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On-Road Driving with Moderate Visual Field Loss

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ABSTRACT: *Purpose:* We examined the relationship between visual field extent and driving performance in an open, on-road environment using a detailed scoring method that assessed the quality of specific skills for a range of maneuvers. The purpose was to determine which maneuvers and skills should be included in future, larger scale investigations of the effect of peripheral field loss on driving performance. *Methods:* Twenty-eight current drivers (67 ± 14 years) with restricted peripheral visual fields participated. Binocular visual field extent was quantified using Goldmann perimetry (V4e target). The useful field of view (UFOV®) and Pelli-Robson letter contrast sensitivity tests were administered. Driving performance was assessed along a 14-mile route on roads in the city of Birmingham, Alabama. The course included a representative variety of general driving maneuvers, as well as maneuvers expected to be difficult for people with restricted fields. *Results:* Drivers with more restricted horizontal and vertical binocular field extents showed significantly ($p \leq 0.05$) poorer skills in speed matching when changing lanes, in maintaining lane position and keeping to the path of the curve when driving around curves, and received significantly ($p \leq 0.05$) poorer ratings for anticipatory skills. Deficits in UFOV performance and poorer contrast sensitivity scores were significantly ($p \leq 0.05$) correlated with overall driving performance as well as specific maneuver/skill combinations. *Conclusions:* In a small sample of drivers, mild to moderate peripheral visual field restrictions were adversely associated with specific driving skills involved in maneuvers for which a wide field of vision is likely to be important (however most were regarded as safe drivers). Further studies using similar assessment methods with drivers with more restricted fields are necessary to determine the minimum field extent for safe driving. (Optom Vis Sci 2005;82:657–667)

Key Words: driving assessment, visual field, glaucoma, low vision, vision impairment, vision rehabilitation

Although it might be obvious that a person with severe visual field restriction could not drive safely, it is far less clear what minimum size of the visual field would be consistent with safe driving. In the U.S., there is wide variability between states in the visual field requirements for driver licensing; only 31 jurisdictions have a minimum binocular horizontal field extent, ranging from 20° to 150°.[1] Studies of driving with vision impairment typically focus on driver safety or driver performance.[2] Safety is usually defined in terms of adverse driving events such as crash involvement or moving violations,[3–9] and is expressed statistically, such as an odds or risk ratio where one group of drivers is compared to another group with respect to the occurrence of adverse events. Because crashes are rare events, very large samples of drivers (at least hundreds) are needed to address questions about safety, i.e., what aspects of visual impairment elevate crash risk? Although Johnson and Keltner[5] found a doubling of crashes and traffic violations in people with severe binocular visual field loss, other studies have found no significant association between crash rate and visual field deficits.[3,4,6–8]

The study of driving performance is more amenable to smaller sample studies. Performance is usually defined in terms of the accuracy or latency of a driving maneuver or control input, or exhibiting certain behaviors according to some graded assessment scale. Performance can be evaluated on-road in a open or closed course by assessing whether the driver passed or failed the test by some criteria,[10] by more detailed scoring of skills for a range of maneuvers,[11–14] or through the use of an instrumented vehicle where maneuvers and control inputs are recorded in real-time.[15] Using simulations of restricted peripheral visual fields, Wood et al.[11,16–18] evaluated a number of driving skills on a closed-road course. In the first study,[11] the simulated visual field impairment was severe (40° or 20° horizontal diameter) and awareness of peripheral objects, obstacle avoidance, reversing accuracy, and lane position (especially at corners) were all significantly affected; however, speed estimation and stopping distance (in response to an object thrown across the road) were not affected. In a second set of studies[16–18] with moderate simulated field loss (about 90° horizontal diameter), peripheral awareness of objects was the only skill from the original set of skills that was affected.

An alternative to using an on-road course is to assess driving skills within the controlled environment of a driving simulator. Coeckelbergh et al.[19] reported that drivers with moderate peripheral visual field loss (mean horizontal field diameter 84° ± 35°) had increased lane position variability and made a greater number of lane boundary crossings than drivers with central visual field defects or mild visual field defects affecting the paracentral or midperipheral areas. Whereas, for drivers with mild to moderate field loss (mean horizontal field diameter 130° ± 21), Szylk et al.[20] found no difference in driving performance when compared to that of normally sighted controls. Simulator studies[19–21] of driving with peripheral visual field loss have primarily reported global measures of driving skills for the whole drive, and have not provided any, or only limited analysis, of skills for specific maneuvers.

In studying the role of vision impairment in driving performance, research using either simulated visual impairment, an on-road closed course, or driving within a virtual environment (no matter how well designed), does not constitute the real-world conditions of on-road driving. Studying functionally impaired drivers in on-road situations always presents safety concerns, and there is little control over external factors such as unexpected events and traffic density. Thus, it is not surprising that there are only limited data on the relationship between visual field extent and driving skills in an open-road driving situation.

Here we describe a study on the relationship between visual field extent and driving skills in an open, on-road environment. A detailed scoring method[22] was employed that assessed the quality of specific skills and maneuvers that were *a priori* expected to be negatively impacted by peripheral field loss (e.g., lane position and path keeping during curve taking or gap judgment when merging or changing lanes), as well as skills and maneuvers that we expected would not be affected by peripheral field loss (e.g., stopping distance at an intersection or speed appropriateness on a straight road segment). The purpose was to determine which maneuvers and skills should be included in future, larger scale investigations of the effect of peripheral field loss on driving performance.

In addition, we also investigated the relationship between driving skills and other measures likely to be related to driving performance,[23,24] namely useful field of view (UFOV)[25] and contrast sensitivity. Deficits in the UFOV task, which relies on rapid visual processing speed and higher-order processing skills (selective and divided attention), have been linked to driving and mobility problems and slowing in visual task performance;[8,18,26–31] reduced contrast sensitivity has also been linked to driving and mobility difficulties.[18,20,28,31–35]

METHODS

Subjects

The recruitment population consisted of patients (ages ≥ 18 years) seen in ophthalmology clinics, affiliated to the University of Alabama at Birmingham (UAB), in the Callahan Eye Foundation Hospital over the previous 12-month period who had conditions that could cause peripheral visual field loss (e.g., glaucoma, retinitis pigmentosa). A contact letter was sent from the referring physician describing the study, which was followed by a telephone call to determine if the patient was interested in participating. If so, the study coordinator set up an appointment after a telephone interview confirming that the person held a current driver's license in Alabama and still drove. The goal was to recruit at least 25 subjects. The Institutional Review Boards of UAB and Schepens Eye Research Institute approved the study.

Procedures

The study visit took place in the Driving Assessment Clinic at UAB. Before enrollment, each participant signed a document of informed consent after the nature and purpose of the study were explained. The visit lasted approximately 2 to 3 hours. The protocol consisted of two parts, in-clinic functional assessments/interviews and an on-road evaluation of driving performance. All testing was carried out by a certified driving rehabilitation specialist (CDRS) who is also a licensed occupational therapist (OTR/L). A second evaluator participated in the on-road evaluation, as described later.

Vision Measures

Visual acuity for distance was measured monocularly and binocularly with habitual (walk-in) correction, since we were interested in the participant's vision while using the correction worn for distance tasks such as driving. Testing was carried out using the Early Treatment for Diabetic Retinopathy Study chart[36] and its standard protocol, and expressed as logarithm of the minimum angle of resolution (logMAR). Contrast sensitivity, measured monocularly using the Pelli-Robson chart and its standard protocol,[37] was scored with the letter-by-letter scoring method, and expressed as log sensitivity.[38]

The extent of the visual field in each eye was assessed with the Goldmann perimeter. Worldwide there is no consensus as to which Goldmann target should be used to assess the functional visual field for driver licensing: the III4e target is recommended in the United Kingdom[39] and some states of the U.S. (e.g., Kentucky[1]), while the IV4e target is used in Australia.[40] As driving primarily involves detection of large objects, we used the largest available target, the V4e stimulus. The outer boundaries of the peripheral field were plotted using a kinetic strategy, moving from peripheral areas of non-seeing to seeing, along each of the main meridians (0°, 15°, 30°, 45° through 345°) in random order. The integrity of the seeing field was checked by static testing (off/on presentation) at 28 locations within the 10° above and below the horizontal midline (the area of the field most likely to be used when viewing through the windshield; Fig. 1). The monocular field plots were superimposed in order to derive the extent of the binocular field. Three binocular field scores were determined: the horizontal extent along the 0°–180° meridian (maximum extent 180°), normally used when specifying the field extent for driver licensing; the vertical extent along the 90° – 270° meridian (maximum extent about 130°); and a measure of the overall field extent, the sum of

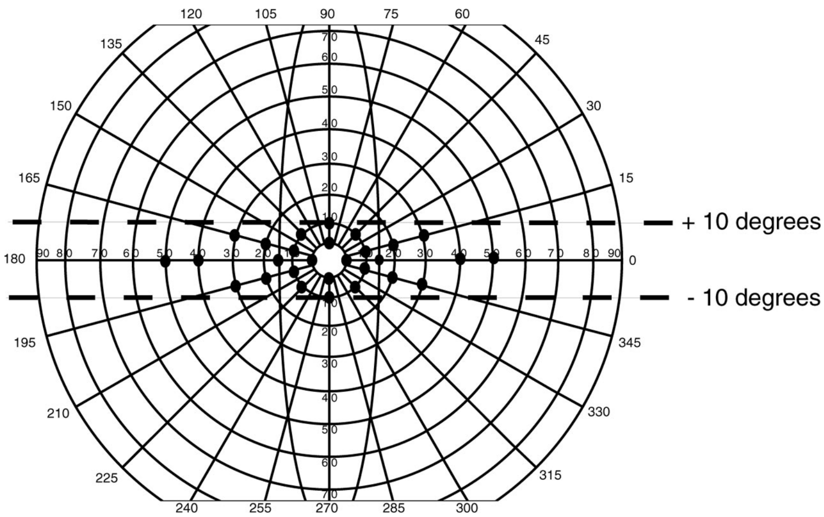

FIGURE 1.

The 28 locations (within the 10° above and below the horizontal midline) evaluated with static testing as part of the visual fields assessment using Goldmann perimetry with the V4e stimulus.

the extents along 12 meridians 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300° and 330° (maximum extent about 970°).

Useful Field of View

The useful field of view test (UFOV®; Visual Awareness, Inc.)[25] was administered to provide a measure of the speed with which participants could rapidly process stimuli under divided attention conditions. In three increasingly complex subtests, central, peripheral, and distractor stimuli were presented as white targets (2 × 1.5 cm) against a black background on a touch-driven 17-inch monitor. Participants viewed the monitor binocularly at a distance of 60 cm. Each trial consisted of four consecutive display screens: a fixation box, a test stimulus, a full-field, white-noise visual mask, and a response screen. The white-noise visual mask was presented following the stimuli in order to control display phosphor persistence[41] and eliminate afterimages or visual persistence. In the first subtest, which addressed speed of processing, the participant was asked to identify a central target (car or truck) presented in the fixation box. In the second subtest, addressing divided attention, the participant identified the central target, while also localizing a simultaneously presented peripheral target (car).

The third test, addressing selective attention, also demanded simultaneous identification of the central target and localization of the peripheral target. However, the peripheral target was embedded among distractors, making the task more difficult. Peripheral targets were presented 11 cm (10.5°) from the fixation box at one of eight radial locations (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). Distractor stimuli were triangles of the same size and luminance as the peripheral target and uniformly filled the spaces between target locations. For each subtest, the duration of the display presentation was varied between 16 and 500 ms using a double staircase method in order to determine a threshold of 75%. Three scores were derived indicating the display time in milliseconds at which participants could correctly perform each subtest 75% of the time. The scores for each subtest can range from 16 to 500 ms.

Questionnaires

General health was assessed with a questionnaire used extensively in our prior work[30,42] that asks participants whether they had problems in 17 areas (e.g., heart disease, cancer, diabetes mellitus) and then a summary measure of general health was created by summing the number of chronic conditions reports. Cognitive status was evaluated using the Mini-Mental Status Examination (MMSE).[43]

The Driving Habits Questionnaire (DHQ)[44] was administered to provide information about driving experiences during the previous three months. Questions address several domains including current driving status, driving exposure (e.g., miles per week, days/week), dependence on other drivers, driving difficulty, and driving space. The DHQ has established construct validity and test-retest reliability,[44] and previous research has also demonstrated that adults can validly report their driving exposure.[45] The questionnaires and MMSE were interviewer-administered.

On-Road Driving Performance

Following completion of the in-clinic functional assessment, the on-road evaluation was carried out. The clinic vehicle consisted of a 1998 Chevrolet Lumina equipped with a passenger side brake. There were two evaluators: the CDRS in the front passenger seat, with a second trained evaluator in the back seat of the vehicle. Their evaluation tasks are described below. Driving assessments were conducted between 10.00am and 3.30pm to avoid peak hour traffic conditions. Assessments took place in both sunny and cloudy weather conditions, but not when it was raining, snowing or foggy.

The on-road driving course and scoring methods were based on a design developed specifically for implementation in a number of related studies in which drivers with a range of different vision impairments (including hemianopia, restricted peripheral fields and central field loss) were to be assessed driving either with or without optical vision devices.[22] The course included a representative variety of general driving maneuvers, as well as maneuvers expected to be difficult for people with vision impairment. The total length of the course was 14 miles on roads in Birmingham, AL. All subjects drove the same course.

The course was divided into two sections: a preliminary off-road section, followed by an on-road section. In the preliminary section, vehicle control skills were evaluated in a parking lot to ensure that the participant had adequate vehicle control before proceeding to on-road driving; this section also provided the participant with an opportunity to become familiar with the car. The on-road section started on low-traffic roads and then proceeded to busier roads and interstate driving. The route comprised a variety of road types (two- and four-lane roads, interstate), intersections (with and without traffic lights, stop and yield signs), and sections with curbed and uncurbed edges, straight sections and curves. At predetermined points along the route performance of specific maneuvers (e.g., turn, merge) was scored with respect to itemized driving skills (e.g., lane position, gap judgment), as listed in Table 1. The back-seat evaluator, masked to functional, medical, and driving exposure characteristics of the participant driver, carried out this scoring on a five-point scale, using a separate score sheet for each maneuver. Scores of 1 to 3 represented various levels of unsatisfactory performance, while 4 and 5 represented increasing levels of satisfactory performance: 1, driving evaluator had to take control of car; 2, skill performed in an unsafe manner (but evaluator did not have to take control); 3 skill performed in an unsatisfactory manner (but did not compromise safety); 4, skill performed in a satisfactory manner; 5, skill performed in a flawless manner.

Global driving performance for the entire drive was assessed at the end of the on-road test by both the front-seat CDRS and the back-seat evaluator. Ratings were made on a 5 point scale (as above) on the following items: interaction with other traffic, anticipatory skills (margin of error), vehicle control, reaction to unexpected events, adjustment of speed to traffic conditions, and overall driving. Global driving was also assessed for interstate driving in terms of the first four items; since the CDRS was focused on safe control of the vehicle during interstate travel at high speeds, these ratings were made only by the back-seat evaluator.

Statistical Analysis

For driving maneuvers that were assessed more than once (Table 1), the mean score for each driving skill was computed and used in correlation analyses. For measures of global driving performance rated by the two evaluators, the mean score of the two raters was used. The three UFOV scores did not conform to a normal distribution; visual field extent data and contrast sensitivity scores were normally distributed. Spearman correlation coefficients and associated tests of significance were calculated between ratings of driving performance (driving skills for each maneuver and global scores) and the three binocular Goldman visual field extent measures, the three UFOV scores and contrast sensitivity scores (better eye and worse eye). Partial correlation coefficients adjusting for the potential confounding factors of age and cognitive status score were also calculated. Inter-rater reliability for global ratings of driving performance, given by the front-seat CDRS and the back-seat

TABLE 1.
Summary of specific maneuvers and driving skills scored along the route of the on-road driving assessment. (Skills scored for each maneuver are indicated by an "x").

Maneuvers		Driving skills scored on 5-point scale for each maneuver							
Description	Number	Lane position[a]	Gap judgment[b]	Path keeping[c]	Steering steadiness	Speed appropriate[d]	Speed match[e]	Spacing[f]	Stop position[g]
Turning at intersection	3 left 3 right	x Pre & Post	x	x		x			x
Merging	3	x Pre & Post	x				x		
Changing lanes	3 left 3 right	x Pre & Post	x		x		x		
Crossing intersection	3	x Pre & Post			x	x			x
Straight road (Lane control)	1 (Highway)	x During			x	x		x	
Curve taking	2 right 2 left	x During		x	x	x		x	
Interstate exiting	1	x Pre & Post					x		

[a] Pre = lane position before maneuver begins; Post = lane position after maneuver completed; During = lane position during maneuver
[b] Judgment of gap or distance between the test vehicle and vehicles from one or both sides when crossing or moving into their lane
[c] Curve of the path taken during a maneuver that involves going around a curve
[d] Whether speed is appropriate for the maneuver
[e] Whether speed is adjusted or matched to the speed of traffic in the new lane
[f] Following distance
[g] Stop position relative to end of lane at intersection

evaluator, was analyzed using weighted kappa coefficient. Kappa values of 0.7 to 0.8 were considered acceptable agreement; the weighted coefficient was 0.72. P-values of ≤ 0.05 were considered statistically significant. Due to an increased risk of type I errors, some researchers argue that an adjustment of p-values should be employed when multiple correlations are performed; however, if the adjustment is too conservative, then there is an increased risk of type II errors occurring.[46] In the context of this study, which was essentially exploratory in nature, we chose not to adjust p-values.[47] The p-value associated with each correlation is independent of the others; therefore, the probability of a type I error remains the same for each correlation, with or without adjustment of the level of significance. All analyses were conducted using SAS version 8.2 (Cary, NC).

RESULTS

Twenty-eight persons enrolled in the study whose characteristics are listed in Table 2. The majority of participants were older adults with 75% over age 58 (range 33 to 84 years). The sample was mostly male and split about evenly between African Americans and whites. The etiology of vision impairment was almost entirely due to primary open angle glaucoma (27 of 28), with one participant having retinitis pigmentosa. Participants averaged approximately 2 to 3 co-morbid medical conditions, and cognitive status (MMSE score) was very good on average. With respect to driving exposure, participants reported driving on average 5 to 6 days per week, to 4 places in 12 trips. In terms of miles per week behind the wheel, there was wide variability in the sample from 2 to 348; however, all subjects were drivers since young adulthood.

With respect to vision, binocular visual acuity was good, averaging 20/25, contrast sensitivity was within the range that might reasonably be expected for our sample, and binocular visual field loss was (qualitatively) mild to moderate (Table 2). The binocular horizontal field extent ranged from 78°-165° (mean 123°) and the binocular vertical field extent from 50°-124° (mean 89°). Eighty percent would have met the requirement for driver licensing in 16

TABLE 2.
Demographic, medical, functional, and driving exposure characteristics of sample (N = 28)

Variable name	Descriptive statistics		
	N (%)	Mean ± SD	Median (QR)
Demographic characteristics			
Age (years)		67 ± 14	71 (18)
Gender			
Male	18 (64%)		
Race/ethnicity			
African American	13 (46%)		
Asian American	1 (4%)		
White	14 (50%)		
Medical characteristics			
Number of medical conditions		2.8 ± 1.7	3.0 (2.5)
Etiology of visual field impairment			
Glaucoma	27 (96%)		
Retinitis Pigmentosa	1 (4%)		
Functional characteristics			
Cognitive status		28 ± 2	29 (4)
Visual acuity (logMAR)			
Both eyes		0.09 ± 0.11	0.10 (0.20)
Better eye		0.11 ± 0.11	0.10 (0.20)
Worse eye		0.27 ± 0.24	0.20 (0.30)
Contrast sensitivity (log sensitivity)			
Better eye		1.37 ± 0.20	1.35 (0.25)
Worse eye		1.24 ± 0.29	1.28 (0.38)
Binocular visual field ()			
Horizontal field width		123 ± 20	120 (22)
Vertical field height		89 ± 21	93 (29)
Total field		628 ± 117	614 (179)
Useful field of view (ms)			
Subtest 1 (visual processing speed)		77 ± 132	18 (40)
Subtest 2 (divided attention)		267 ± 190	297 (427)
Subtest 3 (selective attention)		404 ± 135	500 (175)
Driving exposure characteristics			
Days driven per week		5.7 ± 1.7	7.0 (2.0)
Places driven per week		4.4 ± 1.8	4.5 (2.0)
Trips driven per week		11.7 ± 7.2	10.0 (10.0)
Miles driven per week		140 ± 97	126 (148)

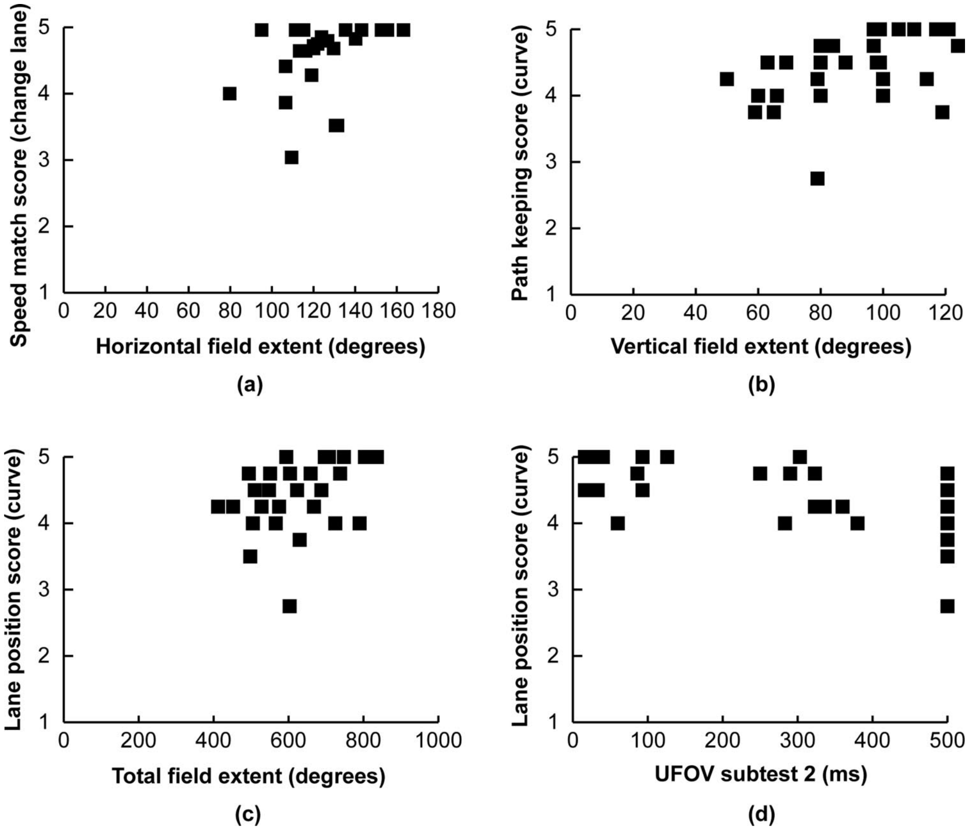

FIGURE 2.

Scatter plots of *raw* data for driving skills and binocular visual field scores and UFOV® scores, for which the correlations (adjusted for age and cognitive status) were significant ($p \leq 0.05$; Table 3). (a) Horizontal field extent and speed matching when changing lane. (b) Vertical field extent and path keeping during curve taking. (c) Total field extent and lane position during curve taking. (d) UFOV subtest 2 and lane position during curve taking. More restricted fields or difficulties with divided attention (UFOV subtest 2) were associated with poorer driving skills (lower score represents worse performance).

states in the U.S., with minimum horizontal field extents of 20° to 110°; 54% would have met the minimum 120° horizontal field diameter required in the European Union. Under binocular viewing conditions, none of the participants had any significant scotomata within the seeing field, as evaluated by the static presentations in the Goldmann perimetry assessment. For UFOV, scores ranged from no or minimal impairment (<138 ms) to severely impaired (>380 ms); the mean score increased (performance became more impaired) as the level of task difficulty increased from subtest 1 to subtest 3 (Table 2). For all participants, binocular visual field extent, as measured with the Goldmann V4e target, was greater than the extent of the UFOV display.

Table 3 shows the correlations between each of the maneuver/skill combinations and the binocular visual field variables, UFOV scores and contrast sensitivity scores, adjusted for age and cognitive status; raw unadjusted data is included in the form of scatter plots in Fig. 2 (to visually demonstrate representative significant correlations). A more restricted binocular horizontal field, vertical field and total field were all significantly ($p \leq 0.05$) associated with poorer performance in speed matching when changing lanes (Fig. 2a), and with poorer performance in path keeping (Fig. 2b) and lane positioning (Fig. 2c) during curve taking, as expected. In addition, both a restricted horizontal and a restricted total field were significantly associated with poorer performance in maintaining an appropriate following distance (spacing) during curve taking, a more restricted vertical field was related to poorer performance in path keeping when turning, and a smaller total field with poorer performance in lane positioning when exiting the interstate.

Slower processing speed (UFOV subtest 1) was significantly ($p \leq 0.05$) related to difficulties with gap judgment when turning and maintaining an appropriate speed during curve taking. Divided attention problems, as assessed in UFOV subtest 2, were significantly associated with poorer performance in lane positioning when merging, lane positioning (Fig. 2d) and steadiness of steering during curve taking, and speed matching when exiting the interstate. UFOV subtest 3 (selective attention) was unrelated to all maneuver/skill combinations. Poorer contrast sensitivity scores in the better eye were significantly associated with poorer performance in speed matching when changing lanes, and in steadiness of steering and maintaining an appropriate speed during curve taking.

Significant ($p \leq 0.05$) associations with the global ratings for the binocular field variables, the UFOV subtests and contrast sensitivity in the better eye, adjusted for age and cognition, are as follows (Table 4): A reduced width of the horizontal field, a restricted vertical field and a reduced total field were all related to poorer ratings for anticipatory skills (Fig. 3a) and interaction with other traffic on the interstate. In addition, a restricted vertical field was associated with difficulties adjusting speed to traffic conditions and with poorer scores on reaction to the unexpected in the road-

TABLE 3.
Spearman correlations (p-values) between ratings on specific driving maneuvers and binocular visual field scores, UFOV scores and contrast sensitivity scores, adjusted for age and cognitive status.

Driving maneuver skills scored	N[a]	Binocular horizontal field	Binocular vertical field	Binocular total field	UFOV Subtest 1 visual processing speed	UFOV Subtest 2 divided attention	UFOV Subtest 3 selective attention	Contrast sensitivity better eye	Contrast sensitivity worse eye
Turning	28								
Lane position		0.123 (0.548)	0.280 (0.166)	0.211 (0.301)	0.127 (0.536)	−0.289 (0.152)	−0.147 (0.472)	0.323 (0.115)	0.113 (0.616)
Gap judgment		0.052 (0.802)	0.192 (0.346)	0.027 (0.898)	0.385 (0.052)*	−0.182 (0.374)	−0.263 (0.194)	0.081 (0.701)	−0.026 (0.909)
Path keeping		0.099 (0.632)	0.419 (0.033)*	0.299 (0.137)	0.233 (0.252)	−0.346 (0.084)	0.048 (0.814)	0.057 (0.787)	−0.181 (0.420)
Speed appropriate		0.214 (0.294)	0.174 (0.394)	0.288 (0.153)	0.045 (0.828)	−0.153 (0.456)	−0.021 (0.918)	0.186 (0.374)	−0.102 (0.651)
Stop position		0.143 (0.485)	0.207 (0.310)	0.146 (0.477)	−0.006 (0.975)	0.042 (0.839)	−0.092 (0.654)	0.242 (0.244)	−0.041 (0.855)
Merging	24								
Lane position		0.252 (0.257)	0.145 (0.520)	0.274 (0.217)	0.262 (0.238)	−0.522 (0.013)*	−0.133 (0.555)	0.084 (0.716)	−0.260 (0.268)
Gap judgment		0.185 (0.410)	0.142 (0.529)	0.171 (0.448)	−0.030 (0.896)	−0.123 (0.586)	0.109 (0.630)	−0.055 (0.814)	−0.279 (0.234)
Speed match		0.265 (0.234)	0.410 (0.058)	0.068 (0.763)	−0.207 (0.356)	−0.109 (0.631)	0.166 (0.461)	−0.119 (0.608)	−0.325 (0.161)
Changing lanes	27								
Lane position		0.379 (0.062)	0.281 (0.173)	0.330 (0.108)	−0.146 (0.486)	−0.390 (0.054)	−0.123 (0.558)	0.247 (0.245)	0.082 (0.718)
Gap judgment		0.106 (0.615)	0.310 (0.132)	0.348 (0.088)	−0.082 (0.696)	−0.189 (0.365)	−0.187 (0.370)	−0.061 (0.777)	0.144 (0.522)
Steering steadiness		0.166 (0.427)	0.184 (0.378)	0.161 (0.442)	−0.294 (0.154)	−0.224 (0.281)	0.015 (0.944)	0.272 (0.199)	0.149 (0.509)
Speed match		0.555 (0.004)*	0.587 (0.002)*	0.472 (0.017)*	−0.312 (0.130)	−0.325 (0.113)	−0.262 (0.205)	0.441 (0.031)*	0.198 (0.378)
Crossing intersection	28								
Lane position		0.170 (0.405)	0.151 (0.461)	0.085 (0.678)	0.196 (0.338)	−0.074 (0.718)	−0.017 (0.936)	0.035 (0.870)	−0.061 (0.789)
Steering steadiness		0.231 (0.257)	0.165 (0.421)	0.167 (0.415)	0.081 (0.694)	−0.231 (0.256)	0.001 (0.998)	0.276 (0.182)	0.052 (0.818)
Speed appropriate		0.309 (0.125)	0.291 (0.149)	0.340 (0.090)	0.163 (0.426)	−0.133 (0.518)	−0.009 (0.964)	0.230 (0.269)	−0.086 (0.702)
Stop position		0.194 (0.342)	0.381 (0.055)	0.104 (0.614)	−0.234 (0.250)	0.005 (0.981)	−0.102 (0.621)	0.049 (0.818)	−0.062 (0.784)
Straight road	27								
Lane position		0.071 (0.736)	0.226 (0.277)	0.196 (0.347)	0.112 (0.595)	−0.294 (0.153)	0.196 (0.347)	0.060 (0.782)	−0.197 (0.380)
Steering steadiness		−0.050 (0.813)	0.169 (0.420)	0.121 (0.564)	−0.231 (0.266)	−0.191 (0.360)	0.026 (0.901)	0.061 (0.778)	0.092 (0.682)
Speed appropriate		0.301 (0.144)	0.306 (0.138)	0.177 (0.397)	−0.037 (0.859)	−0.083 (0.694)	0.181 (0.386)	−0.172 (0.421)	−0.216 (0.334)
Spacing		0.351 (0.086)	0.327 (0.110)	0.267 (0.197)	−0.123 (0.557)	−0.037 (0.862)	0.001 (0.996)	0.033 (0.877)	−0.126 (0.577)
Curve taking	28								
Lane position		0.509 (0.008)*	0.547 (0.004)*	0.567 (0.003)*	−0.225 (0.269)	−0.494 (0.010)*	−0.188 (0.356)	0.345 (0.091)	0.253 (0.256)
Path keeping		0.460 (0.018)*	0.580 (0.002)*	0.577 (0.002)*	−0.325 (0.105)	−0.363 (0.068)	−0.177 (0.388)	0.276 (0.182)	0.039 (0.862)
Steering steadiness		0.232 (0.254)	0.277 (0.171)	0.289 (0.153)	−0.262 (0.195)	−0.492 (0.011)*	−0.019 (0.925)	0.449 (0.024)*	0.195 (0.385)
Speed appropriate		0.375 (0.059)	0.318 (0.114)	0.311 (0.122)	−0.450 (0.021)*	−0.380 (0.056)	−0.044 (0.830)	0.440 (0.028)*	0.014 (0.949)
Spacing		0.445 (0.049)*	0.343 (0.139)	0.446 (0.049)*	−0.005 (0.985)	−0.334 (0.150)	−0.216 (0.360)	0.427 (0.060)	−0.272 (0.274)
Interstate exiting	23								
Lane position		0.416 (0.061)	0.416 (0.061)	0.441 (0.046)*	−0.188 (0.415)	−0.243 (0.288)	0.061 (0.793)	0.221 (0.349)	−0.116 (0.635)
Speed match		0.353 (0.116)	0.187 (0.418)	0.302 (0.183)	−0.138 (0.552)	−0.445 (0.043)*	−0.046 (0.843)	0.292 (0.212)	−0.235 (0.333)

[a] N is not always 28, as some measures could not be scored or were not applicable for all participants (four would not drive on the interstate); N is always 1 fewer for correlations with contrast sensitivity scores (contrast sensitivity was not recorded for 1 subject).

* $p \leq 0.05$ (two-tailed)

TABLE 4.
Spearman correlations (p-values) between summary driving ratings and binocular visual field scores, UFOV scores and contrast sensitivity scores, adjusted for age and cognitive status.

	N[a]	Binocular horizontal field	Binocular vertical field	Binocular total field	UFOV Subtest 1 visual processing speed	UFOV Subtest 2 divided attention	UFOV Subtest 3 selective attention	Contrast sensitivity better eye	Contrast sensitivity worse eye
Entire drive[b]									
Interaction with other traffic	28	0.350 (0.080)	0.339 (0.090)	0.324 (0.107)	−0.180 (0.378)	−0.029 (0.889)	−0.099 (0.632)	0.397 (0.050)*	0.059 (0.794)
Anticipatory skills	28	0.462 (0.018)*	0.506 (0.008)*	0.456 (0.019)*	−0.165 (0.421)	−0.321 (0.110)	−0.471 (0.015)*	0.587 (0.002)*	0.241 (0.280)
Vehicle control skills	28	0.153 (0.454)	0.365 (0.067)	0.255 (0.209)	0.049 (0.813)	−0.238 (0.243)	−0.312 (0.120)	0.532 (0.006)*	0.152 (0.500)
Adjusting speed to conditions	24	0.400 (0.067)	0.508 (0.016)*	0.300 (0.175)	−0.129 (0.567)	−0.428 (0.047)*	−0.438 (0.042)*	0.373 (0.096)	0.060 (0.801)
Reaction to unexpected	18	0.488 (0.055)	0.331 (0.210)	0.314 (0.236)	−0.082 (0.763)	−0.397 (0.128)	−0.343 (0.193)	0.373 (0.170)	0.133 (0.666)
Overall driving performance	28	0.320 (0.111)	0.274 (0.176)	0.264 (0.193)	−0.052 (0.799)	−0.346 (0.083)	−0.414 (0.036)*	0.419 (0.037)*	−0.154 (0.493)
Interstate[c]									
Interaction with other traffic	24	0.418 (0.053)*	0.479 (0.024)*	0.487 (0.022)*	0.108 (0.631)	−0.227 (0.310)	−0.356 (0.104)	0.167 (0.469)	−0.143 (0.548)
Anticipatory skills	24	0.339 (0.123)	0.309 (0.162)	0.342 (0.119)	−0.276 (0.214)	−0.013 (0.955)	−0.333 (0.130)	0.237 (0.300)	0.001 (0.995)
Vehicle control skills	23	0.018 (0.939)	0.306 (0.177)	0.233 (0.311)	−0.004 (0.986)	−0.294 (0.195)	−0.484 (0.026)*	0.464 (0.039)*	0.142 (0.562)
Reaction to unexpected	17	0.308 (0.265)	0.517 (0.049)*	0.434 (0.106)	0.158 (0.575)	−0.391 (0.149)	−0.302 (0.273)	0.206 (0.481)	0.106 (0.720)

[a] N is not always 28, as some measures could not be scored (e.g. if no unexpected events occurred during a drive) or were not applicable for all participants (four would not drive on the interstate); N is always 1 fewer for correlations with contrast sensitivity scores (contrast sensitivity was not recorded for 1 subject).
[b] Mean of two raters' scores
[c] Scored by back-seat evaluator only
* $p \leq 0.05$ (two-tailed)

TABLE 5.
Spearman correlations (p-values) between driving exposure variables[a] and binocular visual field scores, UFOV scores and contrast sensitivity scores, adjusted for age and cognitive status.

	N[b]	Binocular horizontal field	Binocular vertical field	Binocular total field	UFOV Subtest 1 visual processing speed	UFOV Subtest 2 divided attention	UFOV Subtest 3 selective attention	Contrast sensitivity better eye	Contrast sensitivity worse eye
Days driven per week	28	0.340 (0.090)	−0.003 (0.988)	0.063 (0.760)	−0.017 (0.993)	−0.161 (0.433)	−0.150 (0.464)	0.254 (0.221)	0.016 (0.945)
Places driven per week	28	0.617 (0.001)*	0.260 (0.200)	0.353 (0.077)	−0.012 (0.955)	−0.188 (0.359)	−0.120 (0.561)	0.389 (0.055)	0.026 (0.908)
Trips made per week	28	0.543 (0.004)*	0.134 (0.513)	0.268 (0.185)	0.013 (0.948)	−0.206 (0.312)	−0.174 (0.395)	0.317 (0.122)	0.252 (0.258)
Miles driven per week	28	0.316 (0.116)	−0.090 (0.663)	0.059 (0.775)	−0.165 (0.419)	0.019 (0.925)	0.087 (0.672)	0.307 (0.135)	0.090 (0.690)

[a] As reported on the Driving Habits Questionnaire.[44]
[b] Contrast sensitivity scores were not recorded for one subject; therefore, sample sizes are one fewer for contrast sensitivity correlations
* $p \leq .05$ (two-tailed)

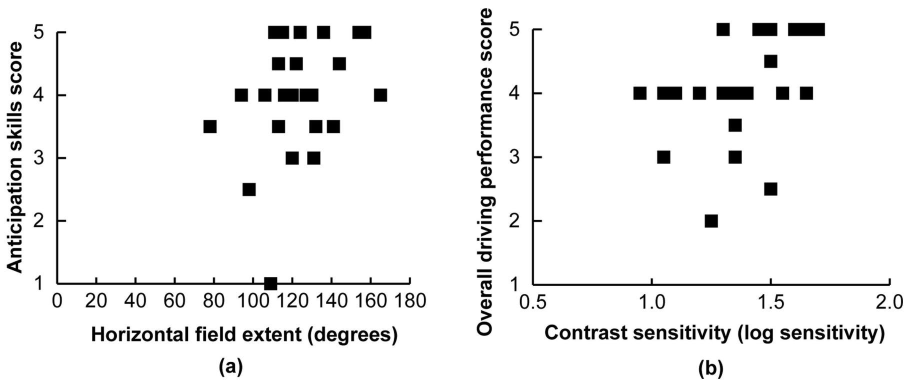

FIGURE 3.

Scatter plots of *raw* data for global driving scores and binocular visual field scores and contrast sensitivity scores, for which the correlations (adjusted for age and cognitive status) were significant ($p \leq 0.05$; Table 4). (a) Horizontal field extent and anticipatory skills. (b) Contrast sensitivity (better eye) and overall driving performance. More restricted fields and poorer contrast sensitivity scores were associated with poorer driving performance (lower score represents worse performance).

way during interstate driving. UFOV subtest 1 was unrelated to global scores. Divided attention problems (UFOV subtest 2) were associated with poorer scores on adjusting speed to traffic conditions. Difficulties with selective attention (UFOV subtest 3) were associated with a number of global scores including poorer ratings for anticipatory skills, adjusting speed to traffic conditions, vehicle control skills on the interstate and overall driving performance. Poorer contrast sensitivity in the better eye was also associated with several global scores including poorer ratings for interaction with other traffic, anticipatory skills, vehicle control skills (whole route and interstate), and overall driving performance (Fig. 3b).

Table 5 displays associations between various aspects of driving exposure and the field characteristics, UFOV scores and contrast sensitivity scores. The only aspect of the binocular visual field significantly ($p \leq 0.05$) associated with exposure was the horizontal field; those with narrower fields tended to drive to fewer places per week (Fig. 4) and made fewer trips per week. UFOV score and contrast sensitivity were not associated with driving exposure.

DISCUSSION

These results are consistent with the notion that even mild to moderate peripheral visual field restrictions can negatively impact specific driving skills, especially for maneuvers for which a wide field of vision may be important. Drivers with more restricted fields showed poorer skills in speed matching when changing lanes, and poorer skills in maintaining lane position and keeping to the path of the curve when driving around curves. By comparison, there were no significant correlations between field extent and driving skills in other situations that require information primarily from the central visual field, e.g., maintaining appropriate following distance and speed on straight road segments, and determining the correct stop position at an intersection. The effects of restricted peripheral fields on driving skills were also apparent in the summary measures of driving performance, assessed for the entire test drive, where more restricted fields were associated with poorer ratings for anticipatory skills.

Both horizontal and vertical field extent were related to the driving skills of path keeping and lane position during curve taking, and vertical field extent was related to path keeping when making a turn. Similarly, drivers with restricted peripheral fields in a driving simulator evaluation[19] were found to have poorer lane positioning skills, deviating to the left in left curves and to the right in right curves, than drivers with central visual field defects whose lateral lane position did not vary as a function of the curvature of the road. The importance of the vertical field in curve taking is implicit in the double model of steering proposed by Donges[48] and is supported by the findings of Land and Horwood.[49] More distant parts of the road, close to the horizon in the vertical meridian, provide information about road curvature, whereas accurate position-in-lane information comes from the nearer part of the road further below the horizon (about 10° below).[49] The drivers in our study had only mild restrictions of the vertical field; the narrowest measured extent (50°) is greater than the vertical field of view through a typical windshield, nevertheless mild vertical field narrowing did adversely affect path keeping both in curve taking and when making turns. Currently, visual field requirements for driver licensing are primarily specified in terms of the horizontal field diameter.[1] However, our results suggest that vertical field extent may also be an important consideration, especially in turning or curve-taking maneuvers.

Previous studies, which have reported an effect of peripheral visual field restriction on aspects of driving performance, have either used simulations of severe visual field restrictions on a closed

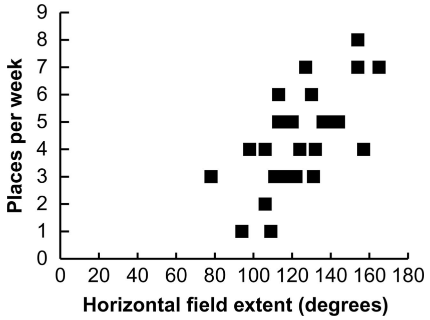

FIGURE 4.

Scatter plot of driving exposure (number of places visited per week) as a function of horizontal field extent. Drivers with more restricted fields drove to fewer places.

course,[11,16,18] or have carried out driving simulator evaluations using patients with more restricted fields than the sample in this study.[19,21] The only study of the relationship between field extent and driving performance, which has a similar range of restricted horizontal visual field extents (130° ± 21°, range 70°–140°)[20] to the range in this study, failed to find any significant correlations between binocular field width and driving performance in a driving simulator; furthermore there were no differences in scores between drivers with peripheral field loss and the control group of normally sighted drivers who were matched for age, gender and driving exposure. The difference in findings between this driving simulator evaluation[20] and our on-road evaluation of drivers with mild to moderate peripheral field loss may relate to differences in the duration of the driving assessment (5 min compared to > 30 min), differences in the driving environment (virtual compared to a real traffic environment), or differences in the sensitivity of the assessment to the effects of peripheral field loss. Our assessment comprised detailed scoring of specific skills and maneuvers, including those that *a priori* would be expected to be affected by peripheral field loss, whereas Szlyk et al.[20] used a general set of simulator performance indices and did not score performance for specific maneuvers.

In addition to our primary research question, the relationship between visual field extent and driving performance, we also examined the relationship between driving skills and UFOV and contrast sensitivity. Slower processing speeds (UFOV subtest 1) and divided attention problems (UFOV subtest 2) were primarily associated with poor driving skills for specific maneuvers (merging, curve taking, interstate exiting), whereas difficulties with selective attention (UFOV subtest 3) were associated with poorer scores on summary driving measures (including overall driving performance and anticipatory skills). The trends in our data are consistent with previously reported associations between reduced performance on UFOV tests and both crash-involvement[6,8,30] and reduced driving performance on closed-road circuits[16,17,28] and open-road courses.[31]

Poorer contrast sensitivity scores were associated both with poorer driving skills for specific maneuvers as well as poorer ratings on summary driving measures. Szlyk et al.[20] reported that lower contrast sensitivity was correlated with slower driving speeds in a driving simulator evaluation of patients with mild to moderate visual field restrictions. Similarly, we found that lower contrast sensitivity scores were associated with difficulties in speed matching when changing lanes and maintaining an appropriate speed during curve taking. Our finding of significant associations between contrast sensitivity and overall driving performance is consistent with previously reported associations between contrast sensitivity score and overall driving score on closed-road[16,17,28] and open-road courses.[31] Given that subjects in our study were recruited on the basis of peripheral visual field restriction, not contrast sensitivity impairment, it is noteworthy that we found significant associations between contrast sensitivity and driving skills. This underscores the potential importance of contrast sensitivity as a predictor of driving performance.

The majority of driving skill ratings were in the 3 to 5 range, i.e., from unsatisfactory (but does not compromise safety) through to excellent; only one participant was rated unsafe to drive based on driving performance across the whole course (his horizontal visual field was 109°). By comparison, in an on-road study of drivers with more restricted peripheral fields than the range in this study (mean 84° ± 35°compared to 123° ± 20° here), only 43% passed a test of practical fitness to drive.[19] As previously reported for drivers with peripheral field loss,[9] drivers in the current study appeared to be aware of their visual limitations and self-regulated their driving accordingly; those with more restricted fields drove to fewer places and made fewer trips per week.

Our results demonstrate, in a small sample of drivers, that mild to moderate peripheral visual field restrictions adversely affect specific driving skills in maneuvers for which a wide field of vision is likely to be important (although the majority of subjects were regarded as safe drivers). From this preliminary study, the skills and maneuvers, which should be evaluated in subsequent investigations of driving with peripheral field loss, can be identified. A follow up study employing similar assessment methods with a larger sample of drivers and a wider range of field extents would be necessary to determine the minimum field extent required for safe driving.

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