

The Effects of Age and Central Field Loss on Head Scanning and Detection at Intersections

Alex R. Bowers¹, P. Matthew Bronstad¹, Lauren P. Spano², Robert B. Goldstein¹, and Eli Peli¹

¹ Schepens Eye Research Institute of Massachusetts Eye and Ear, Department of Ophthalmology, Harvard Medical School, Boston, MA, USA

² Vision Science, University of California, Berkeley, CA, USA

Correspondence: Alex R. Bowers, Schepens Eye Research Institute of Massachusetts Eye and Ear, 20 Staniford Street, Boston, MA 02114, USA. e-mail: alex_bowers@meei.harvard.edu

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Purpose: Using a driving simulator, we quantified the effects of age and central field loss (CFL) on head scanning when approaching an intersection and investigated the role of inadequate head scanning in detection failures.

Methods: Participants with CFL ($n = 20$) and with normal vision (NV; $n = 29$), middle-aged (36–60 years) or older (67–87 years), drove along city routes with multiple intersections while head movements were recorded. The effects of age and CFL on scanning were analyzed at 32 intersections with stop/yield signs. The relationships between age, CFL, scanning, and detection were examined at four additional intersections with a pedestrian appearing on the far left.

Results: Older NV participants made fewer total scans than middle-aged NV participants and had smaller maximum scan magnitudes. Head scanning of older CFL and NV participants did not differ, but middle-aged CFL participants made fewer head scans, had higher rates of failing to scan, and made smaller head scans than middle-aged NV participants. For the older NV and both CFL groups, detection failures were high ($\geq 58\%$); head scan magnitudes were 15° smaller when the pedestrian was not detected than when it was detected.

Conclusions: Both older NV and CFL participants exhibited head scanning deficits relative to middle-aged NV participants. Unexpectedly, however, it was the middle-aged CFL group that performed least well when scanning, a finding that warrants further investigation.

Translational Relevance: Failing to head scan sufficiently far at intersections may place older drivers and drivers with vision impairment at a higher risk for causing collisions.

Introduction

Older drivers are the most rapidly increasing segment of the driving population.^{1,2} They are particularly at risk for collisions at intersections,^{3–6} especially when there is no intersection control device (stop or yield sign or traffic signal).^{7,8} A field of view of almost 180° (the clear-sight triangle⁹; Fig. 1) needs to be visually examined before entering a non-signal-controlled four-way (+) or three-way (T) intersection. Usually this is achieved by using lateral head and eye movements to scan (look) in each direction before entering the intersection.^{10–12} Hazards could be

detected with peripheral vision so the scan does not necessarily need to cover the full 90° on each side of the intersection. However, a large scanning movement (e.g., 60°) would be needed to bring the objects at the extremes of the clear-sight triangle sufficiently close to the fovea to be detected. Detection failures might, therefore, be a result of not scanning far enough. A large scan of 60° usually comprises a large head rotation (e.g., $>40^\circ$)¹⁰ with one or more eye saccades.^{11,12} (Eye movements alone may not be sufficient because the maximum eye scanning range is limited to about 40° to 60° ,^{13,14} and naturally occurring eye saccades typically do not exceed a

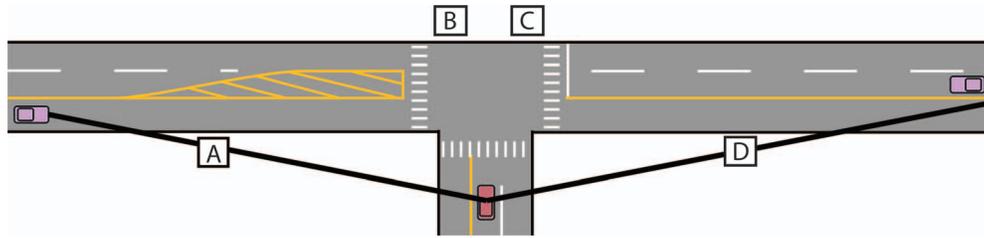


Figure 1. Schematic, approximately to scale, of the clear-sight triangle (*thick black lines*) for a stop-controlled intersection at a 30-mph cross street.⁹ The pedestrian at A (40 m along the sidewalk from the intersection) could only be seen if participants made a head scan in that direction. Pedestrians at B and C (near the center of the intersection) and D (only appeared on a right turn) could be seen without needing to make a head scan.

magnitude of 15° ¹⁵). Given that the head rotation is an important component of these large scans, it is possible that head scanning deficits (e.g., failing to make a head scan or making only a small head scan of inadequate magnitude)¹⁰ may contribute to failures to detect hazards at the extreme edge of the clear-sight triangle. Decreased neck flexibility (head rotation)^{16–18} might increase the likelihood of older drivers exhibiting such head scanning deficits. Alternatively, older drivers might simply develop an unsafe habit in which they focus on the area of the roadway toward which they are headed at the expense of scanning to check for peripheral hazards.^{19,20}

Only a few studies^{17,21,22} have investigated intersection head scanning of older drivers with normal vision (NV). Results were conflicting: older NV drivers were reported to either make a similar number of head turns^{17,22} or fewer head turns²¹ than middle-aged NV drivers. However, those studies^{17,21,22} did not quantify aspects of head scanning that might contribute to detection failures such as failing to head scan in the direction of a hazard or making a head scan of inadequate magnitude. Only one study²¹ provided a rough estimate of the magnitude of the head movement (whether it was greater or less than 45°). In studies that recorded gaze movements (combined eye and head movements), older NV drivers were reported to spend a greater proportion of time looking at or close to the direction of travel²⁰ and were less likely to make gaze scans to recheck for hazards after entering the intersection.^{20,23,24} To our knowledge, however, only one study²⁴ has reported that failing to gaze scan toward hazards at intersections resulted in detection failures. In the current study we extended prior research^{17,21,22} on head scanning at intersections by evaluating the number, direction, and magnitude of head scans, as well as failures to scan in a specific direction. In addition, we investigated the role of inadequate head scanning in

failures to detect a pedestrian at the far left of the clear-sight triangle (Fig. 1), which, based on results from a prior study,¹⁰ required a substantial head scan ($\approx 50^\circ$) to be detected by drivers with NV.

Central field loss (CFL) in older age is accompanied by reduced visual acuity and reduced contrast sensitivity and might contribute to difficulties of older drivers in detecting hazards at intersections. CFL is often caused by age-related macular degeneration (AMD), a major cause of central vision impairment in the United States.²⁵ People with CFL with visual acuity that does not meet the requirement for an unrestricted license (e.g., 20/40 in many states and countries) may be permitted to drive with a restricted license. With the advent of new anti-vascular endothelial growth factor treatments for neovascular AMD,^{26,27} there will be increasing numbers^{28,29} of older people with AMD who retain visual acuity sufficient to meet the vision requirements for driving with a restricted license (visual acuity can be as low as 20/200 in some states).³⁰ It is therefore important to study the effects of CFL on driving performance. However, there is a paucity of data about drivers with CFL,³¹ in particular their scanning behaviors and detection performance at intersections. In a questionnaire study,³² about one third of drivers with CFL caused by AMD reported difficulty with making turns across traffic, while 13% reported no longer making the maneuver because of their vision. In a driving simulator study,^{33,34} participants with CFL, mostly caused by AMD, were much slower to respond to pedestrian hazards than age-similar NV drivers; however, the hazards were not at intersections. Only one study³⁵ has recorded head scanning of drivers with CFL at intersections. The results suggested that the number of head scans did not differ between drivers with CFL and NV,³⁵ but failures to head scan, head scan magnitudes and the relationship between

scanning and detection performance were not investigated.

In the current study, we used the controlled environment of a driving simulator to investigate the effects of age and CFL on head scanning behaviors at intersections. Age effects were investigated by comparing head scan behaviors of older drivers to those of middle-aged experienced drivers rather than young novice drivers whose scanning behaviors may differ from those of experienced drivers.³⁶ We predicted that older drivers would make fewer head scans with a smaller average magnitude than would middle-aged drivers. The effects of CFL were investigated by comparing scanning behaviors of older CFL to older NV drivers, and scanning behaviors of middle-aged CFL to middle-aged NV drivers. We predicted that head scan numbers and magnitudes would not differ substantially between participants with CFL and NV because the central scotoma occupies only a small area of the total area to be scanned at an intersection. Nevertheless, we did examine the relationship between scotoma location and head scanning patterns in the CFL group. Finally, we investigated the relationship between head scanning deficits and detection failures. We predicted that older drivers would have lower detection rates than middle-aged drivers for a pedestrian at the far left of the intersection and that lower detection rates would be associated with smaller head scan magnitudes in both drivers with NV and drivers with CFL. For drivers with CFL, we expected that, in addition to head scanning deficits, the level of vision impairment might also affect detection performance: specifically, that larger scotomas and poorer contrast sensitivity would be associated with lower detection rates, as reported previously.³³

Methods

The study was conducted in accordance with the tenets of the Declaration of Helsinki and approved by institutional review boards at the Schepens Eye Research Institute and the Boston Veterans Administration Healthcare System. Voluntary written informed consent was obtained from all participants.

Participants

Participants (Table) were recruited in two age groups: middle-aged (range, 36–60 years) and older (range, 67–87 years). CFL participants ($n = 52$) were recruited from the Schepens subject database and

Veterans Administration hospital database. Study criteria included a central scotoma in binocular viewing (measured with 0.74° square target at 1 m) and binocular single-letter visual acuity of at least 20/200. Of the 52 CFL participants screened, 17 did not meet the study criteria, 11 withdrew due to simulator discomfort, one could not maintain speed in the simulator, and three had poor-quality head-tracking data. Data from the remaining 20 CFL participants were included in analyses. Thirteen participants had a lateral scotoma (to the right or left of the binocular preferred retinal locus [PRL] in visual field space), and seven had a vertical scotoma (above or below the PRL). Results for detection of nonintersection pedestrians were previously reported for 11 of the 13 participants with a lateral scotoma³³ and the seven participants with a vertical scotoma.³⁴

NV current drivers ($n = 29$, binocular visual acuity at least 20/25) were recruited from the Schepens subject database and the Harvard Cooperative Program on Aging. They were selected to have an age and sex distribution similar to the CFL group. All CFL participants passed (≤ 4 errors) the Short Portable Mental Status Questionnaire (SPMSQ).³⁷ NV participants either passed the SPMSQ or had a Mini-Mental State Examination (MMSE)³⁸ score of ≥ 26 . All participants (NV and CFL) had to meet the visual field requirements for driving in Massachusetts (120° binocular extent); the actual minimum visual field extent across participants was 160° (Goldmann V4e target).

Vision Measures

Single-letter visual acuity (VA) was measured in binocular viewing conditions (TestChartPro2000; Thomson Software Solutions, Hatfield, UK). Letter contrast sensitivity (2.5° letters) was also measured in binocular viewing using a custom computer-based test that gives results consistent with the Pelli-Robson chart.³⁹ The central scotoma of CFL participants was mapped using a custom computer-based test (74-cd/m^2 bright 0.74° square targets, 21-cd/m^2 gray background, viewed binocularly from 1 m, fixating a 1.23° cross).⁴⁰ Standard kinetic perimetry was used, measuring the scotoma from inside to outside. Scotoma size was defined as the average diameter of four cardinal meridians through the center. Binocular scotoma location was categorized as above, below, left, or right of the binocular PRL in visual field space.

Table. Demographics, Vision Status, and Driving Characteristics of Participants Who Completed the Study

Parameter	NV		CFL	
	Middle-aged (<i>n</i> = 15)	Older (<i>n</i> = 14)	Middle-aged (<i>n</i> = 9)	Older (<i>n</i> = 11)
Age, <i>y</i> , mean ± SD	47 ± 9	76 ± 7	50 ± 7	79 ± 7
Male, <i>n</i> (%)	9 (60)	11 (79)	5 (56)	8 (73)
Cause, <i>n</i>				
AMD	N/A	N/A	2	10
Stargardt disease	N/A	N/A	3	1
Optic atrophy	N/A	N/A	2	
Other ^a	N/A	N/A	2	
Age at onset, <i>y</i> , median (IQR)	N/A	N/A	25 (16–47)	65 (62–79)
Binocular VA, logMAR, mean ± SD	−0.13 ± 0.12	−0.02 ± 0.09	0.65 ± 0.27	0.57 ± 0.22
Binocular contrast sensitivity, log, mean ± SD	1.89 ± 0.07	1.68 ± 0.18	1.25 ± 0.25	1.22 ± 0.27
Binocular scotoma diameter, degrees, mean ± SD	N/A	N/A	12.4 ± 6.3	11.5 ± 6.5
Scotoma location, <i>n</i>				
Above	N/A	N/A	3	3
Below	N/A	N/A	0	1
Left	N/A	N/A	2	1
Right	N/A	N/A	4	5
Left and right	N/A	N/A	0	1
Age when licensed, <i>y</i> , median (IQR)	18 (16–19)	16 (16–18)	18 (17–27)	19 (16–25)
Years driving with vision loss, median (IQR)	N/A	N/A	13 (10–19)	8 (4–19)
Current driver, <i>n</i> (%)	15 (100)	14 (100)	6 (67)	5 (45)
Miles per week, <i>n</i> , median (IQR)	168 (50–260)	80 (18–172)	35 (20–70)	42 (31–114)

^a Maculopathy from presumed ocular histoplasmosis syndrome (1) and Plaquenil toxicity (1).

Driving Simulator Apparatus

Participants drove in a simulator (PP1000-x5; FAAC Corp., Ann Arbor, MI), with five 60 × 45-cm cathode ray tube monitors (1024 × 768 pixels, 60 Hz, field of view 225° horizontal by 32° vertical). The wide field of view enabled realistic intersection scenarios to be presented. The simulator had automatic transmission and controls typical of American sedans. Data output was at 30 Hz, including vehicle position and speed, controls use, and locations of programmable entities in the virtual world. Additional details are available.^{10,33}

A remote infrared system (TrackIR 3; Natural-Point, Corvallis, OR) was used to record head movements. Participants wore a lightweight headband with three reflectors attached in a triangular pattern. The infrared source and tracking camera were mounted above the central screen of the simulator. The system tracked the head with 1° accuracy and a horizontal range of ± 70°, sufficient to capture large lateral scanning movements at

intersections. Head position data were collected at 60 Hz but were synchronized to the slower driving simulator data feed (30 Hz).

Driving Simulator Procedures

Two driving simulator sessions were conducted approximately 1 week apart. However, because of fatigue or simulator discomfort, five participants needed three sessions (with 1 week between each session) to complete all test drives. Each driving simulator session started with a period of acclimation to the driving simulator followed by a practice drive that included all of the elements of the test drives. Across the two (or three) driving simulator sessions, each participant completed 10 test drives, each about 10 minutes, including six routes on city roads (30 mph) and four routes on highways (60 mph) with a variety of traffic situations. All participants completed the same set of test drives in a pseudorandomized order. City drives included a variety of intersections (see below), while highway drives did not (thus, data from highway drives are not included in this paper).

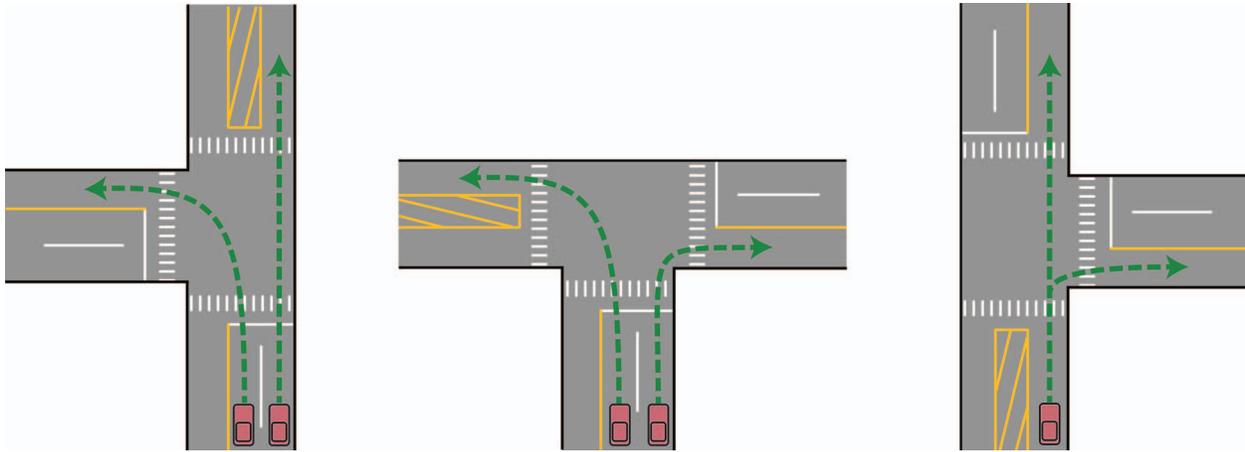


Figure 2. Head scanning was evaluated at T-intersections that had a stop or yield sign. The intersections had three configurations: (a) Incoming road on left only; (b) incoming roads on both sides; and (c) incoming road on the right only.

Participants performed a detection task while driving,³³ pressing the horn button as soon as a pedestrian was seen. Participants were instructed to obey normal traffic laws and were not given any instructions about scanning at intersections.

Lateral head movements were recorded during each test drive. The head tracker was calibrated using a five-point sequence (-67.5° , -22.5° , 0° , 22.5° , and 67.5°) at the start and end of every drive. The time to complete each simulator session (acclimation and 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.

Intersections

T-intersections with stop or yield signs were the most common type of intersection along the six city routes. Other types of intersections (e.g., Y and four-way) or intersections with traffic lights did not occur with sufficient frequency to be included in analyses. The T-intersections had three configurations (Fig. 2): incoming road on left only, incoming roads on both sides, and incoming road on right only. Cross traffic was programmed at about one third of intersections along each route, with no more than one vehicle in each direction.

Pedestrians at Intersections

A stationary life-size (2-m tall) pedestrian figure appeared at 10 intersections across the six city drives¹⁰: four times at location A (twice on a right turn and twice on a left turn) and twice at each of the other locations B (on a left turn), C (on a left turn), and D (on a right turn) (Fig. 1). Pedestrians appeared

only at T-intersections with incoming roads on both sides (Fig. 2b). Each pedestrian appeared as the driver was slowing to a stop at the intersection and disappeared as soon as the turn was completed; only one pedestrian appeared at a time. When they first appeared, pedestrians at A and D were at an eccentricity of about 85° with respect to the car heading direction, while pedestrians at B and C were at eccentricities of about 20° and 15° , respectively. Pedestrian appearances at intersections were an uncommon event; there were over 100 pedestrian appearances across all the test drives,³³ but only 10 of these were at intersections. Cross traffic was not programmed at intersections with pedestrians.

Quantifying Head Scanning at Intersections without Pedestrians

In the first set of analyses, we quantified the effects of vision group (NV or CFL) and age group (middle-aged or older) on head scanning at the intersections without pedestrians. These analyses included data from 32 intersections across the six city routes (11 with incoming road on left only, 12 incoming roads on both sides, and nine incoming road on right only).

On approaching an intersection, head movements typically comprised a series of single large rotations, taking the head away from the straight-ahead position to the left or right, with a subsequent single large rotation in the opposite direction, bringing the head back to the center, sometimes directly continuing with a large rotation to the other side (Figs. 3 and 4). A head scan was defined as a lateral head rotation (yaw) away from the straight-ahead position for at least 0.2 seconds with a net monotonic change in

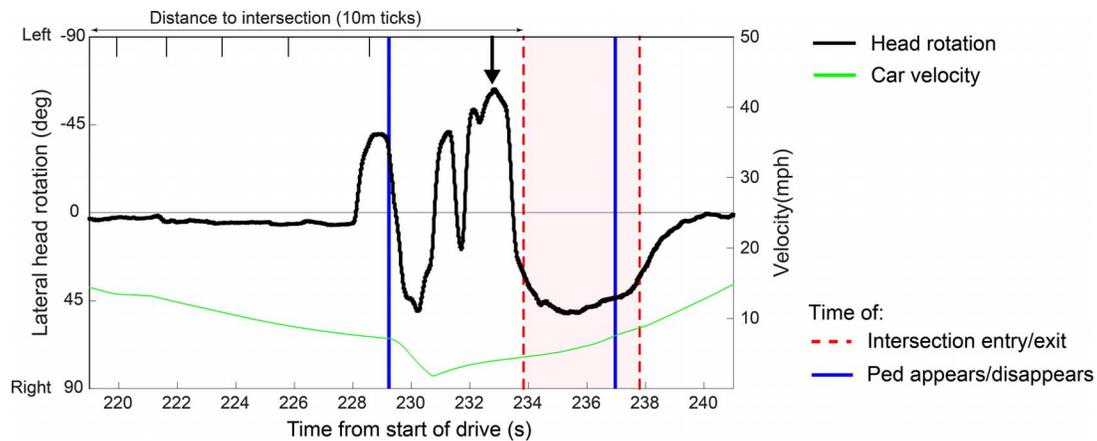


Figure 3. Lateral head rotation (*black line*) of a middle-aged participant with CFL on approach to a T-intersection with a stop sign, incoming roads on both sides, and a pedestrian at the far left (-85° ; location A on Fig. 1). The participant detected the pedestrian. As the participant's car velocity (*green line*) decreased, the participant started to execute large head scans (movements away from straight ahead) first to the left, then to the right, followed by two more to the left. The pedestrian appeared just after the end of the first leftward scan (at about 229 seconds). At the end of the final leftward head scan of 57° magnitude, the horn was pressed (*large black arrow*) to indicate detection. After entering the intersection (*light red-shaded region*), the participant executed a right turn.

angle of more than a three-tier threshold magnitude (4° , 6° , and 10°), depending on the distance from the intersection.¹⁰ The thresholds were derived from a computation of the minimum movement required to turn the head to the middle of the oncoming traffic lane on the right when there were two lanes in each direction in the cross street (a minimum movement of: 4° for $50\text{ m} < d \leq 100\text{ m}$, 6° for $25\text{ m} < d \leq 50\text{ m}$, and 10° for $0\text{ m} < d \leq 25\text{ m}$, where d = distance to the intersection).

Head scans were analyzed from 100 m before the

intersection until the front axle of the car crossed the white stop line on entering the intersection.¹⁰ A custom algorithm, developed for a prior study of head scanning at intersections,¹⁰ was used to quantify the direction and magnitude of each head scan. Scan direction was assigned a left/right binary code in terms of whether the scan took the head away from the straight-ahead position toward the left side or the right side. The mean numbers of left and right scans per intersection were computed for each participant and used in statistical analyses. For head scan

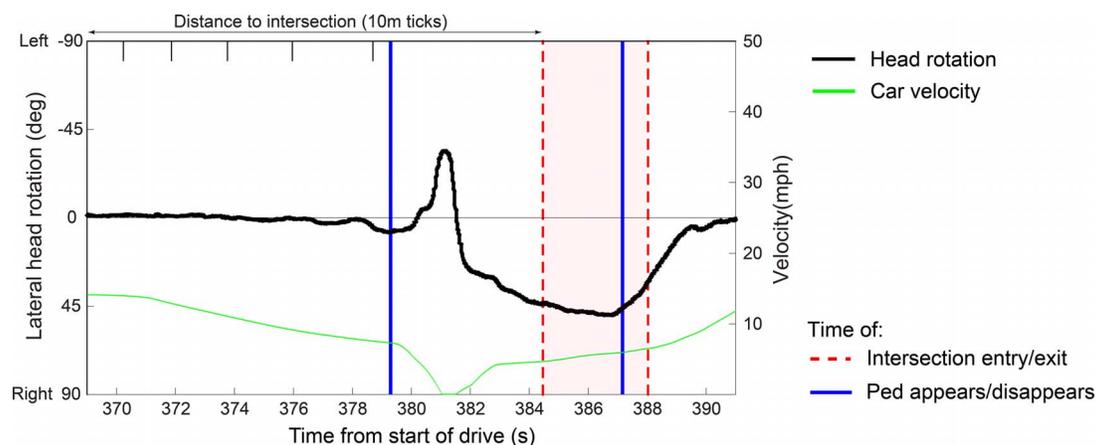


Figure 4. Lateral head rotation (*black line*) of a middle-aged participant with CFL on approach to a T-intersection with a stop sign, incoming roads on both sides, and a pedestrian at the far left (-85°). The participant failed to detect the pedestrian. The pedestrian appeared at about 379 seconds. The participant made one head scan of 32° magnitude to the left at about 381 seconds. There was no horn-press response, suggesting that the head scan was of insufficient magnitude to bring the gaze close enough for the pedestrian to be detected. After entering the intersection, the participant executed a right turn.

magnitudes, the 100-m approach distance was split into two pseudologarithmic bins: 100 to 15 m (far) and 15 to 0 m (near). For each participant, a median scan magnitude was calculated for each bin and used in statistical analyses.

We also quantified the number of intersections at which participants failed to scan in the direction of an incoming road. For failures to scan to the left when there was a road on the left, we combined data for the two intersection configurations with a road on the left, that is, incoming road on the left only (Fig. 2a) and incoming roads on both sides (Fig. 2b). Similarly, for failures to scan to the right when there was a road on the right, we combined data for the two intersection configurations with a road on the right, that is, incoming road on the right only (Fig. 2c) and incoming roads on both sides (Fig. 2b).

The Relationship Between Head Scanning and Detection at Intersections With Pedestrians

In the second set of analyses, we investigated the relationship between head scanning and detection of a pedestrian at location A, on the far left of the intersection (Fig. 1). All participants had to head scan in order to see the pedestrian at this location. By comparison, the pedestrians at locations B and C near the center of the intersection could easily be seen without a head scan. The pedestrian at location D on the far right, which appeared only on a right turn, could also be seen without a head scan as it came close to the line of gaze near the end of the turn maneuver. Given that pedestrians at B, C, and D could be seen without needing to make a head scan, they were not included in analyses of the relationship between scanning and detection. Detection rates for pedestrians at locations B, C, and D are reported in the Appendix.

For the four intersections with a pedestrian at location A, head scans toward the pedestrian were analyzed between the time it appeared and either the time of the horn press or the time when it disappeared, whichever occurred first (Figs. 3 and 4). Each pedestrian event was then categorized as follows: (1) driver failed to scan toward pedestrian and did not detect; (2) driver scanned toward the pedestrian but did not detect; or (3) driver scanned toward pedestrian and detected. When there were leftward head scans in the direction of the pedestrian, the maximum scan magnitude, either before the horn

press when detected or before the pedestrian disappeared when not detected, was used in analyses.

Statistical Analyses

Effects of Vision Status and Age on Head Scanning at Intersections Without Pedestrians

We first analyzed the effects of vision group (NV or CFL) and age group (middle-aged or older) on head scanning at T-intersections without pedestrians (32 intersections per subject). The mean number of scans per intersection was analyzed with a repeated-measures ANOVA. Vision and age were the two between-subjects factors, and head scan direction (left or right) and intersection configuration (incoming road on left only, both sides, right only) were the two within-subjects factors. Head scan magnitudes were also analyzed with a repeated-measures ANOVA. Vision and age were the two between-subjects factors, and head scan direction (left or right) and distance to intersection (≤ 15 or > 15 m) were the two within-subjects factors. Intersection configuration was previously¹⁰ found to have a strong effect on the number of head scans in each direction but not head scan magnitudes, hence it was included as a within-subjects factor for the analysis of the numbers of scans per intersection but not scan magnitudes. Finally, a mixed effects binary logistic regression analysis was used to evaluate whether participants scanned in the direction of an incoming road. Fixed factors included vision, age, and side of road (left or right), with subject as a random factor.

For the CFL group, we conducted additional analyses to evaluate the effects of driving status (former or current driver) and scotoma location, as both these factors could potentially affect head scanning behaviors. Only two scotoma locations, above and right, had sufficient subjects for analysis (Table). If scotoma location had any effect on scanning, then we expected that a lateral right scotoma would be more likely to have an effect than a vertical above scotoma; for example, participants with a right scotoma might make more scans to the right, larger scans to the right, or would be less likely to fail to scan to right than participants with an above scotoma. Each of the analyses for the main head movement measures (number of scans, scan magnitudes, and scanning toward an incoming road) was repeated for the CFL group only, first replacing the factor vision with driving status (former or current driver) and then scotoma location (above or right).

Relationship Between Head Scanning and Pedestrian Detection

In the second set of analyses, we addressed the relationship between head scanning and detection of the pedestrian at location A (four intersections per subject). First, a mixed effects binary logistic regression analysis was used to evaluate whether participants made a head scan in the direction of the pedestrian. Fixed factors included vision and age, with subject included as a random factor. Second, a mixed effects binary logistic regression analysis was used to evaluate whether participants detected the pedestrian when there was a head scan in the direction of the pedestrian. Fixed factors included vision, age, and maximum leftward head scan magnitude. Subject was included as a random factor. The effects of age on the maximum leftward head scan magnitude were evaluated separately for each of the vision groups using a mixed effects linear regression, with the maximum leftward head scan magnitude as the dependent variable, age as a fixed factor, and subject as a random factor. Finally, additional analyses were conducted separately for the CFL group only. For events when there was a head scan toward the pedestrian, mixed effects binary logistic regression analyses were used to evaluate whether VA, contrast sensitivity, scotoma size, scotoma location, and driving status were predictive of pedestrian detection.

Results

Participant Characteristics

As planned, there were no significant differences between NV and CFL participants for gender distribution and age (Table; all $P > 0.70$). However, as expected, CFL participants had significantly worse VA and contrast sensitivity than did NV participants (all $P < 0.001$). The majority of NV and CFL participants were first licensed to drive before 20 years of age. All NV participants were current drivers compared to only 55% (11/20) of CFL participants.

AMD was the predominant cause of the CFL in the older CFL group, whereas the causes were more varied in the middle-aged CFL group (Table). The older CFL group was significantly older at disease onset than was the middle-aged CFL group (Table; $P < 0.001$). However, the older and middle-aged CFL groups did not differ in the severity of the vision impairment. There were no significant differences between the two groups for VA, contrast sensitivity, scotoma diameter, or scotoma location (Table; all P

> 0.50). Most scotomata were to the right or above the PRL (Table).

All of the older CFL participants were first licensed before the onset of the vision loss (median 46 years, interquartile range [IQR] 39–61). By comparison, five of the nine middle-aged CFL participants were first licensed before the onset of the vision loss (median 29 years, IQR 20–39), and four were first licensed after the onset of the vision loss (median 12 years, IQR 6–15). The three middle-aged CFL participants who had stopped driving did so 1, 11, and 13 years prior to the study, compared to a median of 5 years (IQR 2–7) for the six older CFL participants who had stopped driving. However, the total years of driving with vision impairment did not differ statistically between the middle-aged and older CFL participants (Table; $P = 0.47$).

Middle-aged NV participants drove significantly more miles per week than did middle-aged CFL participants ($P = 0.05$), but older NV and CFL participants did not differ for weekly mileages (Table). CFL participants were more likely to avoid difficult driving situations than NV participants, in particular, driving at night; six of nine CFL participants who answered that question did not drive at night compared to only one NV participant.

Effects of Vision and Age on Head Scanning at Intersections Without Pedestrians

Number of Scans per Intersection

Although there were no significant main effects of either vision or age on the number of scans ($P > 0.2$), there was a weak but significant interaction between these factors ($F_{(1,45)} = 4.65$, $P = 0.04$). Within the middle-aged group, NV participants made a significantly greater number of scans than did CFL participants, whereas in the older group, the number of scans did not differ between NV and CFL participants (Fig. 5). As expected when driving on the right-hand side of the road (as in the United States), participants made significantly more scans to the left than the right (overall means 1.3 and 0.9 per intersection, respectively; $F_{(1,225)} = 55.33$, $P < 0.001$). When data for participants in the CFL group only were analyzed, we found a significant interaction between scan direction and driving status. Current CFL drivers made more scans to the left than the right, whereas former CFL drivers did not ($F_{(1,90)} = 12.84$, $P = 0.001$; Fig. 6). We did not, however, find any significant effects of scotoma location ($P > 0.15$).

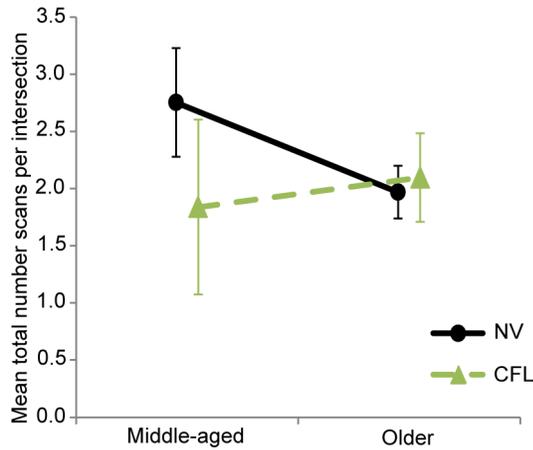


Figure 5. Mean total number of scans per intersection for middle-aged and older NV and CFL participants. Middle-aged drivers made more scans than older drivers in the NV group but not the CFL group. Error bars are 95% confidence limits.

As reported previously,¹⁰ the configuration of the T-intersection also affected the number of scans. When there was no road on the left (incoming road on right only), the number of leftward scans was significantly lower than when there was a road on the left (mean 0.5 vs. 1.7 per intersection). Equally, when there was no road on the right (incoming road on left only), the number of rightward scans was significantly lower than when there was a road on the right (mean 0.3 vs. 1.2 per intersection). This two-way interaction between intersection configuration and scan direction was highly significant ($F_{(2,225)} = 104.14, P < 0.001$).

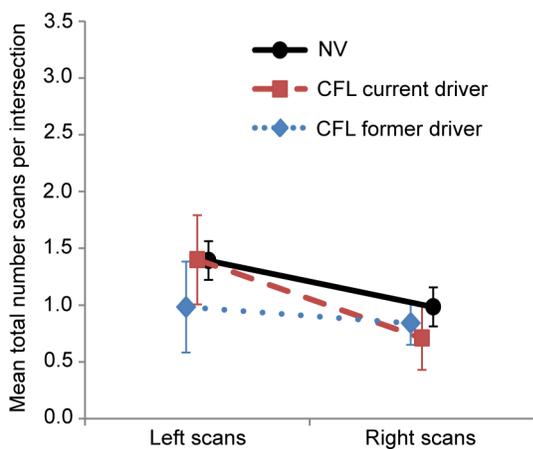


Figure 6. Mean number of scans per intersection for leftward and rightward scans by driving and vision status. In the CFL group, current drivers made more scans to the left than the right (as did NV drivers), whereas former drivers did not. Error bars are 95% confidence limits.

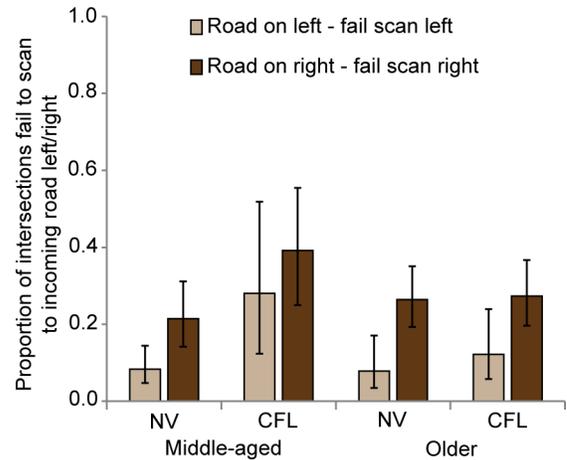


Figure 7. Mean proportion of intersections at which participants failed to scan to an incoming road on either the left or right, for middle-aged and older NV and CFL participants. Scan failure rates were higher for roads on the right than the left in all groups except the middle-aged CFL group. Error bars are 95% confidence limits.

Rates of Failing to Scan to an Incoming Road

Rates of failing to scan to the left when there was a road on the left were lower than the rates of failing to scan to the right when there was a road on the right (overall, 12% vs. 27%, $z = 8.77, P < 0.001$). CFL participants had significantly higher rates of failing to scan than did NV participants (overall, 26% vs. 16%, $z = 2.78, P = 0.005$), but older participants did not have higher rates of failing to scan than did the middle-aged participants (overall, 18% vs. 21%, $z = 0.97, P = 0.330$). There was, however, a trend for an interaction between age category and vision group ($z = 1.83, P = 0.068$). Specifically, the middle-aged CFL participants had higher rates of failing to scan to both the left and right than middle-aged NV participants, while CFL and NV participants in the older age group did not differ (Fig. 7).

Finally, we examined whether there were any effects of driving status (current or former driver) on rates of failing to scan in the CFL group. Current drivers with CFL had higher rates of failing to scan for roads on the right than roads on the left, whereas former drivers with CFL had rates of failing to scan that did not differ for roads on the right and left (Fig. 8) (significant road side by driving status interaction; $z = 3.41, P = 0.004$). We did not, however, find any significant effects of scotoma location on rates of failing to scan to either the left or the right ($P > 0.30$).

Head Scan Magnitudes

CFL participants made significantly smaller head scans than NV participants (means 24.9° vs. 32.6°;

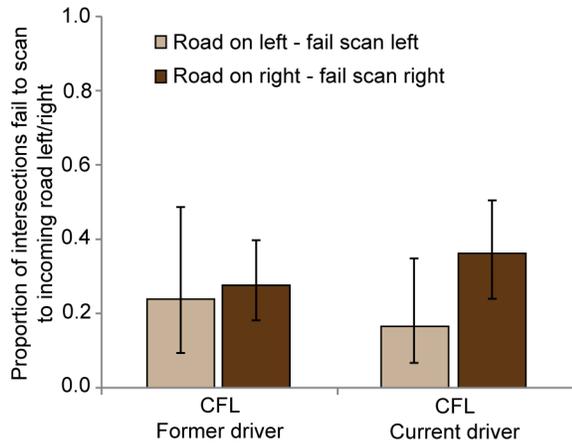


Figure 8. Proportion of intersections at which former and current CFL drivers failed to scan in the direction of an incoming road on the left or right. Scan failure rates were higher for roads on the right than the left for current but not former CFL drivers. Data are pooled across both age groups. Error bars are 95% confidence limits.

$F_{(1,45)} = 12.35, P = 0.001$; Fig. 9). However, older participants did not make smaller head scans than middle-aged participants (means 29.4° vs. 29.6° ; $F_{(1,45)} = 0.01, P = 0.90$). There was a trend for an age category by vision group interaction ($F_{(1,45)} = 3.12, P = 0.08$). Within the middle-aged group, NV participants made significantly larger head scans than did CFL participants, whereas in the older group, head scan magnitudes did not differ between NV and CFL participants (Fig. 9).

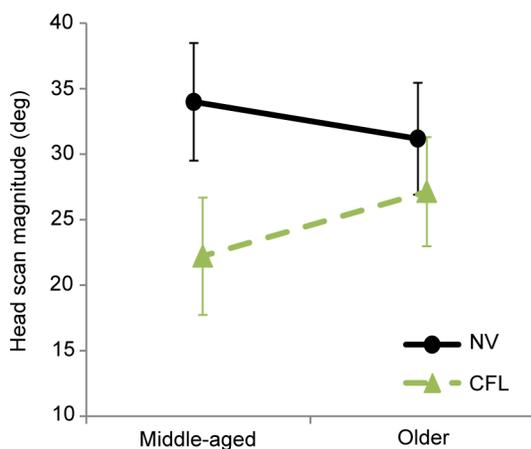


Figure 9. Mean head scan magnitudes for middle-aged and older NV and CFL participants. CFL participants made smaller head scans than NV participants. Data are pooled across the two scan directions and two distance bins. Error bars are 95% confidence limits.

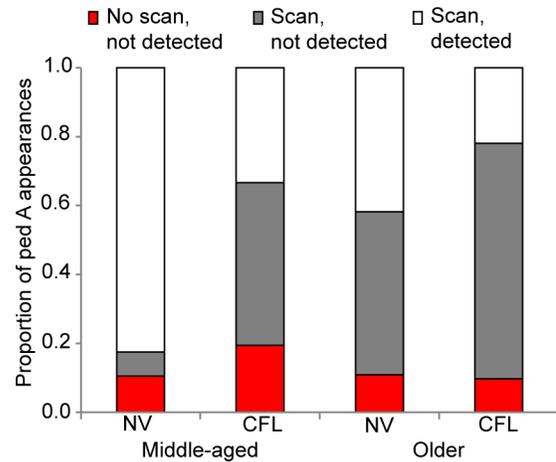


Figure 10. Reasons for detection failures for the pedestrian at location A (far left, see Fig. 1) for NV and CFL drivers. Inadequate scan magnitude (gray shading) was the main reason older NV, older CFL, and middle-aged CFL drivers failed to detect the pedestrian. Data are pooled across participants in each group.

As expected, participants made larger head scans when closer to intersections ($F_{(1,144)} = 158.29, P < 0.001$); average head scan magnitude was 21.5° when far (>15 m) from the intersection and 37.1° when close to it (≤ 15 m). There was also a significant effect of head scan side ($F_{(1,144)} = 19.78, P = 0.01$); leftward scans (30.9°) were on average larger than rightward scans (28.0°). In separate analyses including data for CFL participants only, neither driving status ($P = 0.87$) nor scotoma location ($P = 0.72$) significantly affected head scan magnitudes.

Head Scanning and Detection of Pedestrian at Location A

Rates of failing to detect the pedestrian at A were high: 58% in the older NV group, 68% in the middle-aged CFL group, and 78% in the older CFL group (Fig. 10, combined red- and gray-shaded areas). The only exception was the middle-aged NV group, with a detection failure rate of 18%. When there was no head scan in the direction of the pedestrian, it was never seen; this was the case for both NV and CFL participants. Rates of failing to scan toward the pedestrian (and not see it) did not differ across the groups (Fig. 10, red-shaded areas). There were no significant effects of either age or vision ($z = 0.07, P = 0.948$, and $z = 1.19, P = 0.223$, respectively), and no significant age by vision interaction ($z = 0.93, P = 0.354$) on rates of failing to scan toward the pedestrian at A. However, when a scan was made in

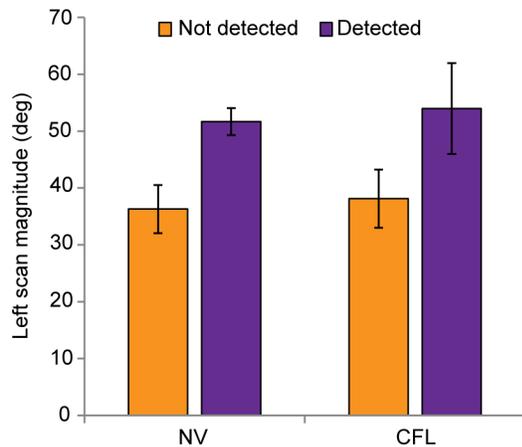


Figure 11. Mean maximum head scan magnitude toward the pedestrian at position A when the pedestrian was and was not seen. Head scan magnitudes were significantly larger when the pedestrian was detected in both the NV and CFL groups. Error bars are 95% confidence limits.

the direction of the pedestrian, then there were highly significant effects of both age and vision on rates of failing to see the pedestrian (Fig. 10, gray-shaded areas). Older participants were significantly less likely to detect the pedestrian than middle-aged participants ($z = 3.28$, $P = 0.001$) and CFL participants were significantly less likely to detect the pedestrian than NV participants ($z = 3.30$, $P = 0.001$). There was also an age by vision interaction that approached significance ($z = 1.73$, $P = 0.08$), suggesting a trend for the difference in detection failure rates between NV and CFL to be greater in the middle-aged group than the older group.

Scanning toward the pedestrian but not detecting it was more common than not scanning and not detecting it (Fig. 10, gray-shaded areas compared to red-shaded areas); the only exception was the middle-aged NV group. When a scan was made, larger maximum head scan magnitudes were strongly associated with successful detection of the pedestrian ($z = 4.32$, $P < 0.001$). When the pedestrian was detected, the maximum head scan magnitude was significantly larger, by about 15° ($z = 7.6$, $P < 0.001$), than when it was not detected (Fig. 11). This was the case both for drivers with NV ($z = 7.15$, $P < 0.001$) and drivers with CFL ($z = 3.54$, $P < 0.001$). In the NV group, the maximum head scan magnitude was smaller for the older than for the middle-aged participants (means 44° and 50° , respectively, $z = 2.25$, $P = 0.024$), which contributed to the higher rate of detection failures in the older group. By compar-

ison, there was no difference in the maximum head scan magnitude between the older and middle-aged participants in the CFL group (means 44° and 42° , respectively, $z = 0.57$, $P = 0.57$). For the CFL group, the level of vision impairment affected detection likelihood (in addition to maximum head scan magnitude). Better contrast sensitivity scores and smaller scotomas were associated with successful detection of the pedestrian ($z = 2.10$, $P = 0.036$, and $z = 2.36$, $P = 0.018$, respectively). Other vision measures (VA and scotoma location) and driving status (current/former) were not associated with detection of the pedestrian (all $P > 0.17$).

Discussion

In this study we investigated the effects of both age and CFL on head scanning and detection at intersections. We found evidence of age effects in the NV group for the numbers of head scans and head scan magnitudes, but not for failures to scan. In general, the older CFL group behaved in a manner similar to the older NV group, but the middle-aged CFL group behaved in a manner different from the middle-aged NV group.

When approaching an intersection, older participants in the NV group made fewer total head scans than middle-aged participants but did not have higher rates of failing to scan to either the right or left; that is, they typically made at least one scan in each direction. The finding of fewer total head scans in the older NV group is consistent with the results of Bao and Boyle,²¹ who reported that older drivers made fewer head scans than middle-aged drivers when approaching intersections in an on-road study (head movements were determined from recordings made by in-car cameras). The finding is also consistent with driving simulator studies^{20,23,24} reporting that older drivers made fewer gaze scans at intersections. In contrast, Keskinen et al.²² found no effects of age on the number of head movements. However, in that study, data were derived from videos taken by cameras at the opposite side of the intersection, so some head movements might not have been captured, and only 12% of the sample was over 60 years (approximate age of drivers was estimated from the video footage).

Contrary to our expectations, the mean head scan magnitudes of older and middle-aged participants did not differ significantly in the NV group. However, age differences were apparent in the analysis of the maximum magnitude of head scans to the far left

when very close to the intersection (at intersections with the pedestrian at location A). In that situation, the maximum leftward head scan magnitude was smaller in older than in middle-aged participants. This finding is consistent with older participants having less neck rotation flexibility,^{16–18} making it more difficult to execute very large head movements. The current study focused solely on head scanning at intersections; however, eye scanning may also play an important role. It is possible that older drivers might make more use of eye scanning if they find it difficult to execute large head movements (Savage SW, et al. *IOVS* 2019;60:ARVO E-Abstract 3912).

As expected, we found essentially no differences in head scanning behaviors between older NV and older CFL participants. The total number of head scans, the rates of failing to scan to the right and left, and the mean head scan magnitudes did not differ between these two groups. There was also no evidence that scotoma location (vertical above versus lateral right) affected scanning behaviors; however, analyses of scotoma location were limited by small sample sizes. In direct contrast, individuals with lateralized field loss from homonymous hemianopia exhibited clear evidence of compensatory head scanning at intersections in a prior driving simulator study.¹⁰ The first scan was usually toward the side of the hemifield loss, and these drivers made more scans to that side than NV drivers. People with homonymous hemianopia have no peripheral vision on the side of the field loss and therefore need to scan toward the side of the hemianopia in order to detect peripheral hazards on that side. By comparison, people with CFL have peripheral vision on all sides of the scotoma, and the scotoma occupies a much smaller portion of the total area to be scanned. Thus, people with CFL might not need to modify their head scanning behaviors much (if at all), compared to NV drivers, to compensate for the scotoma at intersections. Furthermore, they may be unaware⁴¹ of their scotoma.

The middle-aged CFL group stood out as behaving in a manner different from both the middle-aged NV and the older CFL participants. Compared to the middle-aged NV group, the middle-aged CFL participants made fewer head scans, had higher rates of failing to scan to both the left and right, and made smaller head scans. Compared to the older CFL group, they had higher rates of failing to scan and made smaller head movements, which is opposite to the age effects observed within the NV group. So why might the middle-aged CFL participants differ from the other groups in their head scanning behaviors?

Severity of vision impairment can be excluded as a reason because the middle-aged and older CFL groups did not differ for any of the vision measures. One possibility might be that the older CFL participants had substantial experience (median 46 years) of driving with NV before the onset of the vision loss, whereas four of the nine middle-aged CFL participants received their first license to drive only after the onset of the vision loss and thus had no experience of driving with NV. Furthermore, the weekly mileages of current drivers in the middle-aged CFL group were significantly lower than in the middle-aged NV group. Thus, the overall lower levels of driving experience in the middle-aged CFL group could have contributed to the higher rates of failing to scan and smaller scan magnitudes in that group when compared to the middle-aged NV and older CFL groups.

We evaluated the relationship between head scanning behaviors and detection of the pedestrian at the far left of the intersection. The pedestrian was located about 85° to the left of straight ahead (when the participant was at the white line before entering the intersection). In general, rates of failing to detect the pedestrian at A were high ($\geq 58\%$) in all of the groups except the middle-aged NV group (18%). The maximum head scan magnitude in the direction of the pedestrian was significantly smaller, by about 15°, when the pedestrian was not detected than when it was detected, and this was the case both for drivers with NV and drivers with CFL. These results suggest that when the pedestrian was not detected, the head scan magnitude was inadequate (too small) to bring the gaze close enough for detection to occur. Across all participants, about 45% of detection failures were associated with an inadequate scan magnitude compared to about 10% associated with not making a scan at all toward the pedestrian. Inadequate head scan magnitude was the main reason for detection failures in older drivers with NV and older and middle-aged drivers with CFL. It was only in the middle-aged NV group that an inadequate head scan magnitude was not the primary reason for detection failures (Fig. 10). For that group, the small numbers of detection failures were equally split between failing to scan and inadequate head scan magnitude.

For CFL participants, head scan magnitude was the strongest predictor of pedestrian detection for the pedestrian at the far left of the intersection. However, the degree of vision impairment also played a role. Consistent with a prior study,³³ larger scotomas and poorer contrast sensitivity (but not VA) were signif-

icantly associated with an increased likelihood of failing to detect the pedestrian. Participants with CFL used a nonfoveal PRL for fixation, thus the absolute retinal eccentricity of the pedestrian would have differed between participants with CFL and NV. For participants with a right scotoma, the pedestrian would actually have been at a larger absolute retinal eccentricity. Even if CFL and NV participants made a head (and eye) scan of similar magnitude, the pedestrian would be imaged on more eccentric retina with lower contrast sensitivity for the CFL than the NV participant, especially with more eccentric PRLs (i.e., larger diameter scotomas). However, eye position was not tracked in the current study so we could not confirm whether pedestrians were further from the gaze point at the time of the maximum leftward head movement for participants with CFL compared to participants with NV.

In a prior driving simulator study,³³ lateral scotomas significantly delayed response times to pedestrians that appeared in the area of visual field loss (e.g., responses of a participant with a right scotoma were very delayed for a pedestrian about to step off the curb on the right of the travel lane). Those pedestrians appeared at 4° or 14° eccentricity from the car heading direction. However, in the current study, the pedestrian at the far left of the intersection usually appeared outside of the scotoma area at such a large retinal eccentricity (about 85°) that it could only be detected after a large head (and eye) movement to bring the PRL close enough. If a large head (and eye) movement were made, then there were only three participants with scotomas to the left of the PRL for whom the pedestrian might have been obscured by the scotoma. Thus, it is not surprising that we did not find any significant effects of scotoma location on pedestrian detection in the current study.

The group of participants with CFL was representative of the cross-section of patients with CFL who might attend a vision rehabilitation clinic. They were heterogeneous in terms of CFL cause, years of vision impairment, driving experience, and whether a current or former driver. About half of the CFL participants were no longer driving whereas all of the NV participants were current drivers. The effects of driving status were primarily evident in the pattern of head scanning rather than head scan magnitudes of CFL participants. Specifically, for former drivers the number of scans to the left and right did not differ, and the rates of failing to scan toward roads on the left and right also did not differ. By comparison, current CFL drivers, similar to the NV drivers, made

more scans to the left than the right (as expected when driving on the right-hand side of the road) and had lower rates of failing to scan to the left than the right.

In examining the relationship between head scanning and detection, study limitations need to be considered. First, the stationary pedestrians did not present an imminent threat or hazard; therefore, participants might have failed to notice them even if gaze was close enough for detection to occur. Second, the lack of an eye tracker in the simulator limited our ability to determine how close gaze came to each pedestrian and whether, in the absence of large head scans, participants used larger eye saccades, and whether an eye saccade might have been made toward the pedestrian even when a head scan was not made. Nevertheless, it is reasonable to assume that if a pedestrian was not detected, gaze (head combined with eye movement) did not come close enough for detection to occur and that the overall gaze scan magnitude was inadequate. Third, the relationship between scanning and detection was evaluated at only four intersections per subject and only for detection of a pedestrian at the extreme left edge of the clear-sight triangle.

The relationship between scanning and detection was not evaluated for the pedestrian at the extreme right of the clear-sight triangle (location D, Fig. 1) because it was possible for participants to see that pedestrian without making a head scan (the pedestrian appeared only on a right turn and could be seen without a scan at the end of the turn maneuver). However, given that we found higher rates of failing to scan to the right than to the left at intersections without pedestrians, it is quite possible that we would have found higher rates of failing to detect the pedestrian on the right if it had disappeared from the scene before the start of the turn maneuver (and thus required a large scan for detection). Indeed, in prior studies,^{10,11} failing to make a head scan to the right was a major cause of detection failures for drivers with right homonymous hemianopia who had no vision on the right side and had to make a large scan to the right in order to see the pedestrian on the far right.

The current study focused on head scanning at intersections with stop or yield signs. These signs are placed at intersections to provide cues to drivers that they need to stop or at least slow down and check for potential hazards on the cross streets before entering the intersection and that the other traffic has the right of way. However, even with such environmental cues, we still found that participants sometimes failed to

head scan in the direction of an incoming road. At intersections without any traffic control devices, where older drivers are particularly at risk for collisions,^{7,8} it is possible that we might have found greater age-related deficits in scanning (higher rates of failing to scan in a specific direction and/or not scanning far enough). Cross traffic is another environmental factor that can affect scanning at intersections. Drivers are more likely to make repeated scans in each direction when there is a lot of cross traffic than when there is little or no cross traffic.^{22,42} We programmed cross traffic at about one third of intersections along each route, with no more than one vehicle in each direction. Thus, our experimental conditions simulated the situation of somebody driving in a relatively quiet urban area. If there had been cross traffic at more of the intersections with more vehicles in each direction, then we would have expected to have recorded more head scans per intersection. However, even when there is no cross traffic, drivers should still make at least one scan in each direction at intersections with stop or yield signs.

In conclusion, our results suggest that, although older NV drivers made fewer total head scans than middle-aged NV drivers, they did not fail to scan to either the left or right any more frequently. Older NV drivers were less likely to make very large head scans than the middle-aged NV drivers, and it was this lack of large head scans that was the primary cause of failing to detect the pedestrian at the far left of the intersection. Thus, older drivers might be at risk for not scanning the full width of the clear-sight triangle at intersections, which may contribute to an increased risk for causing collisions. Older drivers with CFL had head scan behaviors that did not differ from older NV drivers. However, middle-aged drivers with CFL exhibited deficits in head scanning compared to both NV and older CFL drivers. This was an interesting and novel finding of the study that deserves further investigation. A key question is whether our findings will be replicated in a larger sample of middle-aged current CFL drivers and, importantly, whether head scanning deficits are generally found more often in young and middle-aged drivers with reduced VA (either with or without CFL) than in older drivers who acquired vision impairment later in life.

The results of the current study are of relevance to clinicians and driver rehabilitation professionals as well as to the design of driver rehabilitation programs for older drivers and drivers with vision

impairment. Romoser and colleagues^{23,43} demonstrated the efficacy of a training program for older drivers that focused on the importance of making secondary scans to check for hazards *after* entering an intersection. Our findings suggest that training programs also need to raise awareness of the importance of scanning the full width of an intersection to check for hazards before entering an intersection and that such large scans require rotation of the head. Body and shoulder movements may help older drivers to make such large lateral scans. Our results also highlight the possibility that younger and middle-aged people with CFL who have little driving experience may need specific training in how to scan at intersections (with at least one large scan involving head rotation in each direction); however, our findings for the middle-aged CFL group need to be replicated before firm conclusions can be drawn.

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Appendix: Detection Rates for Intersection Pedestrians

Older drivers had significantly lower detection rates than middle-aged drivers for intersection pedestrians (overall, 62% vs. 79%, $z = 3.70$, $P < 0.001$), and CFL drivers had significantly lower detection rates than NV drivers (overall, 58% vs. 79%, $z = 3.96$, $P < 0.001$). However, there was a significant age by vision interaction ($z = 2.2$, $P = 0.027$). For the older group, detection rates did not

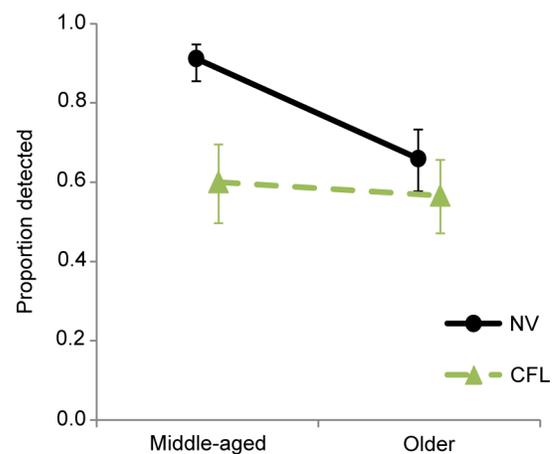


Figure A1. Mean detection rates for intersection pedestrians for middle-aged and older NV and CFL participants. Data are pooled across the four pedestrian locations. Error bars are 95% confidence limits.

differ between NV and CFL participants, whereas in the middle-aged group, CFL participants had lower detection rates than NV participants (Fig. A1). There was also a significant effect of pedestrian location ($\chi^2 = 70.51, P < 0.001$). Detection rates at location A were significantly lower (all $P < 0.001$) than at each of the other locations, while detection rates at B were significantly higher (all $P \leq 0.01$) than at each of the other locations (Fig. A2). This difference is most likely explained by the fact that a head scan was necessary to see the pedestrian at location A. By comparison, the pedestrians near the center of the intersection could easily be seen without a head scan, and the pedestrian at the far right, which appeared only on a right turn, could also be seen without a head scan as it came close to the line of gaze near the end of the turn maneuver.

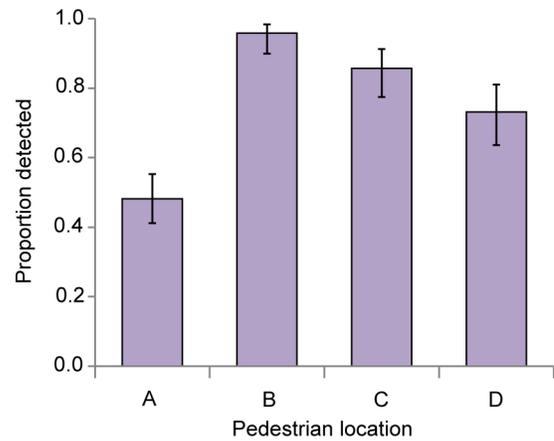


Figure A2. Mean detection rates at each of the four intersection pedestrian locations (Fig. 1). Data are pooled across both age groups and both vision status groups. Error bars are 95% confidence limits.