participants with NV and those with CFL ($F[1, 32] = 0.88$, $p = 0.36$) (Figure 1); however, the CFL group took a more central/rightward lane position than the NV group on left curves, especially on the highway drives ($t\ [32] = 2.6$, $p = 0.01$). Although both groups took a relatively more rightward lane position on highway than city drives (overall 0.22 metres versus -0.13 metres) ($F[1, 31] = 10.51$, $p = 0.003$), there were no consistent effects of segment type on lateral lane offset ($F[2, 30] = 1.71$, $p = 0.20$). In city drives both the CFL and the NV group tended to take a leftward lane position on left curves and a rightward position on right curves but that was not the case for highway drives, where neither group cut right curves and only the NV group cut left curves. This interaction between drive and segment type was significant ($F[2, 31] = 23.7$, $p < 0.001$) but the three way interaction of vision, drive type and segment type was not significant ($p = 0.08$).

Participants with CFL appeared to have slightly higher variability (standard deviation) of lateral lane offset than participants with NV but this was not statistically significant ($F[1, 32] = 1.92$, $p = 0.18$) (Figure 2). In general, there was greater variability of lane offset on highway than city segments ($F[1, 32] = 37.05$, $p < 0.001$) and on curved segments than straight segments ($F[1, 31] = 54.75$, $p < 0.001$) (Figure 2). Participants with CFL made more steering reversals per second than participants with NV (0.55 versus 0.45, 95 per cent CI 0.5 to 0.6 versus 0.4 to 0.51) ($F[1, 32] = 6.66$, $p = 0.015$) (Figure 3). Steering reversal rates were

	CFL (n = 19)	**NV (n = 15)**	**Test for group differences**
Current driver, number (%)	10 (53%)	15 (100%)	M–W U = 75, **p = 0.002**
Years driving, years*	45 ± 18 (13–68)	48 ± 18 (23–71)	M–W U = 124.5, p = 0.53
Male, number (%)	12 (63%)	9 (60%)	Not significant
Age, years*	65 ± 16 (43–88)	66 ± 16 (40–87)	M–W U = 138, p = 0.85
SPMSQ*	10 ± 0.6 (9–11)	11 ± 0.8 (9–11)	M–W U = 139, p = 0.92
Binocular VA, logMAR*	0.63 ± 0.25 (0.20–1.00)	-0.02 ± 0.08 (-0.12–0.12)	M–W U = 14, **p < 0.001**
Contrast sensitivity, log units*	1.24 ± 0.25 (0.75–1.73)	1.78 ± 0.15 (1.43–1.95)	M–W U = 14, **p < 0.001**
CFL cause			
AMD, number	10	n/a	n/a
Stargardt's, number	4	n/a	n/a
Other, number	5	n/a	n/a

AMD: age-related macular degeneration, CFL: central field loss, M–W: Mann–Whitney, NV: normal vision, VA: visual acuity
*Average ± standard deviation (range)
†SPMSQ: Short Portable Mental Status Questionnaire; a score of nine or greater indicates 'intact intellectual functioning'.[15]

Table 1. Participant characteristics

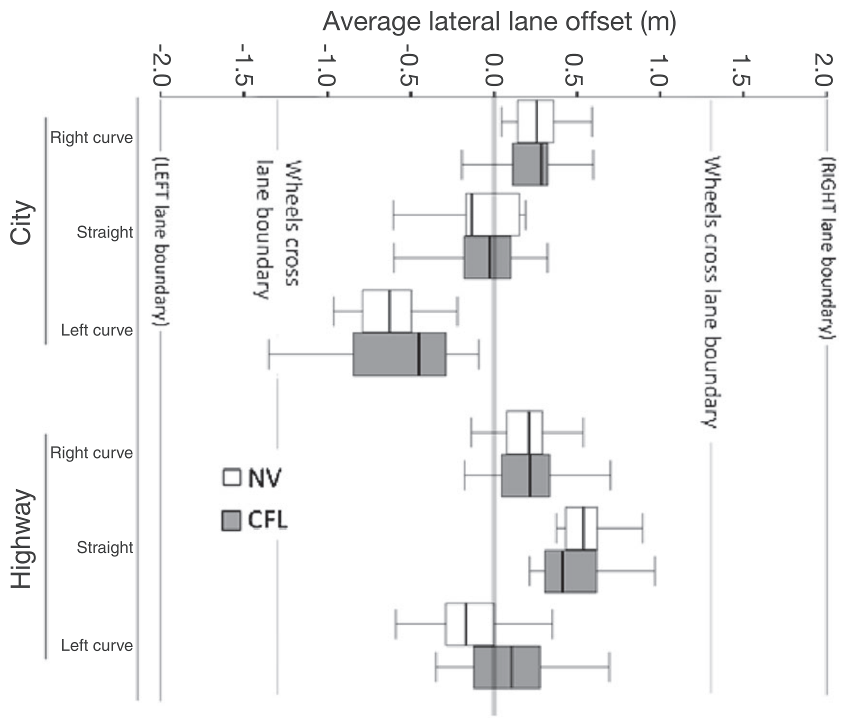

Figure 1. Boxplots of average lateral lane offset for participants with normal vision (NV) and those with central field loss (CFL) (where zero is the lane centre and negative values are to the left). Participants with CFL and NV were largely similar; however, participants with CFL were more variable and cut left curves less than participants with NV.

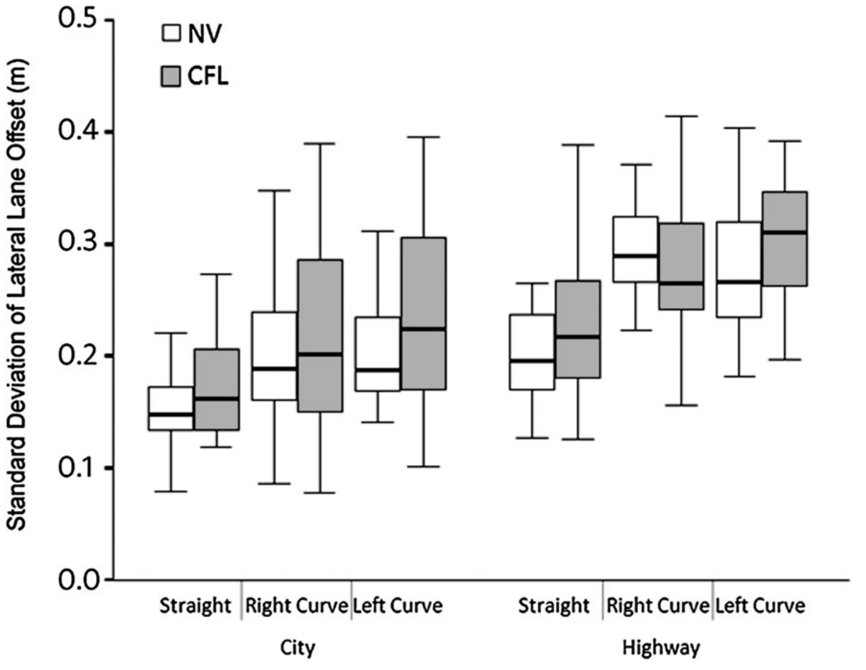

Figure 2. Boxplots of variability (standard deviation) of lateral lane offset for participants with normal vision (NV) and those with central field loss (CFL). There was a trend for participants with CFL to have greater variability than those with NV.

higher on highway than city drives (0.59 versus 0.42, 95 per cent CI 0.53 to 0.64 versus 0.39 to 0.45) (F[1, 64] = 71.96, $p < 0.001$) but there were no significant differences in steering reversal rates across segment types (F[2, 31] = 0.82, p = 0.92) (Figure 3).

Overall, participants were not out of lane for any considerable time. It was only on curves that there were any deviations from zero per cent time out of lane, most notably participants with CFL on city left curves. Participants with CFL were out of lane about as often as were participants with NV. As the median percentages for time out of lane were almost all zero, highly non-normal and all deviations from zero were outliers, this variable was not analysed with inferential statistics.

Lead car following

The median distance participants with CFL were from the lead car was almost identical to that of normal control participants (23.2 metres versus 23.0 metres, not significant) but the standard deviation in following was greater in the CFL group than controls (3.9 metres versus 2.3 metres, p = 0.01) and they were more likely to lose sight of the lead car and become unable to follow it (five of 35 drives versus zero of 29) ($\chi^2[1] = 4.49$, p = 0.03). Participants with CFL maintained a safe following distance 98.4 per cent of the time, whereas normal controls did so 99.9 per cent of the time (p = 0.24, not significant); one participant with CFL was safe with 54 and 100 per cent of her two drives, respectively; the remainder kept a safe following distance nearly 100 per cent of the time.

Vehicle crashes

Two participants with CFL had at-fault crashes, in which they rear-ended other vehicles: one (current driver) did not notice that a school bus was stopped until it was too late to brake in time; a second (former driver) crashed into a pedestrian, who was in the travel lane (he also rear-ended a taxi in a practise scenario, not counted in results). None of the normal controls had an at-fault crash; however, the rate of at-fault crashes was not significantly greater for participants with CFL (χ^2 = 1.68, p = 0.20) probably due to the small number of such crashes.

Effect of driving status, age and characteristics of scotomata

About half of the participants with CFL were not currently driving. Therefore, we

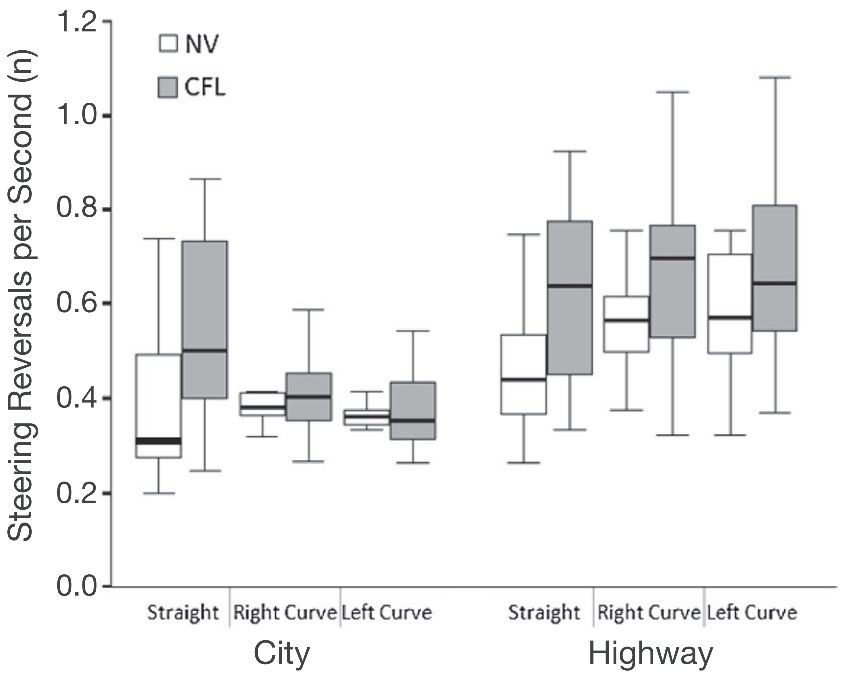

Figure 3. Boxplots of steering wheel reversals per second for participants with normal vision (NV) and those with central field loss (CFL). Participants with CFL had higher reversal rates than those with NV.

evaluated the effect of driving status (current versus former driver) on performance. There were no significant differences between current and former drivers with CFL for average speed ($p = 0.62$), lateral lane offset ($p = 0.75$), standard deviation of lane offset ($p = 0.32$), steering reversals ($p = 0.43$) or measures of lead-car following (all $p > 0.49$). We looked for correlations between age and vehicle control parameters and found inconsistent and mainly non-significant correlations. We also found no significant relationships between scotoma location or size and vehicle control measures.

DISCUSSION

Contrary to expectations, most measures of vehicle control did not significantly differ between participants with CFL and age-similar participants with NV. Participants with CFL tended to drive a few kilometres per hour more slowly, especially on highway drives and had a higher frequency of steering wheel reversals than participants with NV but did not differ in their overall lateral lane offset, lane offset variability or the percentage time out of lane. These small differences are unlikely to represent a safety concern. Our sample was modest ($n = 19$ CFL), yet it was similar in size to two earlier simulator studies by Coeckelbergh and colleagues[8] ($n = 23$ CFL) and Szlyk and colleagues[6] ($n = 10$ AMD).

We hypothesised and found that drivers with CFL would have a greater number of steering reversals. This result suggests that the steering task might have been more difficult for them than the NV participants and that their overall steering effort was greater.[19] In addition, steering reversal rates of both the CFL and NV participants increased in response to the greater steering demands of driving at higher speeds in the highway scenarios, as expected.[18,19] Despite the greater steering effort, participants with CFL did not have a significantly greater variability in lane position than participants with NV and their overall average lane offset did not differ from that of the NV participants, suggesting adequate steering compensation, which may have been helped by driving at slightly slower speeds on the highway. We also note that if the main analyses (analyses of variance for the main measures) were Bonferroni corrected, the reversal rate would not significantly differ between participant groups.

In the city drives, the lane offset of participants with CFL was similar to that of NV participants with both groups showing typical curve-cutting behaviour; driving more to the left on left curves and to the right on right curves, which went against our hypothesis that they would adopt a more central lane position. By comparison, in the highway drives, participants with CFL showed relatively little change in lane position with changes in road curvature, while participants with NV cut only left curves. Not cutting right curves in highway drives may have been a result of wanting to avoid leaving the travel lane, as there was no breakdown lane on the right side.

Our findings for left curves in highway drives are consistent with the results of Coeckelbergh and colleagues,[8] who reported that drivers with CFL cut curves less than drivers with peripheral field loss, when driving at 80 km/h (50 mph); however, Coeckelbergh and colleagues[8] did not evaluate lane position on curves when driving at lower speeds. Thus, our findings provide some support for the hypothesis proposed by Coeckelbergh and colleagues[8] that reduced ability of drivers with CFL to see lane markers further down the road causes difficulties anticipating road curvature and that they tend to maintain a more central lane position. In our study, this behaviour was more likely to manifest in the highway than the city because the curves were much longer (median highway 198 metres versus city 22 metres) and participants were driving at higher speeds, where road curvature needed to be anticipated at a greater distance.

Participants with CFL were not out of lane any more than participants with NV or for any considerable time. By contrast, Szlyk and colleagues[6] reported that participants with CFL were out of lane on average 14.5 times compared to normal participants three times. Coeckelbergh and colleagues[8] reported an average 2.9 crossings for 57 per cent of participants with CFL. It is possible that the total amount of drive time could account for the differences in results; Szlyk's participants drove for only eight minutes after 15 minutes training, whereas Coeckelbergh and colleagues'[8] participants drove for 30 minutes with 10 minutes training. Our participants with CFL practised for 39.5 minutes, on average, during acclimatisation, whereas the participants with NV practised for 30.4 minutes and the total duration of our test drives was about 120 minutes.

Participants with CFL did not significantly differ from normal participants in mean following distance and, on average, had no more difficulty maintaining a safe distance; however, we only evaluated following distance on straight road segments, when the lead vehicle was maintaining a constant speed. By comparison, Coekelbergh and colleagues[8] found that drivers with CFL were slower to respond to lead-car velocity changes than drivers with peripheral field loss with normal visual acuity. Furthermore, our analysis used the assumption that participants would have initiated a braking at their minimum reaction time previously measured for responses to pedestrian hazards. We did not measure response times to the onset of brake lights of a lead car and therefore, do not know whether these response times might have been shorter or longer.

The frequency of at-fault crashes seems relatively high in this study, but was smaller than other simulator studies (16 per cent for CFL in our study versus 35 per cent for CFL in Coeckelbergh and colleagues's study[8]) and was similar to a prior study[21] in the same simulator (16 per cent for drivers with hemianopia and 16 per cent for drivers with NV). By comparison, Szlyk and colleagues[6] reported a higher average total number of crashes for participants with CFL (1.5 per participant) than NV (0.55 per participant) during a brief eight-minute session of driving, most due to '…wandering out into the oncoming lane and colliding with another vehicle.' We observed no such behaviour. Driving simulator scenarios are often designed to be more challenging than typical on-road driving to avoid ceiling/floor effects, without safety concerns.[22] Thus, a higher crash rate is to be expected in driving simulator studies than in on-road driving where crashes are extremely infrequent events.

A potential limitation of our study is that nine of the 19 participants with CFL were not current drivers, although former drivers had an average 47 years of driving experience. We found few differences in driving performance measures between those who were current drivers and those who had stopped driving; however, our study was not powered to find such small differences (for example, the number of steering reversals per second for current drivers with CFL on left city curves was 1.20 ± 0.4, whereas it was 1.33 ± 0.5 for former drivers). Our analyses suggest that the higher steering wheel reversal rates and greater variability in following distance in the CFL than the NV group were not a result of poorer driving performance by those who had stopped driving. As discussed earlier, participants with CFL were given as much time as needed to become familiar with driving in the simulator and all had extensive prior driving experience (Table 1). We do not know of any studies demonstrating deteriorated driving ability following postponement of driving for a few years, although some decrement may be expected.

The results of this study suggest that, in comparison to age-similar drivers with NV, individuals with reduced acuity and CFL do not have major problems with steering and lane position control during city driving or when driving at higher speeds. CFL drivers were similar overall to NV drivers in those aspects of their driving; however, the increased steering reversal rate is evidence that they devoted more steering effort to maintain adequate vehicle control, which may reduce attentional resources for other driving tasks such as hazard detection. Indeed, participants with CFL and longer response times to pedestrian hazards[11] had higher steering wheel reversal rates ($r = 0.39$; $p = 0.02$).

Previously, we reported that response times to pedestrian hazards were delayed even when pedestrians appeared in non-scotomatous areas of the visual field and more delayed response times were strongly correlated with poorer contrast sensitivity.[11,16] Thus, our prior results[11,16,17] suggest that drivers with CFL may be at greater risk for collisions than age-similar drivers with NV, due to difficulties with timely responses to other road users rather than poor vehicle control. Our results point to the importance of evaluating hazard detection skills as well as vehicle control skills in on-road driving evaluations.

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