The Effect of Visual Field Defects on Driving Performance

A Driving Simulator Study

Tanja R. M. Coeckelbergh, PhD; Wiebo H. Brouwer, PhD; Frans W. Cornelissen, PhD; Peter van Wolffelaar, MSc; Aart C. Kooijman, PhD

Objectives: To investigate the effect of visual field defects on driving performance, and to predict practical fitness to drive.

Methods: The driving performance of 87 subjects with visual field defects due to ocular abnormalities was assessed on a driving simulator and during an on-road driving test.

Outcome Measures: The final score on the on-road driving test and simulator indexes, such as driving speed, viewing behavior, lateral position, time-headway, and time to collision.

Results: Subjects with visual field defects showed differential performance on measures of driving speed, steering stability, lateral position, time to collision, and time-headway. Effective compensation consisted of reduced driving speed in cases of central visual field defects and increased scanning in cases of peripheral visual field defects. The sensitivity and specificity of models based on vision, visual attention, and compensatory viewing efficiency were increased when the distance at which the subject started to scan was taken into account.

Conclusions: Subjects with visual field defects demonstrated differential performance on several driving simulator indexes. Driving examiners considered reduced speed and increased scanning to be valid compensation for central and peripheral visual field defects, respectively. Predicting practical fitness to drive was improved by taking driving simulator indexes into account.

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From the Laboratory of Experimental Ophthalmology (Drs Coeckelbergh, Cornelissen, and Kooijman), the Department of Neuropsychology and Gerontology (Dr Brouwer), and the Computing Center (Mr van Wolffelaar), University of Groningen, and the Department of Ophthalmology (Dr Kooijman), University Hospital Groningen, Groningen, the Netherlands; and Visio, the Dutch National Foundation for the Visually Impaired and Blind (Dr Kooijman), Haren, the Netherlands.

CENTRAL AND peripheral visual field defects pose different problems for performing everyday activities, and it can be expected that these differences will also emerge during driving. In the present study, the effect of visual field defects on driving performance was assessed by means of a driving simulator. For subjects with central visual field defects, it was hypothesized that timely recognition of traffic signs would be reduced and that estimating the distance to and driving speed of lead cars would be more difficult. On the basis of the double model for steering by Donges[1] (also cited in Land and Horwood[2]) it was further expected that subjects with central visual field defects would have more difficulty matching the road curvature but that the ability to keep a proper lane position would be intact. Subjects with peripheral field defects, on the other hand, were expected to have more difficulty detecting stimuli in the periphery, resulting in an increased risk of accidents with traffic participants approaching from the sides.

Further, because subjects with peripheral visual field defects are forced to scan the environment to get an overview, it was expected that lateral position control would decrease.

The second research question relates to the effects of compensation. It has been reported previously that behavioral adaptations, such as reduction of driving speed or increased eye movements, might allow drivers to compensate for their visual impairment and reduce their crash risk.[3,4] Consequently, it was expected that drivers who passed the on-road driving test would exhibit more compensatory behavior than subjects who failed the on-road driving test. In subjects with peripheral visual field defects, it was expected that those who passed the on-road driving test would make more eye and head movements than those who failed the driving test. Further, because making head and eye movements is time consuming, it was hypothesized that driving speed would be reduced in this group. In subjects with central visual field defects, it was expected that those who passed the on-road driving test would drive more

Vision Parameter	Visual Field Defect, Mean (SD)			
	Central (n = 23)	Peripheral (n = 35)	Central and Peripheral (n = 6)	Mild (n = 23)
Binocular visual acuity (decimal notation)	20/80 (0.09)	20/25 (0.26)	20/100 (0.11)	20/25 (0.27)
Binocular horizontal field extent*	142° (14°)	84° (35°)	102° (17°)	142° (14°)

*Goldmann III-4 isopter.

slowly to gain time to discern detailed information in the environment, such as traffic signs.

The third research question relates to the prediction of practical fitness to drive. We previously reported that only a small percentage of variance in practical fitness to drive could be explained by visual acuity and visual field.[5] The predictive power of this model could be improved when taking compensatory viewing strategies into account. The predictive power of this model was equal to the predictive power of a model based on contrast sensitivity and visual attention. Yet, the predictive power of both models remained low, limiting the use of these tests as a practical tool to distinguish between safe and unsafe drivers. The current study investigated whether the predictive power of both models could be improved by adding driving simulator indexes to the models.

SUBJECTS

Sixty men and 27 women with visual field defects due to ocular abnormalities such as age-related macular degeneration, glaucoma, or retinitis pigmentosa participated in this study. Subjects with visual field defects due to postchiasmal abnormalities were not included in the study. Subjects were recruited by short reports in newspapers and folders at ophthalmologists' offices and rehabilitation centers and from patients' associations. All subjects were regular drivers, although most had been told they no longer met the vision requirements for driving. Most subjects (81 [93%] of 87) held a valid driver's license. Participation in the study had no impact on their driver's license. Mean age was 63 years (age range, 37-86 years). When subjects volunteered to participate, they received a letter fully explaining the nature of the experiment. Subjects were asked to return a form indicating whether they wished to participate. They were also sent a questionnaire related to the inclusion and exclusion criteria. For subjects to be included in the study, visual field defects had to be present, binocular visual acuity had to be greater than 20/200, and subjects had to have sufficient and recent driving experience, which was defined as a minimum of 2000 km during the last 2 years. Exclusion criteria were severe cognitive impairments, including hemispatial neglect. All subjects scored above a predefined cutoff point (22) on the Mini-Mental State examination,[6] a cognitive screening test (mean score, 27; range, 23-29). Hemispatial neglect was screened by means of the Bells test[7] (number of errors: mean, 1; range, 0-8). Two subjects made more than 4 errors and were further tested with a line bisection task.[8] They scored within normal limits, and, therefore, it was assumed that the impaired score on the Bells test was due to visual impairment rather than hemispatial neglect.

To gain insight into how vision parameters affect driving performance, subjects were classified into 4 groups based on the European requirements for driving.[9] According to these requirements, binocular visual acuity should be at least 20/40 and the binocular horizontal field should extend for at least 120°. Subjects in the central field defect group (group 1) did not fulfill the visual acuity requirements, but the binocular visual field outside the central 10° area was intact and extended for at least 120°. Subjects in the peripheral field defect group (group 2) met the visual acuity requirement but failed to meet the visual field requirement. Subjects in the central and peripheral field defect group (group 3) met neither of the requirements. Subjects in the mild visual field defect group (group 4) had scotomas in the paracentral or midperipheral area that did not restrict the binocular horizontal field extent and did not affect visual acuity. Vision parameters for the 4 groups are presented in the **Table**. Examples of the monocular visual fields of a subject with a central and peripheral visual field defect (group 3) and a subject with a mild visual field defect (group 4) are depicted in **Figure 1**.

The study was approved by the ethical review committee of the University of Groningen, Groningen, the Netherlands.

MATERIALS

Vision Examination

Vision examination included refraction (if necessary) and assessment of visual acuity,[10] near visual acuity, visual field (Goldmann III-4 and V-4 isopters and Humphrey Field Analyzer [Zeiss Humphrey Systems, Dublin, Calif] central 10°), contrast sensitivity,[11] dark adaptation, and eye motility. Visual acuity and contrast sensitivity were assessed for each eye separately and binocularly. Visual fields were examined monocularly. The binocular horizontal field extent was obtained by superimposing the III-4 isopters of the monocular visual fields.

Viewing Behavior and Visual Attention

Viewing behavior was assessed by the attended field of view (AFOV) test.[5] The AFOV test is a visual search task that determines the (log) threshold presentation time needed to detect a target at various positions in the field of view. The target is an open circle (C) among 30 closed circles (O). Presentation times vary from 8 milliseconds to 10 seconds.

Visual attention was assessed by a test similar to condition 6 of the usual field of view test as developed by Ball et al.[12] The visual attention test was described previously.[5] It consisted of 4 conditions: a peripheral task without distracters, a peripheral task and concurrent central task without distracters, a peripheral task with distracters, and a peripheral and concurrent central task with distracters. The peripheral tasks involved the localization of a target, whereas the central task required the identification of central stimulus (eg, a sad or happy face). Presentation times varied from 50 to 125 milliseconds.

Driving Simulator

The simulator system[13] was programmed in C[++] and implemented on a 4-processor Onyx RE2 computer (Silicon Graph-
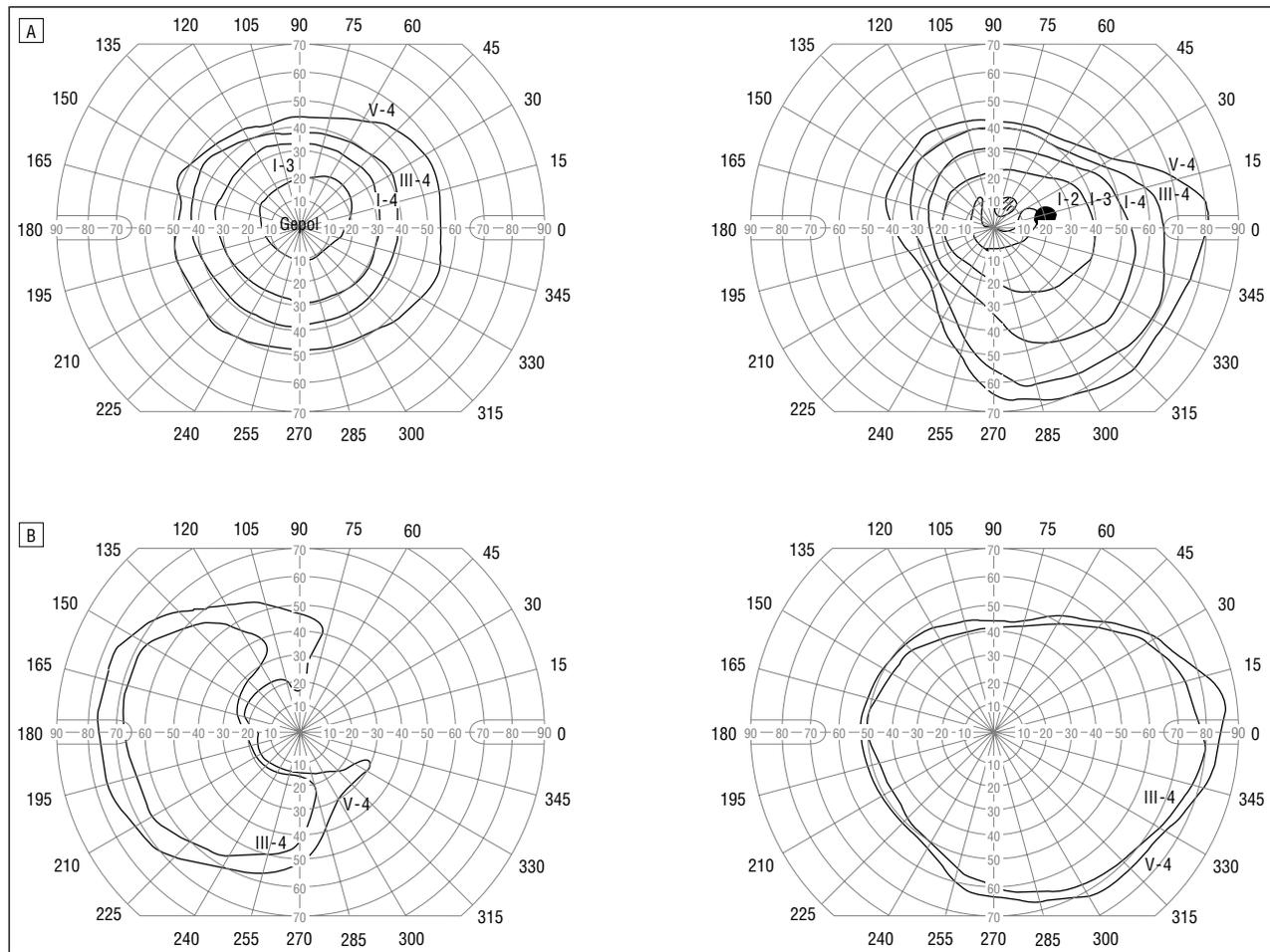
Figure 1. Examples of the monocular visual fields of a subject with a central and peripheral visual field defect (A) and a subject with a mild visual field defect (B). Binocular visual acuity was 20/100 for the subject with central and peripheral visual field defects and 20/16 for the subject with mild visual field defects. To obtain the binocular horizontal extent of the visual field, the Goldmann III-4 isopters of the monocular visual fields were superimposed.

ics, Inc, Mountain View, Calif). A network specification language tool was used to develop a network of roads. A scenario specification language tool was used to define other traffic participants and their individual behavior. Each vehicle perceived its environment, evaluated behavioral rules, and responded appropriately. Three graphics data projectors displayed the computer graphics on a 165° × 45° projection screen. The midscreen had a high resolution (1280 × 1024 pixels), whereas the left and right screens had lower resolutions (640 × 512 pixels). The refresh rate was 20 to 30 updates per second, resulting in a smooth real-time performance with a mean response delay of less than 100 milliseconds. On the screens, the roads, intersections, traffic lights and signs, buildings, objects, other vehicles, and 3 superimposed small rectangular areas simulating the rearview and sideview mirrors of the car were projected (**Figure 2**A). Luminance was 0.5 candela (cd)/m² for the road, 2.4 cd/m² for the buildings, and 3.8 cd/m² for the sky. Mean luminance of the cars was 1.9 cd/m² (range, 0.4 cd/m² [black car] to 3.9 cd/m² [white car]). The road consisted of 2 lanes. The right lane boundary corresponded to 0 m, the middle of the road to 3 m, and the left boundary to 6 m. The width of the car was 1.6 m.

The driving simulator car was a modified BMW 518 on a fixed base, containing all its original controls, including steering wheel, accelerator, brake and clutch pedals, speedometer, dashboard indicators, and a manual and automatic gear shift. The engine was replaced by servomotor systems attached to the steering axle and accelerator pedal, allowing simulated torque

forces while driving. Ambient sounds and engine noise were reproduced by loudspeakers. A head tracker monitored head movements during driving (Figure 2B).

Subjects were instructed to drive as they would normally and to respect all traffic signs and signals. They were allowed to practice for as long as they wished. Mean practice time was about 10 minutes. The actual driving test lasted for approximately half an hour. The route consisted of approximately 3 km in a town center (speed limit, 50 km/h), 15 km in a rural area (speed limit, 80 km/h), and 20 km on a highway (speed limit, 120 km/h). The rural area consisted of straight roads, roads with left curves, and roads with right curves. The route included 14 intersections, 10 intersections without a sign and 4 intersections with a yield sign. In the first case, the driver had to give way to vehicles approaching from the right. In the second case, the driver had to give way to vehicles that turned onto the main road, whichever side they approached from. At the start of the route, traffic density was low with a few cars approaching at intersections. Later in the route, traffic flow increased, resulting in very busy intersections at the final parts of the driving test. After 9 km, a car approached from the right. Subjects had to yield the right-of-way and were instructed to follow that car at a short but safe distance. During the route, the subject was instructed 4 times to follow such a car. Speed of the lead car was 40 km/h for the first car, 60 km/h for the second car, and 80 km/h for the third car. The fourth lead car drove at variable speeds between 60 km/h and 80 km/h.

Figure 2. A, The driving simulator. A modified car was positioned in front of a 165° × 45° projection screen. Roads, intersections, traffic lights and signs, buildings, sideview and rearview mirrors of the car, and other vehicles were projected on the screen. B, A head tracker monitored subjects' head movements while they were driving.

Dependent variables were speed, mean lateral position, SD of lateral position, the distance to the next intersection at which subjects started to brake, the distance to the next intersection at which the subject released the accelerator pedal, mean and minimum time-headway, minimum time to collision, viewing angle, number of head movements, distance to the next intersection at which subjects started to scan, number of times subjects overtook a vehicle, and number of crashes.

Practical Fitness to Drive

Practical fitness to drive refers to the ability of the driver to drive safely and smoothly despite a physical impairment, such as a visual field defect. It was assessed with a driving test on the road. Subjects were evaluated in their own car and their own neighborhood by an experienced driving examiner from the Dutch Central Bureau of Driving Licenses. This method of assessing practical fitness to drive is the official standard in the Netherlands for examining drivers who do not quite meet the vision requirements for driving. Driving examiners determined whether subjects had adapted their behavior to minimize the negative effects of their impairment. Driving examiners knew about the drivers' visual acuity and visual field defects but were unaware of their performance on the driving simulator. After the driving test, the examiner gave a final score, which varied from 0 (insufficient) to 3 (good). This final score was recoded to a pass/fail score and indicated whether the subject had passed (scores 2 and 3) or failed (scores 0 and 1) the driving test. The first driving test was regarded as a practice session to expose subjects to the assessment procedure. During the second session, the actual practical fitness to drive was assessed. Therefore, only the results of the second assessment are reported here.

STATISTICAL ANALYSES

The assumption of normality was assessed by means of a Shapiro-Wilks test. In case data were not normally distributed, data were transformed or a nonparametric analysis was used. When evaluating the effect of visual field defects, only the results of subjects with central visual field defects (group 1; n=23), peripheral visual field defects (group 2; n=35), and mild visual field defects (group 4; n=23) were analyzed. Data from subjects with central and peripheral visual field defects (group 3; n=6) were not analyzed due to the small sample size. All subjects (N=87) were included in the regression analysis to predict practical fitness to drive.

Whenever a multivariate approach (multivariate analysis of variance or doubly multivariate repeated measures design)

was used, the multivariate test statistic (Wilks λ) was used to determine the effect of the independent variable on the combination of dependent variables. If significant, the univariate test statistic was used to determine which dependent variables were affected by the independent variable. If the assumption of sphericity was not met, the Greenhouse-Geisser correction was applied. Bonferroni contrasts were used to determine which groups were responsible for the observed effect. Only the main and interaction effects of visual field defects are discussed here.

The significant univariate interaction effect between visual field defect and path on mean lateral position and the significant univariate interaction effect between visual field defect and driving speed of lead car on minimum time-headway were interpreted, although the multivariate interaction effects were not significant. Interpretation of the univariate interaction effects was legitimate because they addressed the hypotheses as formulated in the introduction.

RESULTS

TOWN CENTER AND RURAL AREA

Subjects with central visual field defects drove at a mean (SD) speed of 67 (9) km/h, subjects with peripheral visual field defects drove 70 (7) km/h, and subjects with mild visual field defects drove 74 (9) km/h ($F_{2,78}$=3.8; P=.03). The difference between central and mild visual field defects was significant (P=.02).

The SD of lateral position was 0.21 (0.09) m for subjects with peripheral visual field defects compared with 0.15 (0.03) m for subjects with central visual field defects and 0.16 (0.03) m for subjects with mild visual field defects ($F_{2,78}$=8.4; P<.001).

The mean lateral position of subjects with central visual field defects did not vary as a function of the curvature of the road, whereas mean lateral position of subjects with peripheral or mild visual field defects shifted to the left in left curves and the right in right curves ($F_{4.1,158.2}$=3.0; P=.02) (**Figure 3**).

Visual field defect had no affect on the distance to the next intersection at which the accelerator pedal was released ($F_{2,78}$=0.60; P=.55) or the distance to the next intersection at which the brake pedal was pressed (Kruskal-Wallis test; speed limit 50 km/h, P=.48; speed
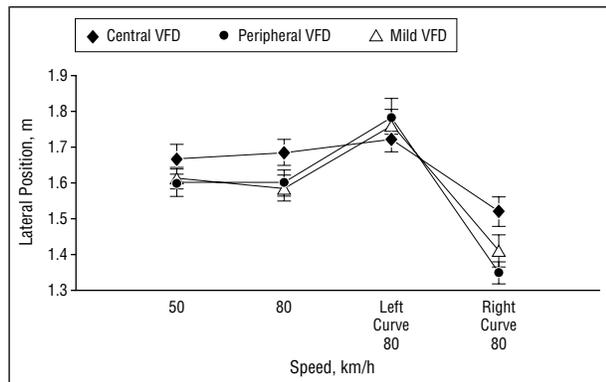
Figure 3. Effect of visual field defect (VFD) and road curvature on mean lateral position while driving in a town center (speed limit, 50 km/h) or rural area (speed limit, 80 km/h). Lateral position of subjects with central VFDs is less affected by road curvature than that of subjects with either mild or peripheral VFDs. Error bars indicate SEM.
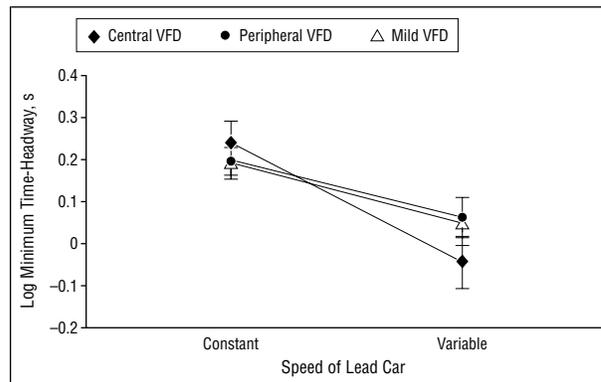

Figure 4. Effect of visual field defect (VFD) and driving speed on minimum time-headway. The decrease of minimum time-headway as a function of driving speed of the lead car is largest in subjects with central VFDs. Error bars indicate SEM.

limit 80 km/h, $P=.25$; speed limit 80 km/h with left curves, $P=.97$; and speed limit 80 km/h with right curves, $P=.76$).

Of 23 subjects with central visual field defects, 13 (57%) made 38 lane boundary crossings, 31 (89%) of 35 subjects with peripheral visual field defects made 146 lane boundary crossings, and 19 (83%) of 23 subjects with mild visual field defects made 52 lane boundary crossings. The proportion of subjects who made at least 1 lane boundary crossing differed significantly as a function of visual field defect ($\chi^2_2=8.7$; $P=.01$).

FOLLOWING THE LEAD CAR

The mean (SD) log minimum time to collision was 0.61 (0.16) (~4.1 seconds) for subjects with central visual field defects, 0.73 (0.16) (~5.4 seconds) for subjects with peripheral visual field defects, and 0.70 (0.15) (~5.0 seconds) for subjects with mild visual field defects ($F_{2,63}=3.6$; $P=.03$). Bonferroni post hoc contrasts revealed that the log minimum time to collision of subjects with central visual field defects was significantly shorter than that of subjects with peripheral visual field defects ($P=.03$).

Visual field defects did not affect mean time-headway ($F_{2,63}=0.87$; $P=.42$) or minimum time-headway ($F_{2,63}=0.14$; $P=.87$). The univariate interaction effect between the driving speed of the lead car and visual field defect was significant for minimum time-headway ($F_{2,63}=4.5$; $P=.02$). **Figure 4** shows that the decrease in minimum time-headway when the lead car drove at a variable speed was largest in the group with central visual field defects.

HIGHWAY

Driving speed on the highway varied as a function of visual field defect ($F_{2,71}=3.2$; $P=.04$). Subjects with central visual field defects had a mean (SD) driving speed of 102 (13) km/h, subjects with peripheral visual field defects drove 107 (8) km/h, and subjects with mild visual field defects drove 109 (8) km/h. None of the Bonferroni comparisons reached significance.

The mean (SD) lateral position of subjects with peripheral visual field defects was 1.86 (0.27) m compared with 2.0 (0.17) m in subjects with central visual field defects and 2.02 (0.15) m in subjects with mild visual field defects ($F_{2,71}=4.6$; $P=.01$). The difference between the peripheral and mild visual field defect groups was significant ($P=.02$).

The SD of lateral position was largest in the peripheral visual field defect group (mean [SD], 0.38 [0.12] m) and differed significantly from that of subjects with central ($P<.001$) and mild ($P=.01$) visual field defects. The SD of lateral position was 0.28 (0.06) m for the central visual field defect group and 0.29 (0.07) m for the mild visual field defect group ($F_{2,71}=9.9$; $P<.001$).

Minimum time-headway did not vary as a function of visual field defect group (Kruskal-Wallis $\chi^2_2=0.29$; $P=.87$). Data on mean time-headway and minimum time to collision were not collected during highway driving.

Overtaking happened 37 times by 27 drivers. The proportion of subjects who overtook at least 1 vehicle did not vary as a function of visual field defect ($\chi^2_2=1.3$; $P=.51$). No difference was observed between visual field defect groups with regard to time spent in the left lane (mean [SD], 10 [9] seconds; Kruskal-Wallis $\chi^2_2=0.04$; $P=.98$), lateral position in the left lane (5.2 [0.41] m; Kruskal-Wallis $\chi^2_2=0.88$; $P=.64$), and SD of lateral position in the left lane (0.35 [0.14] m; Kruskal-Wallis $\chi^2_2=1.25$; $P=.53$).

VIEWING BEHAVIOR
WHILE APPROACHING INTERSECTIONS

Visual field defect did not affect the outcome measures of viewing behavior, including viewing angle, number of head movements, and distance to the next intersection at which subjects started to scan (Wilks $\lambda=0.80$; $F_{6,106}=2.1$; $P=.06$).

DRIVING SIMULATOR CRASHES

Of 23 subjects with central visual field defects, 8 (35%) caused 9 crashes in the driving simulator, 8 (23%) of 35 subjects with peripheral visual field defects caused 11 crashes, and 2 (9%) of 23 subjects with mild visual field defects caused 2 crashes. Eighteen crashes involved collisions with vehicles approaching from the right or left
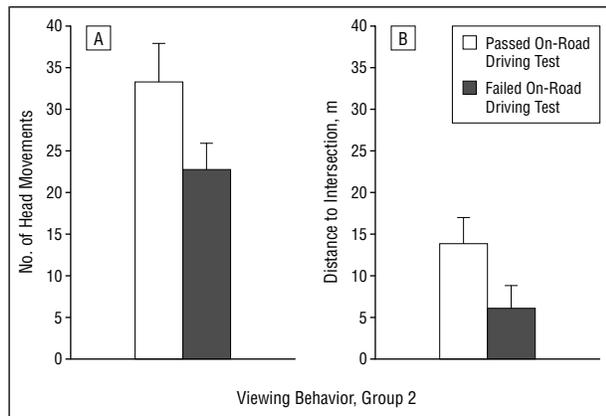
Figure 5. Effect of compensatory viewing behavior on the pass/fail score of the on-road driving test in subjects with peripheral visual field defects. Subjects who passed the driving test made more head movements and started to scan earlier than subjects who failed the driving test. Error bars indicate SEM.

at intersections, 3 crashes involved collisions with stationary or braking lead vehicles, and 1 collision occurred during lane changes on the highway.

The proportion of subjects causing 0 crashes vs at least 1 crash did not vary as a function of visual field defect ($\chi^2_2 = 4.5$; $P = .10$). Likewise, the proportion of subjects causing at least one crash with a car approaching from the left or right did not vary as a function of visual field defect ($\chi^2_2 = 4.4$; $P = .11$).

COMPENSATORY BEHAVIOR

Of 23 subjects with central visual field defects, 5 (22%) passed the on-road driving test; 15 (43%) of 35 subjects with peripheral visual field defects and 13 (57%) of 23 subjects with mild visual field defects passed the on-road test. Subjects with peripheral visual field defects who passed the on-road driving test made more head movements when approaching an intersection with a yield sign while driving on the driving simulator than subjects with peripheral visual field defects who failed the driving test (Mann-Whitney $U = 39.5$; $P = .05$) (**Figure 5**). They also started to scan at a longer distance from the next intersection than did subjects who failed the driving test (Mann-Whitney $U = 36.0$; $P = .03$). Viewing angle did not differ between subjects who failed or passed the on-road driving test (Mann-Whitney $U = 54.0$; $P = .23$). Viewing behavior measures on crossroads without a sign did not differ between the 2 groups (viewing angle, $P = .94$; number of head movements, $P = .17$; and distance at which subjects started to scan, $P = .35$).

Subjects with peripheral visual field defects who failed the on-road driving test drove significantly slower in the town center (mean [SD], 46 [6.8] km/h) than did subjects with peripheral visual field defects who passed the driving test (50 [3.4] km/h; Mann-Whitney $U = 85.0$; $P = .03$). They also drove slower on the highway (105 [7.6] km/h) than did subjects who passed the test (112 [5.9] km/h; Mann-Whitney $U = 52.5$; $P = .02$). Driving speed for the other pathways were in line with this effect but did not reach significance. Subjects with central visual field defects who failed the on-road driving test drove signifi-

cantly faster on the highway (104 [14] km/h) than did subjects with central visual field defects who passed the driving test (93 [6.3] km/h; Mann-Whitney $U = 16.0$; $P = .04$). Results for the other pathways were in line with this effect but did not reach significance.

PREDICTING PRACTICAL FITNESS TO DRIVE

Five variables correlated significantly with the final score on the on-road driving test (Spearman correlations): minimum time to collision ($r = 0.47$; $P < .001$), number of head movements ($r = 0.32$; $P = .01$), the distance to the next intersection at which subjects started to scan ($r = 0.35$; $P = .01$), driving speed ($r = 0.27$; $P = .01$), and the distance to the next intersection at which the subject released the accelerator pedal ($r = 0.24$; $P = .03$). Logistic regression analysis was used to determine whether the 5 simulator indexes improved prediction of the pass/fail score of the on-road driving test. Two models were compared: a model based on visual acuity, visual field, and AFOV threshold presentation times (model 1) and a model based on contrast sensitivity and visual attention (model 2). The vision parameters were entered on a theoretical basis described in a previous study.[5] The simulator indexes were entered into the model in a stepwise manner (forward; Wald method). Nagelkerke R^2 was used as an estimate to express the explained variance. Model 1 explained 37.5% of the variance of the pass/fail score ($\chi^2_3 = 19.6$; $P < .001$). Of the simulator indexes, only the distance at which subjects started to scan was entered into the model by the forward method. Adding this variable to the model improved the predictive power to 47% ($\chi^2_4 = 25.6$; $P < .001$). The sensitivity of this model was 90%, and specificity was 74% (criterion standard, 0.51). The other variables did not improve the predictive power of the initial model. Model 2 explained 34.5% of the variance in the pass/fail score. As in the first model, only the distance at which subjects started to scan was selected. Adding this variable to the model increased the predictive power to 45% ($\chi^2_3 = 24.5$; $P < .001$). Sensitivity and specificity of this model were 90% and 61%, respectively (criterion standard, 0.58).

COMMENT

That subjects with central visual field defects reduced their driving speed has reported before by Szlyk et al[14] and others. The short minimum time to collision indicated that subjects with central visual field defects did not react as promptly as the other groups to the speed differences of the lead car. Minimum time-headway data were in accordance with this finding. Minimum time-headway when the lead car drove at a variable speed was shortest in the group with central visual field defects, corroborating the hypothesis that their reaction to speed changes by the lead car was delayed. The delayed reaction may be related to the use of extrafoveal perception to evaluate velocity changes. Lamble et al,[15] for example, assessed the driver's ability to detect the approach of a decelerating lead car when simultaneously performing an in-car attention task. They observed that time to collision was inversely related to the eccentricity of the in-car attention

task. Likewise, Summala et al[16] showed that the mean delay in braking reaction time was 0.9 seconds when drivers were looking at the lower windshield, 2.1 seconds when they were looking at the speedometer, and 2.9 seconds when they were looking at the midconsole position.

Subjects with peripheral visual field defects showed increased SDs of lateral position and made more lane boundary crossings than subjects with central or mild visual field defects, indicative of increased swaying. Wood and Troutbeck[4] also reported that the relative road position of drivers with artificially restricted visual fields of 20° and 40° in diameter was affected, especially at corners where the middle white line was frequently crossed. Szlyk et al[17] reported that the proportion of individuals who had at least 1 lane boundary crossing was greater for subjects with juvenile macular degeneration (40%) and retinitis pigmentosa (38%) than for control subjects (21%) but that SD of lateral position did not differ among the 3 groups. The same pattern of results was observed by Szlyk et al[14] in a group of drivers with age-related macular degeneration. Increased swaying by subjects with peripheral visual field defects may be the result of the lack of optic flow information in the periphery or the result of the head and eye movements they have to make to get an overview of the environment. Data from our subjects with central visual field defects, however, did not support the conclusion by Szlyk et al[14,17] that subjects with central visual field defects made more lane boundary crossings than control subjects. In the present study, the number of lane boundary crossings was lower in subjects with central visual field defects than in subjects with mild or peripheral visual field defects. Data on mean lateral position also support the finding that road position control was not impaired in subjects with central visual field defects; the interaction effect between visual field defect and path on mean lateral position indicated that the lateral position of the subjects with central visual field defects remained fairly constant and did not vary as a function of the curvature of the road. In contrast, subjects with peripheral and mild visual field defects showed a deviation to the left in left curves and a deviation to the right in right curves. The finding that the lateral position of subjects with central visual field defects was not affected by the curvature of the road concurs with the findings of Land and Horwood[2] and the model by Donges,[1] who proposed a double model of steering. This model asserts that distant parts of the road provide information about road curvature, whereas accurate position-in-lane information comes from the nearer part of the road. Because Land and Horwood[2] further state that drivers rarely fixate on the near region but instead view it peripherally, it was hypothesized that subjects with central visual field defects might perform inferiorly with regard to matching the road curvature but that lane position might be intact. In favor of this hypothesis, results of the present study showed that road curvature did not affect the mean lateral position of subjects with central visual field defects as much as that of subjects with mild or peripheral visual field defects. Further, many subjects with central visual field defects reported that they were unaware of the curvature of the road and asserted that they focused on the right lane boundary.

The effects of peripheral visual field defects on reaction time and peripheral awareness have been investigated frequently. For example, Wood and Troutbeck[18] reported that peripheral awareness was not impaired in a case of a 90°-diameter visual field restriction, although reaction times to centrally and peripherally positioned dashboard LEDs were significantly longer than in the baseline condition. Constriction of the binocular visual field to a diameter of 20° or 40° did impair peripheral awareness, particularly in times of information overload.[4] In the present study, the number of collisions with vehicles approaching from the left or the right did not vary as a function of visual field defect.

The distance at which subjects started to brake when approaching an intersection did not differ between visual field defect groups. This finding does not concur with earlier findings by Szlyk et al[14] who observed that mean braking response time to a stop sign was slightly impaired in subjects with age-related macular degeneration. The same authors observed significantly longer braking response times in subjects with juvenile macular dystrophies (stop sign and traffic light) and in subjects with retinitis pigmentosa (stop sign).[17] In the present study, distance to the intersection at which subjects started to brake was characterized by large individual differences, as indicated by the large SDs in each group, and this may explain the absence of a statistically significant difference among groups.

The second research question related to the effect of compensatory behavior. In favor of our hypothesis, it was observed that subjects with central visual field defects who passed the on-road driving test drove significantly slower on the driving simulator than subjects with central visual field defects who failed the on-road driving test. Data were also in agreement with our scanning hypothesis regarding subjects with peripheral visual field defects. It was observed that subjects with peripheral visual field defects who passed the on-road driving test made more head movements and started to scan earlier than subjects with peripheral visual field defects who failed the driving test. But, contrary to our hypothesis, slowing down was not evaluated as a compensatory mechanism to increase driving safety in this group. Rather, subjects with peripheral visual field defects who drove more slowly were regarded as more unsafe. Clearly, the type of visual field defect determines whether slowing down is regarded as a compensatory mechanism or an impaired aspect of driving.

The third research question related to the prediction of practical fitness to drive. It was observed that minimum time to collision, number of head movements, distance to the intersection at which subjects started to scan, driving speed, and distance to the intersection at which subjects released the accelerator pedal correlated significantly with pass/fail score on the on-road driving test, suggesting that these aspects of driving were considered to be important variables to distinguish between safe and unsafe drivers. Therefore, these driving simulator indexes were used as predictor variables in a regression model to predict practical fitness to drive. Two models were compared: a model based on visual acuity, visual field, and viewing efficiency (AFOV threshold presentation times) and a model based on contrast sensitivity

and visual attention.[5] Adding the variable distance to the intersection at which subjects started to scan to the model improved the predictive power of both models. Increasing the distance is an adaptation at the tactical level.[19] To start scanning while approaching an intersection reflects the decision to avoid time pressure when the intersection is actually reached. This tactical ability to avoid time pressure was an important determinant of the final score by the examiners.

In conclusion, the visual field defect groups showed differential performance on several driving simulator indexes. It was observed that subjects with central visual field defects drove at a lower speed, that they had smaller safety margins, and that their lateral position was not influenced by the curvature of the road. Subjects with peripheral visual field defects showed increased swaying. Official driving examiners regarded reducing driving speed as a good compensatory strategy in subjects with central visual field defects. In subjects with peripheral visual field defects, increasing the number of head movements and starting to scan early were considered necessary behavioral modifications to pass the on-road driving test. Adding a tactical variable (distance to the next intersection at which subjects started to scan) to a model based on visual acuity, visual field, and viewing efficiency (AFOV) or to a model based on contrast sensitivity and visual attention improved the capacity to predict the pass/fail score on the on-road driving test.

Corresponding author and reprints: Tanja R. M. Coeckelbergh, PhD, Laboratory of Experimental Ophthalmology, University of Groningen, PO Box 30001, 9700 RB Groningen, the Netherlands (e-mail: t.r.m.coeckelbergh@ohk.azg.nl).

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