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Driving with central field loss III: Vehicle control

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Abstract

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

Procedures—Nineteen participants with binocular CFL (acuity 20/30 to 20/200), and fifteen controls with normal vision (NV), drove 10 scenarios, each about 8–12 minutes. Speed, lane offset and steering wheel reversal rate were measured on straights, left and right curves, along city (~50 km/h) and rural highway (~100 km/h) routes. Following distance was measured on two city straight segments.

Main Findings—CFL subjects had higher steering wheel reversal rates (0.55 v 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 NV controls 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 CFL and those with NV. However, the higher steering wheel reversal rates suggest that, in compensating for their vision impairment, CFL drivers had to allocate extra steering effort to maintain their lane position, which could in turn reduce attentional resources for other driving tasks.

INTRODUCTION

Central field loss (CFL) is often caused by age-related macular degeneration (AMD), an eye disease that affects up to 1 million Australians[1] and 8 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 drivers' license in Australia[3] (visual acuity between 6/12 and 6/24) or a restricted drivers' license in many jurisdictions in the U.S.A[4] (where visual acuity can be as low as 20/200 (6/60) for a restricted license to drive with a bioptic telescope).

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CFL 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, however, 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 field loss 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 its 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,[1213] Coeckelbergh et al. [8] hypothesized that CFL drivers 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 et al concluded that the results of their driving simulator study provided support for both hypotheses. CFL drivers 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, i.e. they did not move as far to the left on left curves or to the right on right curves. However, 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 et al. reported only the overall age of their sample, and did not report ages for the CFL and peripheral field loss groups separately. Therefore, it is unknown whether the between-group differences in lane position were solely related to differences in the type of vision impairment, or whether between-group age differences might also have been a factor. A recent driving simulator study of participants with normal vision reported that older drivers (age 60+) stayed more in the middle of the lane when driving round curves than younger drivers (aged < 40) 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 hypothesized that drivers with CFL would be more likely to adopt a central position on curves. We also hypothesized 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 hypothesized 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 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 normal vision (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° horizontal binocular field (the visual field extent requirement for driving in Massachusetts). In addition, for participants with CFL, central scotomas were mapped using a custom digital light projector system at 1m from a screen that subtended 60° of visual angle. The participant fixated a bright cross (size 1.23°, 74 candela/m^2) using his or her preferred retinal locus (PRL), over a 24cd/m^2 gray background, to map the scotomas under monocular and binocular viewing. Participants with CFL had 20/200 (6/60) single letter acuity or better with correction measured binocularly (controls 20/25 (6/7.5) or better). Participants completed the Short Portable Mental Status Questionnaire[15] (SPMSQ) and a short computerized test of letter contrast sensitivity that gives results similar to the Pelli-Robson chart (R. Woods, PhD, written communication, May 24, 2012).

Driving Simulator

We used a high-fidelity FAAC PP-1000X-5 driving simulator, which has 5 CRT displays covering 225° horizontal by 32° vertical field of view. The 29 inch (diagonal) monitors viewed at 1 meter had a resolution of 2.2 minutes of arc per pixel, corresponding to acuity of approximately 6/12. The cab has a 3-degrees-of-freedom motion seat and all controls typical for a car with automatic transmission.

Each participant drove four rural highway and six city scenarios, each designed to be completed in 8–12 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 acclimation and practice drives. They were allowed as much time as needed to become comfortable driving in the simulator (average 39.5 minutes for CFL participants across the two sessions and 30.4 minutes for NV participants). Each simulator session lasted about 3 – 3.5 hours with breaks. Data were continually recorded at 30Hz, 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 U.S.A) and to drive close to 30mph (48 km/h) in the city and 60mph (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 (e.g., “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 published previously. [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% 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 centers; 3) variability (SD) 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) percent time out of lane. More details are available in Bowers et al., 2010.[18] As simulator data were recorded at 30 Hz, a straight segment 200m 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 analyze 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 analyzed performance on one straight segment, about 155m 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 time points during which they would have been able to stop in time to avoid a crash had the lead car begun braking (assuming 5 m/s^2 deceleration[20] for both vehicles). The formula used was: (braking distance at current speed + minimum reaction time * current speed) > (distance to lead car + lead car stopping distance). 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 s, range 0.53 to 1.40). This permitted an analysis of relative risk between CFL and NV participants; 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 nonparametric statistical tests were used to determine significance.

RESULTS

Participant Characteristics

Participant characteristics are summarized in Table 1. The NV and CFL groups were not different for age, sex and driving experience. However, as expected, the CFL participants had significantly worse visual acuity and contrast sensitivity. Average scotoma width was 12.6 ± 5.9° (range 5.0–22.5), measured along 4 cardinal directions. The majority of scotomas were to the right (9/19) or above (6/19) the PRL, with a minority to the left (3/19) or below (1/19).

Ten of the CFL participants were current drivers, driving median 57 (inter-quartile range (IQR) = 22 to 100) kilometers per week. The remaining 9 CFL participants had stopped driving median 6 (IQR = 1 to 7) years previously. CFL former and current drivers did not significantly differ for sex (6/9 male former, 6/10 male current, *ns*), age (former mean 70 years, current 61 years; M-W U = 32.5, $p=0.32$), visual acuity (former mean 0.71, current 0.62 logMAR; M-W U = 35.5, $p=0.45$), or contrast sensitivity (former mean 1.15, current 1.33 log units; M-W U = 30, $p=0.24$).

Vehicle Handling - Speed

On average participants with CFL drove slightly slower than NV controls (52.1 km/h vs. 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 vs. 85 km/h, 95% CI of diff 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 $F(1, 32) = 0.88$, $p = 0.36$ (Fig. 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 m vs. −0.13 m), $F(1, 31) = 10.51$, $p=0.003$, 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 NV participants, but this was not statistically significant, $F(1, 32) = 1.92$, $p=0.18$ (Fig. 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, $F(1, 31) = 54.75$, $p<0.001$ (Fig. 2). Participants with CFL made more steering reversals per second than NV participants (0.55 vs. 0.45, 95%CI 0.5 to 0.6 vs. 0.4 to 0.51), $F(1, 32) = 6.66$, $p=0.015$ (Fig. 4). Steering reversal rates were higher on highway than city drives, (0.59 vs. 0.42, 95%CI 0.53 to 0.64 vs. 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 $F(2, 31) = 0.82$, $p = 0.92$ (Fig. 3).

Overall, participants were not out of lane for any considerable time. It was only on curves that there were any deviations from zero percent time out of lane, most notably CFL participants 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 analyzed with inferential statistics.

Lead Car Following

The median distance CFL participants were from the lead car was almost identical to that of NV control participants (23.2 m vs. 23.0 m, *ns*), but the standard deviation in following was greater in CFL than controls (3.9 m vs. 2.3 m, p=0.01) and they were more likely to lose sight of the lead car and become unable to follow it (5/35 drives vs. 0/29) $\chi^2(1)=4.49$, p=0.03. CFL participants maintained a safe following distance 98.4% of the time whereas NV controls did so 99.9% of the time, p=0.24, *ns*; one CFL participant was safe 54% and 100% of her two drives, respectively; the remainder kept a safe following distance nearly 100% 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 practice scenario, not counted in results). None of the NV controls had an at-fault crash. However, the rate of at-fault crashes was not significantly greater for participants with CFL, $\chi^2=1.68$, p=0.20, *ns,* probably due to the small number of such crashes.

Effect of Driving Status, Age and Scotoma Characteristics

About half of the CFL participants were not currently driving; we therefore evaluated the effect of driving status (current vs. former driver) on performance. There were no significant differences between current and former CFL drivers 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) nor measures of lead-car following (all p values > 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 kilometers 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 percent time out of lane. These small differences are unlikely to represent a safety concern. Our sample size was modest (n = 19 CFL), yet it was similar in size to two earlier simulator studies by Coeckelbergh et al.[8] (n = 23 CFL) and Szlyk et al.[6] (n = 10 AMD).

We hypothesized 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 NV participants, 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 (ANOVAs 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 CFL participants was similar to that of NV participants with both groups showing typical curve-cutting behaviors - 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, CFL participants showed relatively little change in lane position with changes in road curvature, while NV participants 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 et al[8] who reported that drivers with CFL cut curves less than drivers with peripheral field loss when driving at 80 km/h (50 mph). Note, however, that Coeckelbergh et al. did not evaluate lane position on curves when driving at lower speeds. Thus, our findings provide some support for the hypothesis proposed by Coeckelbergh[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, these behaviors were more likely to manifest in the highway than the city drives because the curves were much longer (median highway 198 m vs. city 22 m) and participants were driving at higher speeds where road curvature needed to be anticipated at a greater distance.

CFL participants were not out of lane any more than NV participants nor for any considerable time. By contrast, Szlyk et al.[6] reported that participants with CFL were out of lane on average 14.5 times compared to NV participants 3 times. Coeckelbergh et al, [8] reported an average 2.9 crossings for 57% of participants with CFL. It is possible that total amount of drive time could account for the differences in results; Szlyk's participants drove for only 8 minutes after 15 min training, whereas Coeckelbergh's participants drove for 30 minutes with 10 min training. Our participants with CFL practiced for 39.5 minutes, on average, during acclimation whereas the NV participants practiced for 30.4 minutes, and the total duration of our test drives was about 120 minutes.

Participants with CFL did not significantly differ from NV 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 et al[8] found that CFL drivers 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 do not, therefore, 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% for CFL in our study vs. 35% for CFL in Coeckelbergh's study[8]) and was similar to a prior study[21] in the same simulator (16% for drivers with hemianopia and 16% for drivers with NV). By comparison, Szlyk et al.[6] reported a higher average total number of crashes for CFL (1.5 per participant) than NV participants (0.55 per participant) during a brief 8-minute session of driving; most due to "…wandering out into the oncoming lane and colliding with another vehicle." (p. 1036). We observed no such behaviors. 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 9 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 (e.g., 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 above, CFL participants 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, though some decrement may be expected.

The results of this study suggest that, in comparison to age-similar NV drivers, 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, CFL participants with longer response times to pedestrian hazards (reported in Bronstad et al., 2013{Bronstad, 2013 #8285}) had higher steering wheel reversal rates ($r = .39$; $p=.02$).

Previously, we reported[11, 16] 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. Thus, our prior results[11, 16, 17] suggest that drivers with CFL may be at greater risk for collisions, than age-similar NV drivers, 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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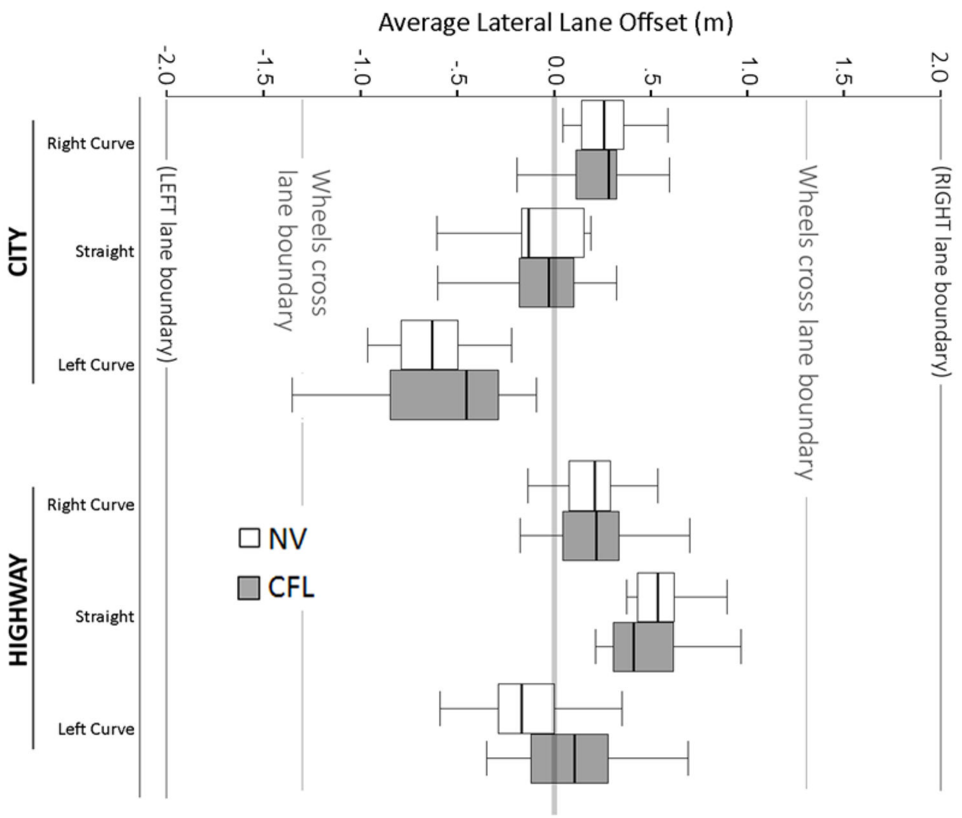

Figure 1.

Boxplots of average lateral lane offset for participants with normal vision and those with central field loss (where 0 is the lane center 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.

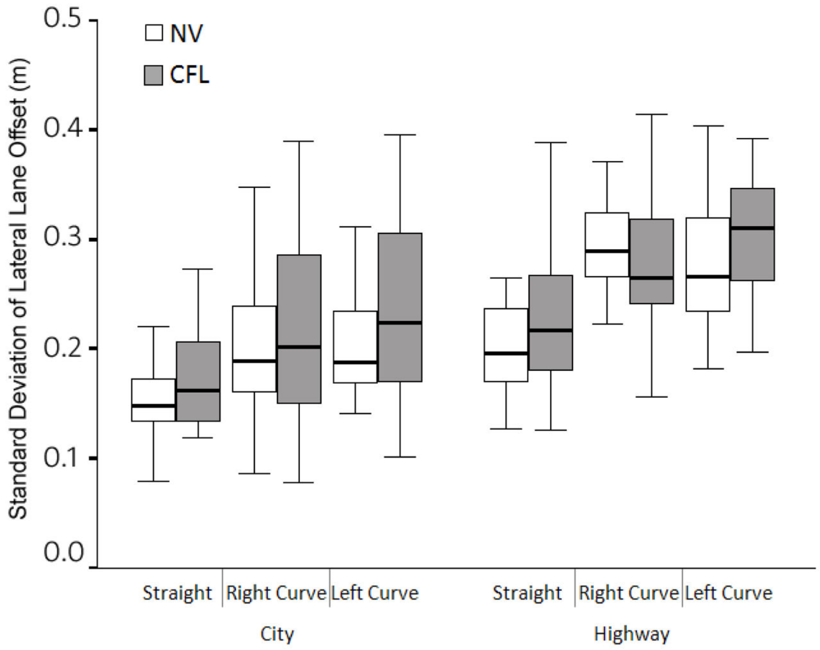

Figure 2.

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

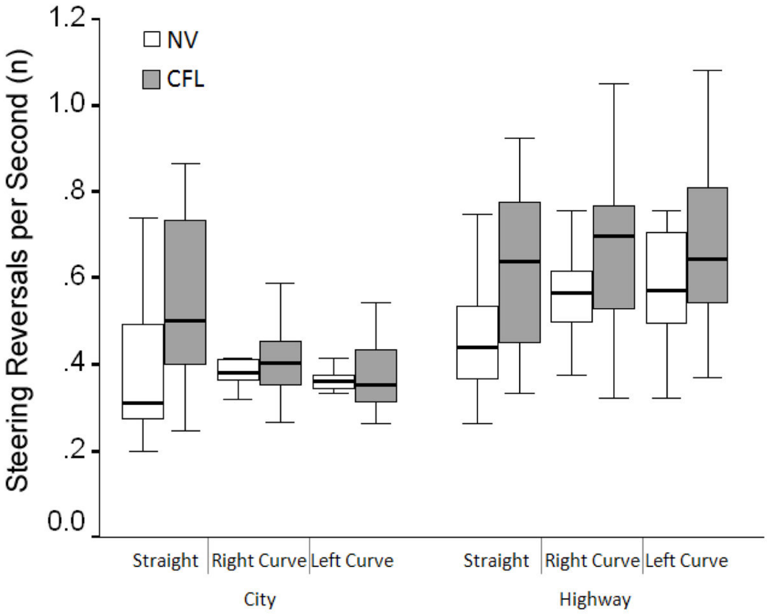

Figure 3.

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

Table 1

Participant Characteristics

	CFL (n = 19)	**NV (n = 15)**	**Test for group differences**
Current driver: n (%)	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: n (%)	12 (63%)	9 (60%)	*ns*
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: n	10	n/a	n/a
Stargardt’s: n	4	n/a	n/a
Other: n	5	n/a	n/a

M-W = Mann-Whitney

[*] average ± standard deviation [range]

[†] SPMSQ: Short Portable Mental Status Questionnaire; A score of 9 or greater indicates “intact intellectual functioning”.[15]