Analysis of Driving Behavior Where it Matters

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Abstract

Computerized driving simulators are ideal platforms for evaluating driving abilities but the wealth of data collected must be analyzed with careful attention to the underlying questions of the research program. In the context of an ongoing study we have developed analyses to quantify vehicle-handling skills and head movement behaviors that are relevant to the condition of hemianopia (loss of half the field of vision on the same side in both eyes). By evaluating skills in specific segments of the drive (straights, curves, turns) we can address behaviors which are important to driving and are relevant to the condition under investigation. These behaviors may be masked when studied across the entire drive rather than in specific segments. In this methodology paper we describe the development of our assessments and analyses for patients with hemianopia, and use sample data plots from individual cases to demonstrate that the analyses are sensitive to lane position biases, vehicle handling difficulties, and inadequate or compensatory head movements at intersections.

Introduction

Driving simulator assessments are a promising way to empirically evaluate driving ability of patients with various types of sensory, motor, and cognitive impairments. The analysis of data obtained from driving simulator systems requires careful attention to the underlying questions of the research program. Using a high-end "off-the-shelf" driving simulator system, we are investigating the impact of various vision impairments on an individual's ability to perform driving related tasks. Here we report on driving with hemianopia.

Hemianopia is a loss of vision on the same side in both eyes. Typically caused by stroke, head trauma, or brain tumors, the condition prevents the individual from seeing objects either to the right or left of where he/she is looking. In the context of driving, a person with right hemianopia, while looking forward along the car's current path can see the oncoming traffic on the left side of the road, but anything on the right side (e.g. pedestrians and roadway signs, Figure 1) will not be seen. However, people with hemianopia may be able to compensate for their visual loss by exploring the affected (non-seeing) side using head- and eye-scanning.

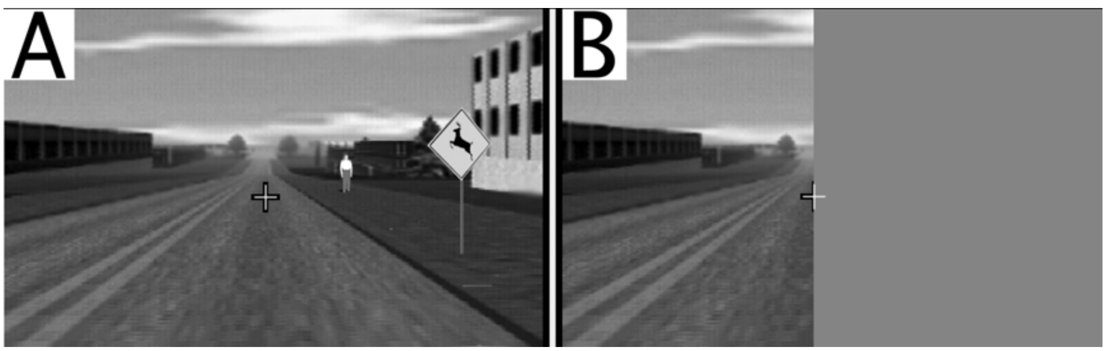

Figure 1: A screen capture from the center video monitor of the driving simulator showing a city scene as it might appear to a driver **(A)** with a normal, full field of vision, and **(B)** with right hemianopia. The superimposed crosshair represents the assumed gaze point. When the right hemianopic driver is looking straight ahead, the pedestrian on the sidewalk on the right, who might be a potential hazard, is not seen. Resolution is lower than that of the driving simulator video images.

Previously we described the development of a simulator-based detection task to evaluate the ability of drivers with hemianopia to detect pedestrians on the seeing and non-seeing sides while driving in a variety of realistic situations.[1] We have subsequently added a head-tracking system which enables us to evaluate head-scanning behaviors. In the Netherlands, where driving with hemianopia is permitted, it was reported that driving examiners consider increased head scanning (especially on approach to intersections) to be an effective compensation for peripheral visual field defects.[2] However, whether drivers with hemianopia show compensatory head scanning and whether increased head scanning results in better detection performance has never been investigated systematically.

Although detection rates are the primary performance measure in our simulator-based study, hemianopic visual field loss may have adverse effects on other aspects of driving behaviors such as vehicle-handling skills. Drivers with hemianopia were reported to make more lane boundary crossings and had greater variability in lane position than normally-sighted drivers when driving in a simulator.[3] Furthermore, in a recent on-road study, the main comment made by driving examiners was that the hemianopic drivers demonstrated a lack of stability in their steering.[4] Although these two studies provide some evidence of an impact of hemianopia on vehicle-handling skills, the results are limited in that the measures used by Szylk et al[3] appear to represent performance across all roadway segment types (straights, curves, or turns), and the study by Tant et al[4] did not report quantitative measures of steering stability. As the effect of hemianopia on vehicle-handling may be different for each roadway segment type, we contend that vehicle-handling skills should be evaluated separately for each segment type. It is also critical to differentiate between right and left hemianopia, as well as between right and left curves and turns. The importance of adopting this approach is highlighted by the results of Tant et al[4] where an effect of the side of the hemianopia on vehicle-handling in straight road segments and turns was apparent. Right hemianopes were noted to drive too close to the right side of the road and to take right turns too widely; although similar left-lateralized anomalies were not noted for left hemianopes.

In this paper we describe the analyses developed to address questions such as: Do hemianopes demonstrate unstable steering compared to matched control drivers? Do vehicle-handling skills vary with segment type (straight, curve, turns)? Do hemianopes demonstrate lateralized differences in lane positioning related to the side of the visual field loss? Do hemianopes use adequate head scanning and show compensatory head movement behaviors at intersections? As data collection is still ongoing, we do not report group data in this paper, but use sample data plots from individual drivers to illustrate the development of the analyses and how the analyses address our research questions.

Methodology

Simulator environment and driving assessment

Details about the simulator environment, pedestrian detection task, and methodology for running the simulator assessments are given in Peli et al.[1] In brief, we use a PP1000-x5 driving simulator (FAAC Corp., Ann Arbor, MI). This system has five 29" (0.74 m) monitors with 1024 × 768 resolution, updated at 60Hz, and providing a total field of 225º horizontally and 32º vertically. The simulator has a motion platform with 3 axes of movement, a force feedback steering wheel, and automatic transmission. Data such as horn presses, brake pedal pressure, and coordinates of scriptable objects in the virtual world are recorded at 30Hz.

A total of 20 different scripted drives have been developed and implemented, including city driving at 30 mph with and without other traffic, and rural driving with traffic at 60 mph.[1] As participants drive along the predetermined routes, guided by directions from scripted auditory cues, pedestrian targets appear at scripted, but unpredictable times, either on the right or left side of the road. Participants honk the horn when they see a target. A typical simulator session includes about 45 minutes of practice driving to familiarize the driver with the simulator environment and pedestrian detection task. This is followed by 6 different scripted drives, each about 10 minutes in duration.

Roadway segments

In each drive, segments of road have been selected for the analysis of vehicle handling skills and head movement behaviors in isolation from other parts of the drive. Three different segment types have been identified: straight road (city and rural), curved road (right and left; city and rural), and turns (right and left; city driving only). Specifications for a typical city drive are listed in Table 1. The numbers reported were measured for that drive and are representative of all city drives; the route is mapped in Figure 2. Equal numbers of right and left turns and curves have been selected from each drive to enable lateralized differences in vehicle-handling of right and left hemianopes to be compared. In addition to the selected right and left turn segments in city drives, we also evaluate head movement behaviors on approach to additional intersections with various geometries and traffic controls (yield sign, stop sign, and traffic light).

Table 1: Segment specifications for a specific city (30 mph) drive (mapped in Figure 2)

Segment type	Length scored	Number analyzed	Constraints
Straight Road	Mean: 225 ± 1.3m	2	No lane changes and no target presentations
Curved Road	R: 20 m L: 24 m	1 right & 1 left	Same as above
Turns	R: Mean: 16 ± 0.7m L: Mean: 25 ± 0.1m	2 right turns & 2 left turns	
Intersection Approach	23 m from intersection + 25 seconds of travel	6 or more	Includes stop signs, yield signs, and traffic lights

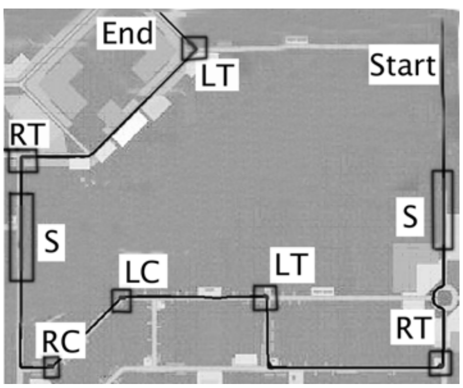

Figure 2: A typical route for a scripted city drive showing the locations of the road segments selected for the analysis of vehicle handling skills and head movement behaviors. Segments were selected such that they were free of any traffic situations or pedestrian appearances that might affect the skills (lane positioning, steering) being assessed. S = Straight segment; RT/LT = Right/left turn; RC/LC = Right/left curve.

Head tracker - Setup and calibration

We have added an inexpensive optical tracking system (NaturalPoint TrackIR 3) to the simulator environment to enable us to investigate possible compensatory head movement behaviors. The data streams of the head tracker and driving simulator are synchronized. This system tracks the head at 120 Hz with 1º accuracy and a range of ± 70º without restricting natural movements. This range is sufficient to capture the large head movements that typically occur when scanning at an intersection. While six dimensions of head position are collected, we report only the calibrated yaw position of the head. The head tracking camera is mounted above the central simulator screen and 1 m from the reflectors. The driver wears a lightweight (193g) headband upon which reflective strips are mounted. This headband is comfortable enough that drivers can wear it for over an hour at a time.

The head tracker is calibrated before and after every drive. Under monocular viewing, the driver looks through a reticule attached to the head tracker at a series of 5 calibration targets on the simulator. When the driver's head is pointed to a calibration target, he/she presses the car horn. In the analysis phase, the calibration data are fit to linear equations. If the sum of squared residuals, R^2, for a calibration sequence is > 10 deg^2, the data point with the largest residual is removed and the fit redone. If the R^2 is still > 10 deg^2, the process is repeated and another point removed. Comparisons are made to confirm that pre- and post-drive calibrations are similar, and then the average of the two linear functions is used to calculate physical head position. If pre- and post-calibration sequences can not be brought into agreement, the calibration sequence with the largest R^2 is discarded and the other one is used for analysis. Figure 3 shows some of the calibration fits with outliers marked. Out of 440 calibrations processed so far, 395 (90%) of them had no problems and did not require any outlier removals.

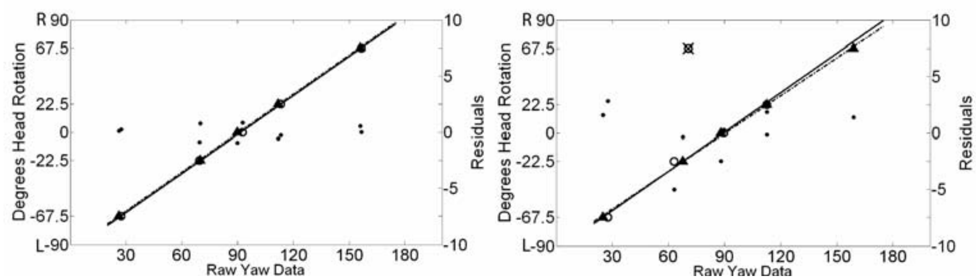

Figure 3: Calibration data for two different drives with linear fits and residuals. The filled triangles and unfilled circles represent the pre- and post- drive calibration points, respectively. The solid line and dashed line represent the linear fit for the pre- and post- drive calibration points, respectively. Residuals to the fits are shown as small circular points with the residual scale on the right hand axis. On the right plot, there is an example of a data point from the post drive calibration which was excluded from the linear fitting (shown with an "X" through the symbol).

Analysis of vehicle-handling skills

For straight and curved road segments, we have implemented the following measures of lane positioning and steering stability: duration and number of lane boundary crossings, mean and standard deviation of lateral position of the car with respect to the center of the travel lane, the magnitude (average magnitude of detected movements within each segment in degrees) and number of steering wheel movements. In addition, a set of measures to quantify vehicle-handling skills when making right and left turns are being developed. To prevent an artificial number of lane crossings accrued by driving on the border of the lane, the analysis software incorporates a hysteresis algorithm that requires the driver reposition the vehicle a minimum of 5 cm back into the original lane after crossing out from the initial lane in order for the car state to be considered "in appropriate lane".

To count steering wheel movements and reversals we implemented an algorithm based on the one described by Reed and Green,[5] in which a discrete steering wheel motion consists of "a series of first-order steering wheel angle differences that do not change sign for more than 0.33 s and that represent a net monotonic change in steering-wheel position of more than 1°". We determined that these thresholds were also appropriate for our simulator set up. By moving the wheel to and fro as quickly as possible on a straight stretch of road, we identified that the maximum frequency at which a driver was capable of oscillating the steering wheel is 5 Hz, and by driving without touching the steering wheel, we determined that the maximum deviation of the angle of the steering wheel from a constant value is 0.03°.

Reed and Green[5] state that the number of reversals is "one less than the number of discrete motions". By inspection of Figures 4A, 4C, and 4E below, we can see that this is clearly not the case since there are many instances where there are two or more successive discrete motions in the same direction. We have modified the algorithm to correctly count reversals by counting only those motions in which the direction of the motion differs from the direction of the prior one.

Analysis of head movement behaviors

To qualitatively evaluate head movement behaviors at intersections, we have plotted head position as a function of time for each participant on approach to each intersection starting 246 feet/75 m before the vehicle reaches the center of the intersection through the next 25 seconds of time. We are implementing measures to quantify the head-scanning pattern (number, direction, and amplitude of head movements), the distance before the intersection of the first head movement, whether the scanning pattern is adequate for the specific intersection type, and/or whether there is evidence of compensatory behaviors. The algorithm to delineate discrete head movements is based on the Reed and Green[5] steering wheel reversals algorithm described above, but with the thresholds changed to be appropriate for head rotations rather than steering wheel rotations. The number of seconds for which the head position does not change sign is set at 0.4 seconds and the net change in head position is > 7.5º. These thresholds were empirically determined.

Results

Sample data plots from individual drivers with complete homonymous hemianopia and matched control drivers (matched for age, gender and driving experience) are presented.

Vehicle-handling skills

Figure 4 provides sample plots of steering wheel position and lateral lane position on straight road segments. Plots A and B show a driver with normal vision on a 30 mph segment. The driver reverses the steering wheel 10 times, while maintaining an average vehicle position at the center of the lane. Plots C and D show a driver with left hemianopia on the same road segment demonstrating unstable steering with large magnitude steering wheel movements, large variations in lane position and a larger number of lane boundary crossings; he made 14 steering wheel reversals. By comparison, plots E and F show another driver with left hemianopia on a 60 mph segment demonstrating smaller magnitude steering wheel corrections, but with a consistent bias in lateral lane position to the right side of the road.

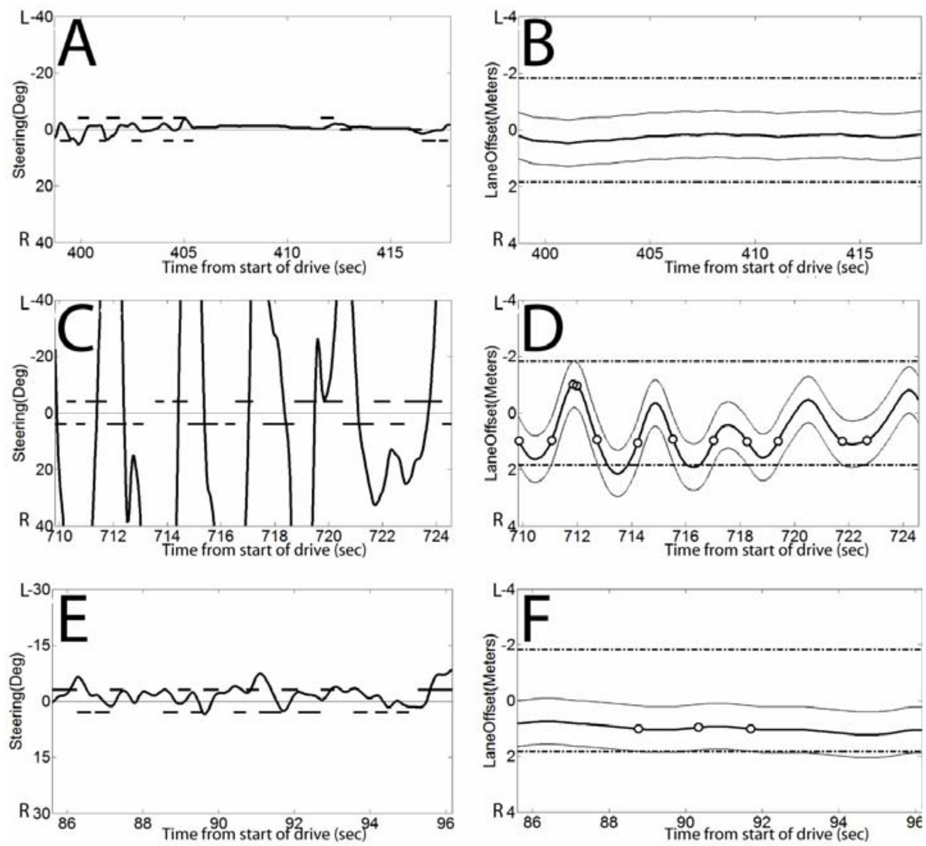

Figure 4: Sample plots of vehicle-handling skills on straight road segments. Steering wheel angle is presented in the left panels. Dark horizontal lines represent discrete movements identified by the algorithm. Lateral lane offsets from the center of the travel lane are plotted on the right panels. The dark line is the center of the vehicle, lighter lines represent the width of the car, dashed-dotted lines are the extent of the travel lane; and small open circles are lane boundary crossings. **(A)** and **(B)**: a driver with normal vision, stable steering, and little variation in lateral lane position at 30 mph. **(C)** and **(D)**: a driver with left hemianopia on the same segment exhibits poor steering control and a large number of lane boundary crossings. **(E)** and **(F)**: a driver with left hemianopia who maintains a consistent lateral position to the right of the lane at 60mph.

Head movement behaviors at intersections

Figure 5 shows an interesting example of compensatory head movement behaviors by a driver with left hemianopia compared to drivers with right hemianopia and normal sight. It is a T-intersection with a yield sign and no incoming road on the left (panel A). The driver with left hemianopia (plot B) scans twice to the left (the non-seeing side) before entering the intersection (despite the fact that there is no risk of traffic from that side), whereas the drivers with normal vision (plot C) and right hemianopia (plot D) both scan to the right first and never scan the head to the left of the straight ahead position. By contrast, Figure 6 shows examples of drivers with hemianopia who do not scan adequately. At a T-intersection with a stop sign and incoming roads on both sides (panel A), the drivers with hemianopia fail to make any significant scanning head movements to the non-seeing side and might therefore fail to detect an oncoming vehicle (plots B and C); the normally-sighted driver scans to both sides (plot D).

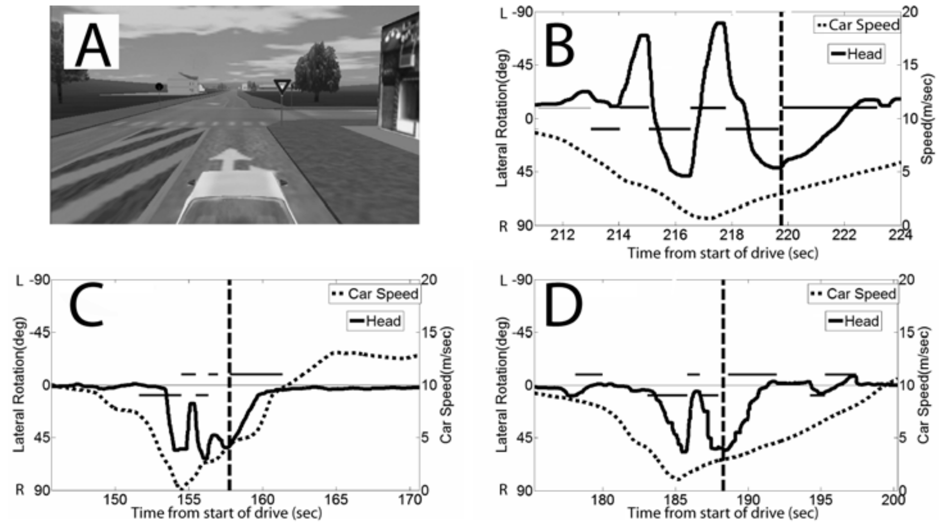

Figure 5: (A) An intersection with no incoming road from the left. **(B) - (D)** Head scanning (solid line) and car speed (dotted line) when making a right turn at this intersection. **(B)** Driver with left hemianopia scans to the left (about -75º) twice, even though there is no road on the left. **(C)** Driver with normal vision only scans to the right of straight ahead (about +55º). **(D)** Driver with right hemianopia shows similar behavior. The head tracker data were filtered with a 0.5 second wide median filter. Dark horizontal lines represent discrete head movements identified by the algorithm. Vertical dashed line is the time when the vehicle passed the center of the intersection.

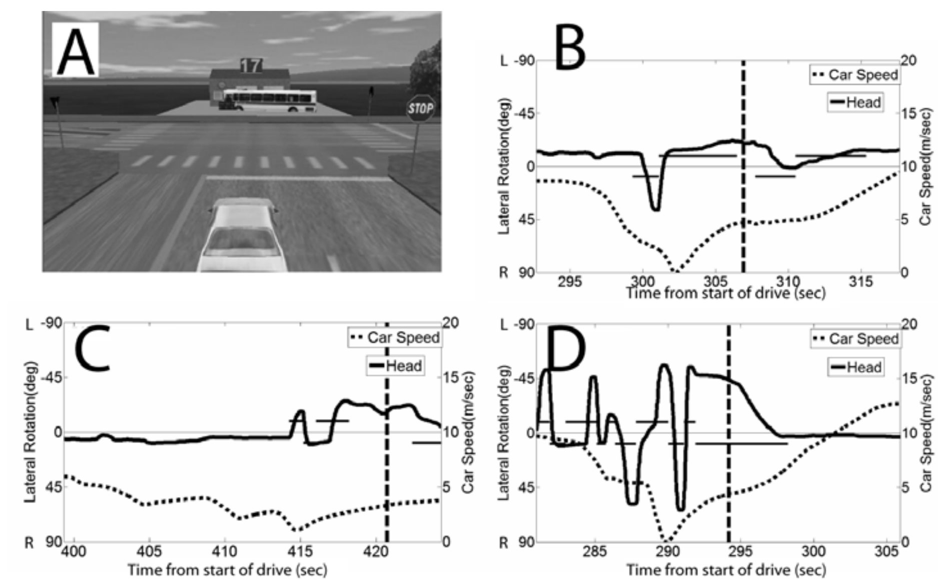

Figure 6: (A) An intersection with incoming roads from the left and right. **(B) - (D)** Head scanning (solid line) and car speed (dotted line) when making a left turn at this intersection. **(B)** Driver with left hemianopia scans to the right (seeing side) only. **(C)** Driver with right hemianopia scans to the left (seeing side) only. **(D)** Driver with normal vision scans to the left and right.

Discussion

This methods paper demonstrates our ability to develop measures of vehicle-handling skills and head movement behaviors that probe performance of drivers with hemianopia and normal vision for specific road segments. We argue that simulator analyses should address specific questions at specific road segments, and in relation to specific maneuvers. Analyzing any behavior or skill across the whole drive is likely to hide important information and may result in false interpretation. As our examples illustrate, different errors and/or compensatory behaviors are expected, or of interest, at different segments and for drivers with different impairments (right-sided versus left-sided field loss).

The raw data plots included in this paper illustrate interesting examples of how the measures we are developing address our research questions. We do not imply that these "case reports" are representative of the behaviors of all our participants, or of all drivers with hemianopia. Group data for the study will be reported in a subsequent paper.

The measures of vehicle-handling for turns are still in the development stage. One of the limiting factors in our analysis of turning behaviors is the lack of realism of the simulator steering wheel feedback in small radius turns. This is a characteristic specific to the current hardware setup. Preliminary data shows that both people with hemianopia and normal vision have a tendency to take turns in this simulated environment that are unrealistically wide. The mechanical limitations of the simulator may mask the effects of the vision loss on steering behaviors, such that we may not be able to evaluate whether there are lateralized differences (in turns) between drivers with right and left hemianopia (as was suggested by the observations of the driving examiners in the Tant et al[4] on-road study of driving with hemianopia).

Further measures of head-movement behaviors at intersections are also in the development stage. The head position plots indicate that this is likely to be a very fruitful approach to quantifying scanning behaviors and identifying inadequate scanning patterns. Examining the relationship between head scanning performance and detection performance at intersections will address the important question of whether apparently better scanning patterns are associated with better detection performance.

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