Driving with Hemianopia, II: Lane Position and Steering in a Driving Simulator

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Purpose. The hypothesis that drivers with homonymous hemianopia (HH) would take a lane position that increased the safety margin on their blind side was tested with a driving simulator.

Methods. Twelve participants with HH (six right HH and six left; nine men; mean age, 50 years; range 31–72), and 12 matched current drivers with normal vision (NV) each completed approximately 120 minutes of simulator driving. Lane position and steering stability were evaluated for specific road segment types (straight segments, curves, and turns) in city and rural undivided highway driving.

Results. The drivers with right HH held a lane position significantly ($P = 0.001$) to the left of NV drivers on the straight road segments and to a lesser extent on the curves. The drivers with left HH had a lane position similar to that of the NV drivers on straights and curves, but followed a significantly ($P = 0.005$) more rightward path on the left turns.

Conclusions. The results support the hypothesis that drivers with HH take a lane position that increases the safety margin on their blind side; however, absolute lane position varies as the steering maneuver and location of the risk from oncoming traffic change with road segment type. (*Invest Ophthalmol Vis Sci.* 2010;51:6605–6613) DOI:10.1167/iovs.10-5310

The loss of half the field of vision in homonymous hemianopia (HH) could affect several driving skills, including detection of traffic-relevant objects, steering and lane position, and eye and head movement. In a previous paper,[1] we reported the effect of HH on detection of pedestrians while driving; this second paper addresses the effect of HH on steering and lane position. The ability to steer a vehicle so that it remains on a steady course within the travel lane is an important aspect of safe driving. Steering behavior that results in incursions into adjacent travel lanes endangers both the driver and other road users. Problems with unstable steering and lane-keeping have been reported as the most common reasons for failure of on-road tests by HH drivers.[2,3] Those findings were based on the most commonly applied scoring methods used in on-road studies: examiner's comments[2] and observer's ratings of steering and lane position.[3] However, those methods do not measure actual lane position.

One of the advantages of using a driving simulator is that steering and lane position can be quantified for all drivers in exactly the same conditions. In an early simulator study, Szylk et al.[4] reported that HH drivers made more lane boundary crossings and had greater variability in lane position than did normally sighted drivers. However, only 5 minutes of driving was evaluated, and the small sample ($n = 6$) included drivers with visual neglect, making it difficult to isolate the effects of the visual field loss from the effects of visual neglect. Furthermore, the lane position measures were apparently averaged across the entire drive without differentiating the various types of roadway segments (straight, curve, turn). A normally sighted driver's lane position varies with roadway curvature: driving close to the center of the lane on straight segments[5] and moving to a leftward position in left curves and to a rightward position in right curves.[6] The same was reported for drivers with peripheral visual field loss[7] (not due to HH), but not for drivers with central visual field loss, who showed little variation in lane position with changing road curvature.[7]

For drivers with HH, the side of the hemifield loss may also affect lane position, and there may be interactions with the road segment type. Therefore, we evaluated steering and lateral lane position of drivers with HH and normal vision (NV) in a simulator for specific road segments (straights, right and left curves, and right and left turns) when driving on the right side of the road (as in the USA.). Our *primary hypothesis* was that drivers with HH would take a lane position that increased the safety margin on the blind side. Starting with this hypothesis, we then made specific predictions about the lateral lane position of drivers with HH for each road segment type. On straight road segments we predicted that they would provide a safety margin by taking a lane position away from the blind side: drivers with RHH would take a leftward lane position, whereas drivers with LHH would take a rightward lane position (relative to NV drivers).

The predictions were more complex for curves and turns. For curves, our predictions depended on whether the curve opened into the blind or seeing hemifield. Drivers with NV usually take a rightward path on right curves. We predicted that drivers with RHH, who would be driving into their blind right field, would maintain a safety margin on the blind right side by staying to the left of drivers with NV. Conversely, we predicted that drivers with LHH (curve opening into seeing field) would have a rightward lane position similar to that of drivers with NV. On left curves, drivers with NV usually take a leftward path. In this situation we predicted that drivers with RHH would take a leftward path similar to that of drivers with NV (curve opening into their seeing hemifield), whereas drivers with LHH would maintain a safety margin on the blind left side by staying to the right of drivers with NV.

We made different predictions for turns. Unlike curves, a turn is usually initiated only after visual scanning to detect potential conflicts with other traffic and to ensure that the path through the intersection is free of obstacles. The main task is then to steer so that the vehicle exits the intersection into the correct lane and avoids danger from the median curb or oncoming traffic at the end of the turn. When turning right, the

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danger of oncoming traffic at the end of the turn starts in the right field and gradually switches to the left field. Therefore, on right turns we predicted that drivers with RHH would take a more *rightward* (tighter) path than drivers with NV, bringing the risk zone of the oncoming traffic (the left lane boundary or median) more quickly from the blind right field into the left seeing field (compared with drivers with NV who maintain the risk zone in their seeing field throughout the maneuver). For LHH, we predicted that the path would be similar to that of drivers with NV, or even slightly more leftward, keeping the risk zone in the seeing right field for as long as possible. On left turns, the oncoming traffic at the end of the turn starts in the left field and remains there throughout the turn. Therefore, we predicted that drivers with RHH (risk zone in the seeing hemifield) would take a path similar to that of drivers with NV, whereas drivers with LHH (risk zone in the blind hemifield) would take a more *rightward* (wider) path to ensure a safety margin on the blind left side, especially at the end of the turn arc where they must avoid entering the oncoming traffic lane (or the median curb).

Methods

Participants

The participants in this study were the same as those reported in the first paper in this series.[1] In brief, 12 participants with HH completed the study, including 6 with RHH and 6 with LHH. They were screened for the following criteria: (1) no more than 5° of residual vision on the hemianopic side of the vertical meridian within 30° above and below fixation, assessed with a Goldmann V4e target[8]; (2) no visual neglect (the bells test[9] and Schenkenberg line-bisection test[10]); (3) no significant cognitive decline (MiniMental State Examination,[11] [MMSE] $\geq$ 24); and (4) visual acuity of 20/40 or better in each eye, with habitual correction. Stroke was the main cause of the HH (Table 1). Despite the fact that drivers with HH do not meet the visual requirements for licensure in Massachusetts, six were current drivers (three RHH and three LHH). Four had stopped driving within the past 12 months, and two had stopped driving within the past 4 to 7 years. Two of the three noncurrent drivers in the LHH group had left hemiparesis, but were able to use the right (previously dominant) hand to control the steering wheel. None of the other participants with HH had any physical impairment that may have affected their ability to control the simulator. None of the participants had received any formal driving training after the onset of the HH.

A comparison group of 12 current drivers with NV were recruited who had demographic characteristics similar to those of the HH participants: matched by sex, age (within 3 years), and years of driving experience (within 5 years; Table 1). The NV drivers had visual acuity of 20/40 or better in each eye, full peripheral visual fields (Goldmann V4e target), and no central visual field deficits. None of the participants had experience using a driving simulator. With the exception of one HH driver and one NV driver, all participants had started driving at 18 years of age or younger. The study was conducted in accordance with the tenets of the Declaration of Helsinki and was approved by Institutional Review Boards at Schepens and the Boston VA Healthcare System.

Driving Simulator Hardware

The driving simulator has been detailed previously in several publications.[1,12] In brief, we used a PP1000-x5 simulator (FAAC Corp., Ann Arbor, MI), which had five 29-in. CRT monitors (1024 × 768 resolution at 60 Hz) providing a 225° horizontal by 32° vertical field of view. The simulator includes a motion platform with three axes of movement, a force-feedback steering wheel, gas, and brake pedals, and all the other controls usually found in a car with automatic transmission. Both auditory feedback (engine noise) and tactile feedback were provided (e.g., when contact was made with the curb in city drives or the shoulder of the road in rural drives, the steering wheel jerked, and the seat bumped up and down). Relative to other simulators tested by the authors, the steering has superior characteristics (the simulator was designed for training police officers for car chases). Software recorded usage of all vehicle controls, locations of the participant's vehicle, and all other scriptable entities in the virtual world at a 30-Hz sampling rate.

Drive Details

The participants drove a simulated BMW 325 virtual car in two driving simulator sessions,[1] each composed of six different drive routes: four on city roads (30 mph) and two on rural highways (60 mph). Rural drives were included to evaluate whether drivers with HH had greater difficulties with steering and lane position under more stressful conditions when driving at higher speeds. Each drive route included a variety of traffic situations and vehicle maneuvers, and was designed to be completed in 8 to 10 minutes. Prerecorded, spoken audio cues (e.g., turn left, turn right, and change to the left lane) were used to direct the driver along each route. Rural drives were on two-lane roads (one lane in each direction) with oncoming traffic and some long curves, but no turning or passing maneuvers. Rural roads had hard shoulders on the right edge of the road, but no curbs. City drives were on one-way streets, two- and four-lane roads, with turn maneuvers and oncoming and passing traffic. City roads always had curbs at the right edge of the road. While driving along each route, the participants performed a pedestrian detection task.[1] Lane position and steering were evaluated from simulator data for segments without pedestrian figures.

Table 1. Characteristics of the Participants

	HH (n = 12)	NV (n = 12)	Test for Difference between Groups
Current driver, n (%)	6 (50)	12 (100)	Fisher's exact test **P = 0.014**
Male, n (%)	9 (75)	9 (75)	N/A
Age in years, mean (SD),	50 (13)	51 (13)	t_{22} = 0.217
range	31–72	33–70	P = 0.830
MMSE score, mean (SD),	28 (1)	28 (2)	t_{22} = 0.273
range	26–30	25–30	P = 0.787
Binocular visual acuity,* mean,	20/19	20/14	t_{22} = 3.041
range	20/14–20/29	20/9–20/20	**P = 0.006**
Right hemianopia, n (%)	6 (50)	N/A	N/A
HH caused by stroke, n (%)	10 (83)	N/A	N/A
Median time since onset of HH, y (IQR)	3.5 (0.9–7.6)	N/A	N/A

* Visual acuity was measured and analyzed in logMAR units; logMAR values are converted to Snellen notation for ease of interpretation. Bold P values denote significant results.

Table 2. Details of the Scored Road Segments

Drive Type	Segment Type	Length (m) Median (Range)	Change in Direction (deg)	Number Analyzed
City, 30 mph	Straight road*	228 (164–231)	0	2 per drive, 16 total
	Left curve	24.0 (23.4–26.7)	45	1 per drive, 8 total
	Right curve	20.4 (17.0–20.7)	45	1 per drive, 8 total
	Left turn			
	3:3	20.5 (0)	90	7 or 8 total
	4:4	23.6 (0)	90	4 or 5 total
	Right turn	11.0 (0)	90	13 or 14 total
Rural, 60 mph	Straight road	229 (225–229)	0	2 per drive, 8 total
	Left curve†	202 (86–462)	30, 45, 60, 90, 135	3 or 4 per drive, 13 total
	Right curve†	194 (97–387)	30, 45, 60, 90, 120, 135	3 or 4 per drive, 12 total

* Straight road segment lengths varied slightly due to the necessity of avoiding sections with events that might affect steering.
† Due to the topography of the virtual world, rural curves varied greatly in length and change in direction.

Procedure

The two simulator sessions were conducted 1 week apart. The participants were acclimated to the simulator with introductory drives (mean, 19 minutes, SD 13) that included all the elements of the test drives.[1] They drove on the right side of the road and were instructed to drive the introductory and all subsequent drives in a manner that "resembled (their) actual driving behavior as much as possible," and "to obey all standard rules of the road." To reduce the likelihood of simulator discomfort, participants were advised to take left and right turns slowly. Steering around 90° turns (most turns in city drives) was also easier at slow speeds. Thus, turns may have been taken more slowly than in real-world driving, but this factor was consistent across drivers. The participants practiced driving on the highway and in the city until they felt confident in their ability to control the vehicle. At various points during the practice drives, the participants rated their vehicle control on a 10-point scale (1, very bad, to 10, excellent). These ratings, along with investigators' judgments of the participant's vehicle control, were used to determine when the participant was ready to start the test drives.

The participants then completed the six scripted test drives. The drive sequence was counterbalanced to control for order effects. The NV participants drove the same sequence of drives as the HH drivers to whom they were matched. Before each rural drive, the participants were reacclimated to controlling the vehicle at the higher speed by driving at highway speeds for approximately 5 minutes. They were advised to drive as close to the speed limit as they could while maintaining good control of the car. The time to complete the whole simulator session (acclimation and six test drives) ranged between 2 and 3 hours. The participants were encouraged to take breaks and step out of the simulator as needed between drives.

Scored Segments

Steering and lane position behaviors were evaluated separately for three types of predefined road segments (Table 2): straight road (city and rural), right and left curves (city and rural), and right and left turns (city only). Across the two driving simulator sessions, the average total distance of all the scored segments was 11,200 m (7 miles), approximately 15% of the total distance driven.

Both city and rural highway straight segments were approximately 230 m long. However, due to the topography of the virtual world, rural highway curves varied in length and change of direction, whereas city curves were shorter and more uniform (Table 2). Curves were analyzed for the complete length of the curve arc, from the first change in road direction to the point at which there was no further change in road direction.

Turns were present only in the city drives. Analyzed left turns all had a 90° change in direction and included two configurations: turning from and into a road with three travel lanes (3-to-3; Fig. 1a) and turning from and into a road with four travel lanes (4-to-4; Fig. 1b). The arc lengths were 20.5 and 23.6 m, respectively. Right turns all had the same geometry: a 90° change in direction with an arc length of 11 m (Fig. 1c). Turns were analyzed for the complete length of the turn arc.

Lane Position and Steering Measures

For straight segments and curves, the measures computed from the simulator data were[13,14] average lateral lane offset (LLO), variability (SD) of LLO, number of times out of lane, percentage of time out of lane, and steering wheel reversal rate. LLO provided a measure from which differences in lane position between drivers with NV and HH could be assessed, whereas variability of LLO provided a measure of steering stability (the higher the variability, the less stable the steering)

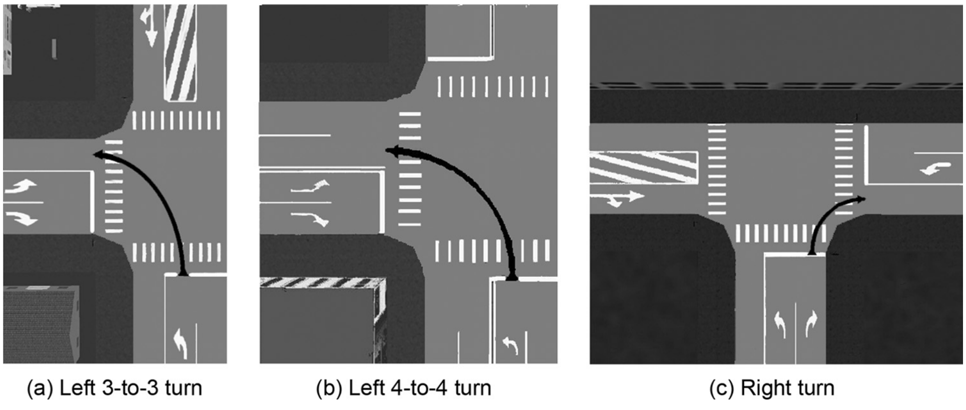

Figure 1. Examples of scored turn segments: (**a**) left 3-to-3 (**b**) left 4-to-4, and (**c**) right turn. The lane centers (ideal paths) for the turn segments were modeled as arcs of ellipses (*thick black line*). The start and end of the scored regions were the points of entry into and exit from the intersection (*arrowheads*).

and number of times out of lane and percentage of time out of lane provided measures relevant to driving safety. Steering wheel reversal rate provided a measure of how demanding the steering task was: higher reversal rates indicated greater steering effort or a more difficult steering task.[15,16] For turns, our primary interest was in examining differences in lane position between drivers with NV and HH; therefore, average LLO was the only measure computed.

LLO was determined with respect to the analytically modeled center of the driving lane (e.g., Fig. 1). Within each segment, average LLO was calculated by averaging the differences between the center of the front axle (derived from simulator data output) and the midpoint of the driving lane across all recorded front axle positions within that segment. The car width was 1.4 m and the travel lane width was 4.0 m. Positive LLOs represent positions to the right of the center of the lane and negative ones, to the left (in the direction of travel). Drivers were considered to be out of lane when the entire width of one tire crossed the lane marker by 5 cm. To prevent multiple false lane-boundary crossings due to the participant's driving essentially at the edge of the lane combined with micromotions of the steering wheel, we implemented a hysteresis algorithm that required that the tire return at least 5 cm back into the appropriate driving lane before the driver was considered to be back in the lane.

The number of times out of lane to the right and left was determined for the complete length of each scored straight and curved road segment. In the extremely rare situation when a driver was out of lane for the whole segment (only occurred for 0.4% of scored segments), it was counted as being out of lane once. The total number of times out of lane to the right and left was determined, and a binary coding of "rarely out of lane" (once or never) or "out of lane at least twice" was used for the analyses. In addition, the percentage of time out of lane was determined (total time out of lane as a percentage of the time taken to drive that segment).

Steering wheel reversal rate was the number of steering reversals per second within each segment. Based on an algorithm developed by Reed and Green,[17] we extracted discrete steering wheel motions (sections where the steering angle changes monotonically and the magnitude of the change is greater than 1°) from the raw data output and then counted the number of reversals (number of sections minus 1). Steering reversal rate was calculated as the total number of reversals divided by the time taken to drive the segment.

Lane Position in the Presence of Oncoming Traffic

The response of drivers to an oncoming vehicle was evaluated for two of the rural (two-lane undivided) highway straight segments. Both segments were from the same drive, and each had an oncoming vehicle in view for the whole segment. Segment 1 had an oncoming bus at a relatively long distance (median distance of closest approach 200 m) and segment 2 had an oncoming bus at a closer distance (median distance of closest approach 47 m). The other six rural straight segments were not included in this analysis, as five had no oncoming vehicle in view, and one had a more complex situation with two oncoming vehicles (one on the main road and one from a side road). Scoring within each segment started when the oncoming vehicles were within 457 m (1500 ft) of the participant vehicle. Within this scoring window, the points of minimum and maximum distance of the participant car from the oncoming vehicle were determined. The LLO shift was defined as the difference in LLO of the participant's car between these two points (LLO at minimum distance subtracted from LLO at maximum distance; positive values indicate a rightward shift in lane position).

Statistical Analyses

Before conducting the main analyses, we evaluated whether there were any between-session learning effects and any differences between drivers with RHH and LHH for each of the steering and lane position measures. There were no significant between-session effects, and the only measures for which there were differences between drivers with RHH and LHH were average LLO and number of lane boundary crossings. In subsequent analyses, the data were pooled across the two sessions and a two-way vision status variable (NV and HH) was used for all measures except LLO and number of times out of lane, when a three-way variable (NV, RHH, LHH) was used. As hemiparesis could affect steering and lane position, all analyses were conducted both with and without the data for the two participants with this condition.

For straight segments and curves, average LLO, variability of LLO, and steering reversal rates conformed reasonably well to normal distributions and were analyzed by using parametric statistics. Repeated-measures ANOVAs were performed, with segment type (straight, right curve, or left curve) and drive type (city or rural highway) as the within-subject factors and vision status as the between-subjects factor. Given the wide range of ages in the sample, age was included as a covariate in the ANOVAs.[18,19] For turns, the average LLOs were not normally distributed; therefore, differences in LLO between the drivers with NV and LHH and drivers with NV and RHH, were evaluated using the Mann-Whitney test.

Results

Because of the possible effect of motor impairments on LLO, we considered excluding the two participants with left hemiparesis. However, including their data had a relatively minor impact on the main lane position and steering measures. Furthermore, the main effects of the ANOVAs were similar with and without the data from these two participants. As hemiparesis frequently coexists with HH, we therefore report results for analyses that included data from the participants with hemiparesis. Age was included as a covariate in the ANOVAs. However, the only measure significantly affected by age was variability of LLO (Table 3); younger drivers with NV had more variable LLO than did older drivers with NV.

Steering and Lane Position on Straight Segments and Curves

Vision status significantly affected LLO (Table 3). Specifically, drivers with RHH had an overall LLO significantly to the left of both drivers with NV and LHH (by approximately 0.39 m in city driving and 0.32 m in rural driving, averaged across all nonturn segments), whereas the LHH drivers had an overall LLO similar to that of the NV drivers (Fig. 2). There was also a highly significant effect of segment type on LLO (Table 3) with more leftward lane positions on left curves and more rightward on right curves (Fig. 2). The direction of a curve (into the blind or seeing field) modified the extent of the curve-cutting behaviors in the drivers with HH. In particular, on right curves, the drivers with RHH did not take as much of a rightward path as did the drivers with NV. All the drivers (NV and HH) held a more rightward lane position in rural than city driving (by approximately 0.26 m averaged across all the drivers and nonturn segments; Fig. 2; Table 3).

The overall LLO variability of the drivers with HH was greater than that of those with NV in both city and rural driving, especially on rural straight segments (Fig. 3; Table 3). However, there was no effect of vision status on steering wheel reversal rates (Table 3). All the drivers had higher reversal rates in rural than in city driving: (mean [SD]) reversals per second rural, 0.64 (0.16); city, 0.50 (0.14), with a greater increase in the reversal rates for the curves than for the straight road segments.

To evaluate the possible impact of LLO biases and LLO variability on driving safety, we determined the number of times that the drivers were out of the travel lane and the percentage of time out of lane during scored segments. The

TABLE 3. Summary of ANOVAs for Each Measure for Straight Segments and Curves

	Main Effects				Interactions		
	Vision Status*	**Segment (Straight, R Curve, L Curve)**	**Drive Type (City or Rural)**	**Age (Covariate)**	**Segment by Vision**	**Drive Type by Vision**	**Segment by Drive Type**
LLO	$F_{2,20}$ = 5.133, ***P* = 0.016**	$F_{2,40}$ = 73.74, ***P* < 0.001**	$F_{1,20}$ = 102.05, ***P* < 0.001**	$F_{1,20}$ = 0.083, *P* = 0.777	$F_{4,40}$ = 2.71, ***P* = 0.043**	$F_{2,20}$ = 0.666, *P* = 0.525	$F_{2,40}$ = 14.794, ***P* < 0.001**
LLO variability	$F_{1,21}$ = 10.686, ***P* = 0.004**	$F_{2,42}$ = 20.555, ***P* < 0.001**	$F_{1,21}$ = 106.750, ***P* < 0.001**	$F_{1,21}$ = 5.111, ***P* = 0.035**	$F_{2,42}$ = 1.546, *P* = 0.225	$F_{1,21}$ = 5.477, ***P* = 0.029**	$F_{2,42}$ = 12.935, ***P* < 0.001**
Steering reversal rate	$F_{1,21}$ = 1.555, *P* = 0.226	$F_{2,42}$ = 2.945, *P* = 0.064	$F_{1,21}$ = 49.368, ***P* < 0.001**	$F_{1,21}$ = 1.064, *P* = 0.314	$F_{2,42}$ = 0.662, *P* = 0.521	$F_{1,21}$ = 5.396, ***P* = 0.030**	$F_{2,42}$ = 12.488, ***P* < 0.001**

* Three-way vision status grouping for LLO (NV, RHH, and LHH); two-way for LLO variability and steering reversal rate (NV, HH).

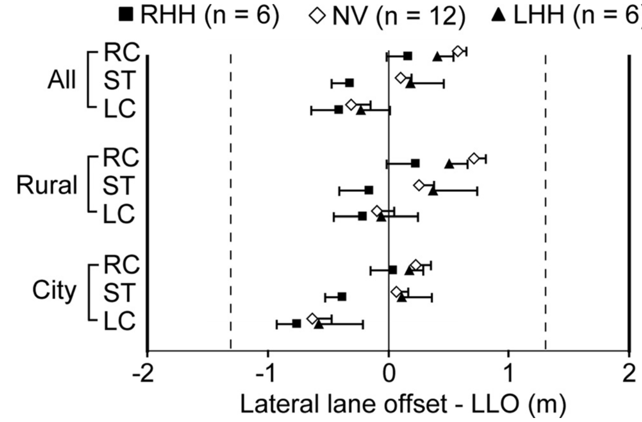

FIGURE 2. Average LLO for HH and NV drivers for left curves (LC), straight segments (ST), and right curves (RC) in city and rural driving. For each vision group, the pattern of LLOs across the segment types was in keeping with our predictions (Table 4). In particular, the LLO of drivers with RHH was to the left of drivers with NV and LHH (especially on straight segments and right curves). *Heavy solid vertical lines* mark the lane boundary. *Dashed vertical lines*: LLO at which the tires of the vehicle would first be out of lane. ALL, data pooled across city and rural drives for each segment type. Error bars, 95% confidence limits of the mean (shown in one direction only for clarity).

results reported here are for data pooled across city and rural highway drives. Compared to the drivers with NV, a greater proportion of those with RHH were out of lane to the left on straight road segments (*P* = 0.03; Fig. 4), whereas a greater proportion of those with LHH were out of lane to the right on straight segments and left curves (*P* = 0.01; Fig. 4). Almost all drivers with NV and LHH were out to the right in right curves compared with only 50% of the drivers with RHH (Fig. 4, *P* = 0.03). For segments when the drivers were out of lane, the median percentage of time out of lane on straight segments was 17% for the drivers with RHH and 11% for those with LHH. All the drivers spent a greater percentage of time out of lane on left curves (medians: NV 32%, LHH 29%, RHH 37%) than on right curves (medians: NV 15%, LHH 17%, RHH 16%).

Effect of Driving Status: Currently or No Longer Driving

Variability of LLO was the only measure for which there was a significant effect of driving status. Specifically, in city (but not highway) drives, the noncurrent drivers with HH had more variable lane position than the current drivers with HH: mean (SD) noncurrent 0.24 m (0.03); current 0.18 m (0.04), t_{10} = 3.04, *P* = 0.012. This difference was still significant (*P* = 0.05) when data for the two drivers with hemiparesis were excluded.

Lane Position on Turns

Car path plots (e.g., Fig. 5) for each scored turn revealed two notable differences between the drivers with HH and NV. The drivers with LHH consistently took a wider path (more to the right) on left 4-to-4 turns, whereas those with RHH tended to take a tighter path (more to the right) on right turns. These differences were confirmed in the average LLOs for data pooled across all turns of each type. Specifically, on left 4-to-4 turns, the drivers with LHH took a path that was on average 1.18 m more rightward (wider) than that of the drivers with NV (Z_{18} = 2.81, *P* = 0.005), whereas on right turns, the drivers with RHH took a path that was on average 0.17 m more rightward (tighter) than that of the drivers with NV (Z_{18} = 1.97, *P* = 0.049). On left 3-to-3 turns there were no significant

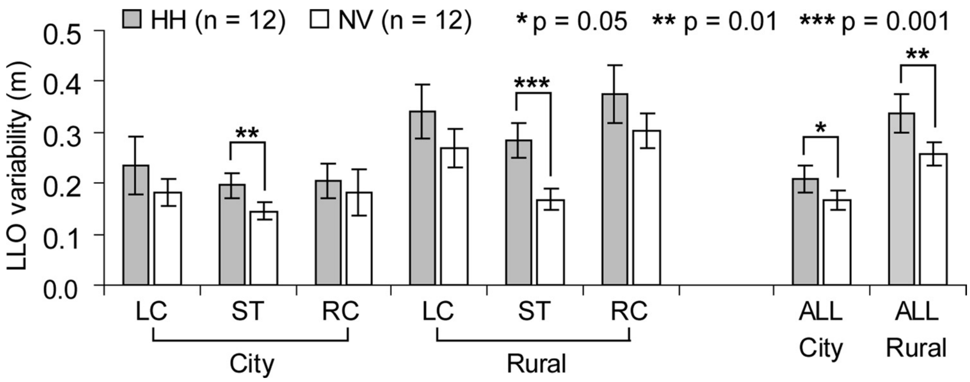

FIGURE 3. Variability of LLO for the HH and NV drivers on city and rural road segments. Variability of LLO was greater in the HH than in the NV drivers, especially in rural driving. LC, left curves; ST, straight segments; RC, right curves. Error bars, 95% confidence limits of the mean.

differences in average LLOs between the drivers with NV and the drivers with LHH or RHH, although there was a trend for the drivers with LHH to take a more rightward (wider) path than those with NV.

Lane Position in the Presence of Oncoming Traffic on Rural Highways

The drivers with NV had a more rightward LLO (further from the center line) in the presence of oncoming traffic on rural highways. The magnitude of this shift depended on the distance of the approaching vehicle, being approximately 0.40 m greater in the segment where the approaching vehicle was relatively close than in the segment where the approaching vehicle was at a greater distance (Fig. 6). By comparison, there was virtually no change in LLO for segments without oncoming traffic (Fig. 6; no oncoming). The drivers with LHH also showed this same tendency to move to the right in the presence of close oncoming traffic. By comparison, those with RHH did not shift to the right, even when the oncoming vehicle was close.

DISCUSSION

Despite a relatively small sample size, we were able to measure significant differences in lane position between drivers with NV and those with HH that provided support for our blind-side safety-margin hypothesis. The effects varied with road segment type, emphasizing the importance of evaluating lane position and steering for straight road segments, right and left curves, and right and left turns separately (especially when investigating a population with a lateralized field loss). Our predictions and the corresponding outcomes are summarized in Table 4.

In agreement with our main hypothesis, the drivers with RHH held a more leftward lane position (away from the blind side) than did the drivers with NV, who held a relatively central lane position (averaged across all drives and nonturn segments). This difference was particularly apparent on straight road segments. By taking a more leftward lane position, the drivers with RHH provided an apparent safety margin on the blind right side, but increased the danger of crossing into a traffic lane on the left (they were driving on the right on undivided roads). Presumably, the perceived threat was greater from objects on the blind right side than from objects on the seeing left side. This finding is further emphasized by the lack of rightward shift for the RHH group in the presence of oncoming traffic on the undivided highway.

Conversely, most drivers with LHH did not take up a lane position farther away from the blind left side than that taken by the drivers with NV. Given that the greatest threat to the LHH group would be from traffic in neighboring lanes on the blind left side, their behavior may appear inconsistent with that of the drivers with RHH. However, it is important to note that in both city and rural drives, the average lane position of the participants with LHH was to the right of the lane center (by 0.11 m on city drives and 0.37 m on rural highways). Drivers with NV took a similar rightward lane position, and thus no difference was found between these two groups. Furthermore, the entire LHH group shifted to the right (toward the edge of the road by 0.74 m) in the presence of oncoming traffic on the undivided rural highway. All the drivers with NV also moved to the right by approximately 0.50 m (on average) in response to oncoming traffic, similar in magnitude to the rightward shift in an on-road study.[20] This result strongly suggests that the oncoming traffic was perceived as a threat and the response was commensurate with the corresponding risk in the real world.

All the drivers with NV cut curves as expected. However, the curve-cutting behavior of the drivers with HH was modified to provide a safety margin when the curve opened into the

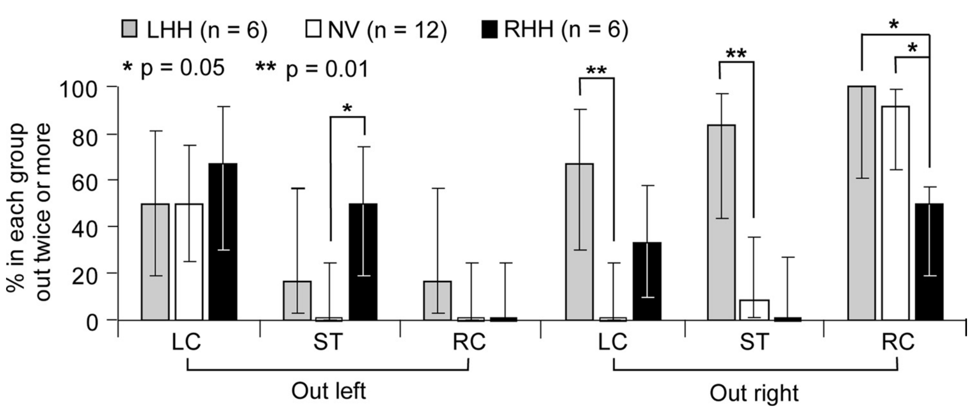

FIGURE 4. Proportion of drivers out of lane twice or more on left curves (LC), straight segments (ST), and right curves (RC). Compared with the drivers with NV, a greater proportion of those with RHH were out of lane to the left on straight road segments, whereas a greater proportion of those with LHH were out of lane to the right on straight segments and left curves. Data are pooled across city and rural highway drives. Error bars, 95% confidence limits.

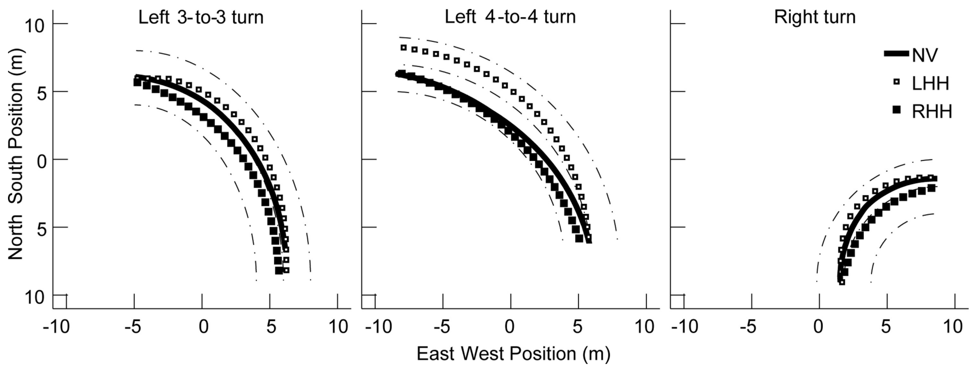

FIGURE 5. Typical car paths on each type of turn for drivers with NV, LHH, or RHH (median data are shown for three specific turns). On left turns, the drivers with LHH took a more rightward (wider) path than did those with NV or RHH. On the right turn, the drivers with RHH took a more rightward (tighter) path than did those with NV and LHH. *Dashed lines*: the lane center (ideal path; Fig. 1) and lane boundaries. The direction of travel is from the bottom of the figure up.

blind hemifield. This result is particularly noticeable on rural highway curves for drivers with RHH. On right curves, which opened into the blind hemifield, they cut the curve to a lesser extent than the drivers with NV (i.e., took a more leftward path providing a safety margin on their blind right side). By comparison, on left curves that opened into their seeing left field, they took a path more similar to that of the drivers with NV.

In agreement with our predictions, on right turns, the drivers with RHH took a significantly more rightward path than did the drivers with NV (bringing the risk zone of the oncoming traffic or the lane boundary more quickly from the blind right field into the left seeing field), whereas the drivers with LHH took a path similar to that of the drivers with NV (keeping the risk zone in the seeing right field for as long as possible; Fig. 5). On left turns, the drivers with RHH took a path similar to that of the drivers with NV (the risk zone was in their seeing left field for the whole turn), but the drivers with LHH took a more rightward path than did the drivers with NV, especially on left 4-to-4 turns, where there was a lane available to the right of the travel lane. This result is consistent with providing a safety margin on the blind left side, especially at the end of the turn arc when the driver must avoid entering the oncoming traffic lane on the blind side.

In terms of steering control, the HH drivers had more variable lane position than did the NV drivers, but steering wheel reversal rates were similar. This observation suggests that the steering of the drivers with HH was less stable than that of the NV drivers, but that the overall steering effort was similar. As expected, steering reversal rates of both the HH and NV drivers increased in response to greater steering demands (driving at high speed and on curves).[15] Although the overall difference in lateral lane position variability between the drivers with HH and those with NV vision appears relatively small in magnitude (average across all segments: 0.27 and 0.20 m, respectively), the greater variability combined with tendencies to hold a position away from the center of the lane, resulted in the drivers with HH being out of lane more often than the drivers with NV. Consistent with our safety margin hypothesis, a *greater* proportion of the drivers with RHH were out of lane to the *left* on straight segments but a *lower* proportion were out of lane to the *right* on right curves, whereas a greater proportion of the drivers with LHH were out of lane to the right on straight segments. As the oncoming traffic lane (or passing traffic lane) was on the left, it is lane boundary crossings to the left that may be considered more crucial. Similarly, a simulator study[4] and on-road studies[2,3] have reported more variable lane position and more lane boundary crossings for HH than for NV drivers.

Despite the wide age range, we found no effect of age on lane position or steering measures for the drivers with HH and only a small effect of age on lane position variability for the drivers with NV. This result is in stark contrast to the strong correlation between age and blind-side detection rate reported in our previous paper[1] (blind-side detection rates decreased as age increased). Taken together, these results suggest that age had little impact on adaptation to HH in overly learned tasks such as steering and lane position control, but that the older drivers compensated less well than the younger in a task that required active scanning to the blind side.

Although no simulator can fully replicate the force feedback experienced when driving a real car, the steering of our simulator did provide force feedback that varied with vehicle speed. Furthermore, the steering characteristics were found to be more realistic than those of other simulators tested by the authors. Any steering limitations would have affected all the drivers equally. Our primary interest was in *relative* differences in lane position and steering between the drivers with NV and HH rather than absolute values. In a few studies, lane position and steering of NV drivers has been compared on the road and in a simulator. The findings with respect to absolute lane position varied. In one study,[17] the drivers tended to take a lane position closer to the edge of the road in real life than in the simulator, whereas in another, the opposite was reported.[21] Although *absolute* lane position may vary between simulator and

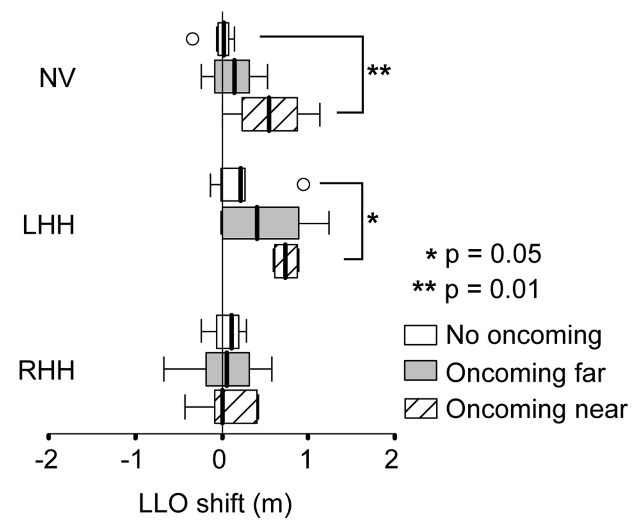

FIGURE 6. LLO shift in response to an oncoming vehicle on two-lane undivided rural highway straight segments (oncoming vehicle in left lane, participant vehicle in right lane). The drivers with NV or LHH showed a rightward shift in the presence of oncoming traffic (especially when the vehicle was near), whereas drivers with RHH showed no shift. "No oncoming" is the difference in LLO between the start and end of rural highway straight segments without oncoming traffic (shown for comparison). The *thick vertical line* within the box is the median; the horizontal extent of the box is the interquartile range (IQR); *lines* at box ends represent the largest nonoutlier data points within 1.5× IQR; *circles* are outliers (1.5×–3×, IQR).

Table 4. Summary of Predictions and Outcomes for Lateral Lane Position of Drivers with LHH or RHH Compared with NV Drivers

	Prediction	Outcome
Straight segments		
LHH	Right of NV	Similar/slightly right of NV (NS)*
		But both NV and LHH to right of lane center, especially on rural drives
		Higher percentage of LHH out of lane to the right ($P = 0.01$)†
RHH	Left of NV	Left of NV ($P = 0.001$)
		Higher percentage of RHH out of lane to the left ($P = 0.03$)
Left curve		
LHH	Right of NV	Similar/slightly right of NV (NS)
		Higher percentage out of lane to the right ($P = 0.01$)
RHH	Similar to NV	Similar/slightly left of NV (NS)
Right curve		
LHH	Similar to NV	Similar/slightly left of NV (NS)
RHH	Left of NV	Left of NV ($P < 0.001$)
		Lower percentage out of lane to the right ($P = 0.03$)
Left turn		
LHH	Right of NV	3-to-3 Similar/slightly right of NV (NS)
		4-to-4 Right of NV ($P = 0.005$)
RHH	Similar to NV	3-to-3 Similar/slightly left of NV (NS)
		4-to-4 Similar/slightly left of NV (NS)
Right turn		
LHH	Similar to NV	Similar/slightly left of NV (NS)
RHH	Right of NV	Right of NV ($P = 0.05$)

* NS, not significantly different from drivers with NV ($P > 0.05$).
† P values for straight segments and curves are for data averaged across rural and city drives.

on-road driving, *relative* differences in response to changes in road curvature, differences in driving experience, or engaging in secondary tasks, are replicated.[5,17,21] We would therefore expect that the relative differences in lateral lane position that we found between the vision groups in the simulator would also hold true for on-road driving. For example, we would predict that drivers with RHH would generally have a more leftward lane position than drivers with NV. However, that prediction is at odds with the observations from the on-road study by Tant et al.,[2] in which 4 of 13 drivers with RHH were noted to drive too close to the right side of the road. As lateral lane position was not measured by Tant et al.,[2] biases in lateral lane position that could be measured in the simulator may not have been observed by the driving examiner. Our findings relate to driving on the right side of the road. For driving on the left, we would simply expect a reversal of the roles and results between drivers with RHH and LHH.

On the basis of the steering and lane position data, most of the participants with HH in this study may appear fit to drive; however, as reported in our previous paper, most had detection rates for pedestrians on the blind side that were so low as to seem incompatible with safe driving.[1] Whereas problems with steering, such as incursions into the next travel lane, are easily detected in an on-road test, problems with detection are noted only when a detection failure puts the driver or other road-users at risk (the number of detection failures in nonrisky situations will never be known to the experimenter/evaluator). Hence, although the results of recent on-road studies[2,3] may suggest that problems with steering and lane position are the most common reasons for drivers with HH failing on-road tests, our driving simulator evaluation suggests that detection may be more of a problem than steering control.

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