

Eye Movements in Curve Negotiation

DAVID SHINAR, *Indiana University, Bloomington, Indiana*, EDWARD D. McDOWELL, *Oregon State University, Corvallis, Oregon*, and THOMAS H. ROCKWELL, *Ohio State University, Columbus, Ohio*

Eye movements and fixations of five drivers were recorded and superimposed on a videotaped recording of the dynamic visual scene as they drove on a two-lane rural road. The results showed that (1) on curved roads, the fixation pattern follows the road geometry, whereas on straight roads, the search behavior is less active, and most of the fixations are close to the focus of expansion. The results indicate that in driving through curves drivers direct foveal fixations to lateral placement cues rather than rely on peripheral vision; (2) the process of curve scanning begins in the approach zone prior to the curve itself, suggesting that perceptually the curve negotiating process precedes the curve by several seconds; (3) the search patterns on right and left curves are not symmetrical; visual excursions to the right on right curves are greater than eye movements to the left on left curves; and (4) fixation duration statistics may be related to accident rates on curves.

INTRODUCTION

Since over 90% of the stimulus input in driving is visual (Hartmann, 1970), drivers' visual fixations while driving can provide us with information concerning the cues that drivers use in processing the visual information. The role of fixations in curve negotiation is amplified because of the selective nature of perception. Perceptual processing is selective both in the locus of fixations in the visual world and in the nature of the information picked up for further analysis. Laboratory studies have shown that people tend to fixate their eyes on areas of high information content (as defined by information theory) (Mackworth and Morandi, 1967; Zusne and Michels, 1964) or where they expect to find whatever information their task requires (Varbus, 1967).

When driving, in order to maintain proper directional and lateral control, the driver's optimal strategy is to maximize the information and time available to use that informa-

tion. Fry (1968) suggests that the most precise directional information is given by the focus of expansion—that point in the moving visual field straight ahead of the driver where objects appear stationary. Since visual acuity is greatest at the fovea, by directing his fixations toward the focus of expansion, the driver maximizes the preview time and distance for objects on, or immediately off, the road. Information on lateral placement is available from the geometrical perspective of the roadway (Fry, 1968, Gordon, 1966).

The difference between a straight and a curved road as it is perceived by the driver may be illustrated in Figure 1. On a straight road (Figure 1a), proper directional and lateral control can be maintained by simply fixating the eyes on the focus of expansion (F) while monitoring the lane markers peripherally to assure that they remain in a fixed position in the driver's visual field. According to Gordon (1966), a change in the position of the lane markers serves as a perceptual cue for

correction in lateral placement. Perceptually the situation is radically different in curves, as can be seen from Figure 1b, since the "end" of the road does not coincide with the focus of expansion and the relationship between the two changes continuously. In a curve, it has therefore been argued (Gordon, 1966) that the driver cannot localize the focus of expansion. Movement parallax could still be an effective cue while driving in a constant degree arc, but since curves are typically parabolic, the relationship between the lane markers and other elements of the scenery further away is not one of steady state, but rather it changes continuously.

Previous research on drivers' visual search patterns seems to support the importance of the focus of expansion in straight-road driving. Mourant and Rockwell (1972) found that experienced drivers tend to concentrate their fixations close to the focus of expansion, while research by Bhise and Rockwell (1971)

indicates that lateral placement can be, and is, effectively monitored peripherally.

It is hypothesized that on curved road drivers must rely on different cues for directional control and may have to monitor lateral placement foveally due to the increased demand in processing positional information. The argument is not that the increased demands necessarily require foveal acuity, but rather a *focusing of attention* to the lane markers. In selective attention tasks, the tendency to direct foveal fixations toward the focus of attention is very common and has been documented even for nonvisual stimuli (Kahneman, 1970).

Thus, the general purpose of this research is to determine drivers' search patterns in curves and from that information suggest the relevant perceptual cues to successful curve negotiation.

Effects of roadway geometry on driver visual search patterns have previously

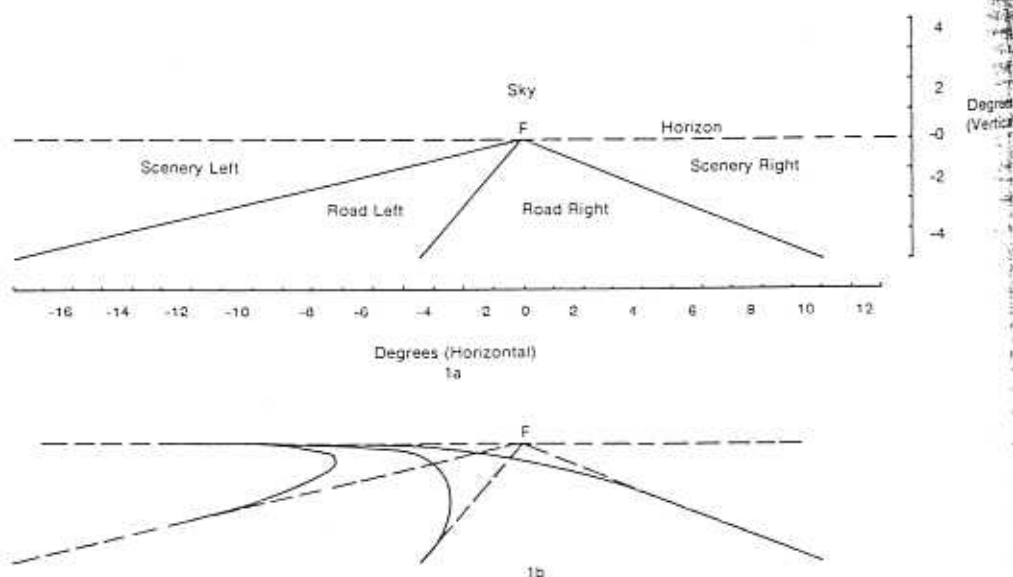


Figure 1. Perspective views of a straight road (a) and a curved road (b) from the driver's sitting position. Also the drawings are the coordinates used in assessing the fixation position, the primary areas in the visual field and the focus of expansion (F).

ceived little attention. Wright (1968) recorded drivers' fixations on a curved road but, due to technical limitations, was unable to determine the critical relationship between the fixation locations and the driver's field of view. In the present study this limitation was overcome by superimposing the foveal fixations on a videotape recording of the driver's dynamic visual field. Also, in the present study, drivers' eye movements were studied in three different situations: (1) on a straight road with no curve in sight; (2) on the approach zone—the straight-road segment immediately preceding a curve, and from which the curve is visible; and (3) in the curve itself. The specific questions of the study were: (1) How is the visual search pattern different on curves than on a straight road segment? (2) What is the relationship between the changing road geometry and the visual search pattern? (3) From where in the visual field does the driver obtain directional and positional cues when entering and negotiating curves? (4) What curve parameters, e.g., right vs. left, are reflected in the search pattern? and (5) What visual search measures, if any, can be associated with a curve's accident rate?

This last question is prompted by previous findings showing very little correspondence between accident rates and curve geometry on the one hand, and initial indications that high accident curves may be illusive in the sense that they are misperceived by the approaching driver (Shinar, 1975).

Aside from the theoretical interest in determining how drivers utilize the information available in curves, answers to these questions may also (1) indicate the optimal location for placement of road-relevant information that would aid the drivers; (2) aid the highway designer in identifying potentially dangerous curves; and (3) provide a methodology to measure the illusory, accident-causing properties of curves.

METHOD

Subjects

The subjects were three male and two female undergraduates at The Ohio State University. All had 20/20 unaided vision, and all were unfamiliar with the driving test route. They were paid \$3.00 per hour.

Road Selection

The route selected consisted of 34 km of two-lane hilly rural highways. Twenty-two curves along the route were studied. These curves included three high-accident curves (with three or more daytime accidents in the three-year period 1969-1971) and 11 no-accident curves (in the same period). The curves varied in length from .05 to .13 km and in central curvature from 5 to 19 degrees. Eye movements were recorded and analyzed on 46 road segments, each classified as either (1) a curve zone (22); (2) an approach zone (22)—that segment on the road preceding the curve, beginning at the point from which the curve can be detected and ending at the beginning of the curve; or (3) a straight road (2)—a straight-road segment for which the perceived "end" of the road coincides with the focus of expansion.

Procedure

To familiarize themselves with the test vehicle, the subjects first drove the car 16 km to the starting point of the test route. There they stopped and were fitted with the eye-movement head gear. After calibrating the system, the experimenter informed the driver that the purpose of this experiment was to calibrate and refine the eye-movement system for a later study.

To minimize visual fixations that are unrelated to the information acquisition process, the driver was instructed to maintain an average speed of 97 km/h throughout the route. It was hoped that at this relatively high speed

the driver's spare visual capacity would be reduced, as has been shown in a previous study (Safford, 1971).

The experimenter sat in the vehicle's back seat where he could monitor the driver's fixations. Throughout the route there were only two conversations between the experimenter and the subject, when the experimenter instructed the subject to turn at intersections.

Apparatus

The television eye-movement recording system has been previously described and illustrated (Mourant and Rockwell, 1972). In brief, the system operates on the principle of corneal reflection, and combines data from three TV cameras into a single display. A miniature TV, mounted on a light-weight helmet worn by the driver, records the driver's visual scene in a $50^\circ \times 40^\circ$ visual field. A second camera records his corneal reflection from a fiber-optic cable connected to the same helmet. A third camera, stationary in the car, records a picture of a digital clock (updated every 50 ms, and thereby defining the temporal resolution of the system at $\pm .05$ s), an odometer, and the driver's eyes. The images of the three cameras are then superimposed using a special effects and fade-in electronic unit.

The output of the system depicts the eye spot (location of the fovea) in the total visual field, at any point in time and place. With proper calibration, the correspondence between the eye spot and the visual scene is 0.5° in the horizontal direction, within a range of $\pm 15^\circ$ from the primary eye position, and 1° in the vertical direction, within a range of $\pm 8^\circ$ from the primary eye position. In interpreting the results, it should be noted that a limitation of the corneal reflectance method as an indicator of the visual axis of the eye is that it is affected by translation as well as rotation of the eyes, the effects of the former becoming more significant for larger eye movements.

RESULTS

Overview: Eye Movements and Roadway Geometry

The most persistent phenomenon observed is the temporal-spatial tracking of the curve by saccadic movements and fixations. This eye movement behavior is illustrated in Figure 2, which is a schematic representation of two drivers' eye movements and fixation patterns over a sequence of left-right-left curves. In this figure, the movements are separated into lateral (2b, 2c) and vertical (2d) components on a time scale. Several observations can be made from this figure. First, there is a strong and immediately apparent positive correspondence between roadway curvature and the lateral component of eye movements. Second, the change in the directionality of the eye fixations precedes the curve by approximately two to three seconds at the nominal velocity of approximately 97 km/h. Third, the search pattern can be characterized as an in-and-out one in which a fixation on the road ahead (out) is often followed by an eye movement closer to the car (in). Fourth, no relationship is apparent between the roadway geometry and the vertical component of the eye movements (Figure 2d).

Statistical Analyses

Statistical analyses were conducted on five different measures of visual behavior. The three direct measures of eye movement activity were fixation durations, travel distance between successive fixations, and the location of each fixation in the visual field. The fourth measure—concentration index—was calculated by computing the ratio of fixation time in the $3^\circ \times 3^\circ$ area of highest fixation density over the total fixation time. Finally, a separate analysis was conducted on the time the drivers spent fixating various objects in the visual field (such as road edges and scenery) and the time spent on blinking and mirror looking. An analysis of variance was con-

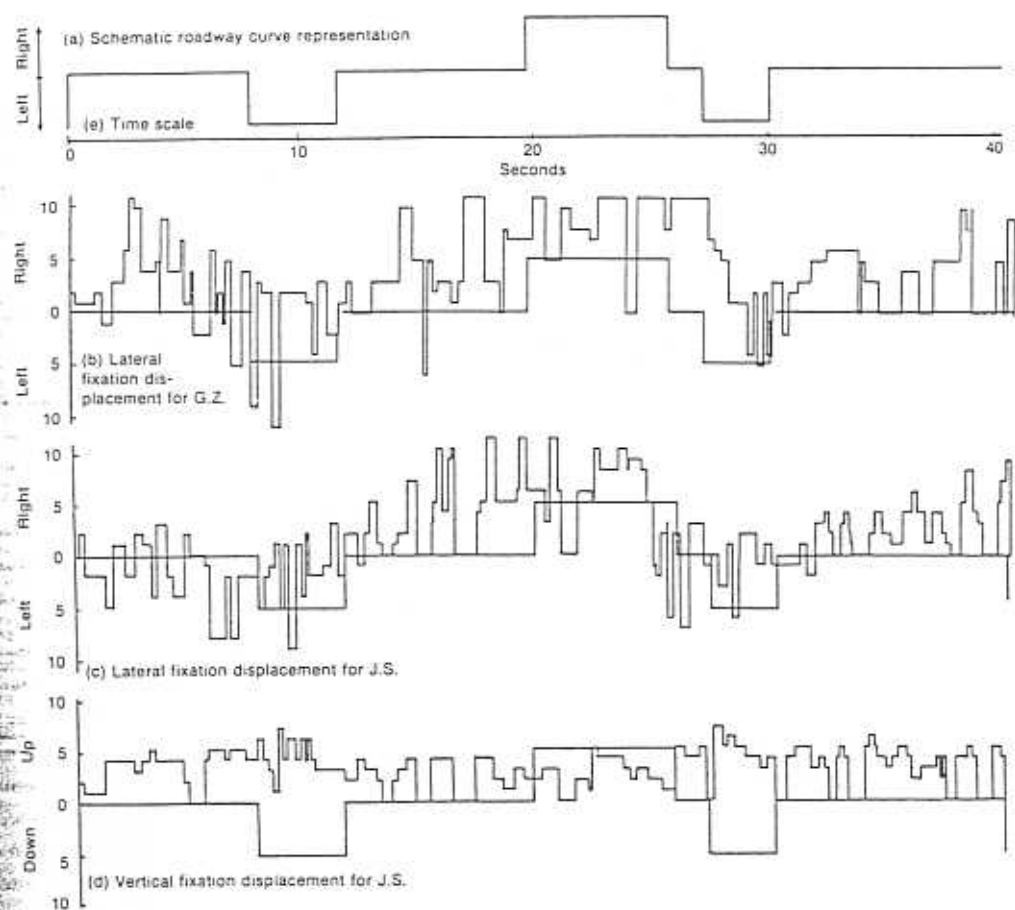


Figure 2. A schematic representation of a roadway segment with a left-right-left curve sequence (a); the lateral fixation displacement of two typical drivers superimposed on the schematic roadway representation (b, c); and the vertical displacement of fixations for one of the drivers superimposed on the same roadway representation (d).

ducted on each of these measures as a function of the curve zone (approach vs. the curve itself), curve direction (right vs. left), and accident rate (high vs. low).

Zone: approach vs. curve. Mean fixation duration (.38 s) and travel distance between fixations (3.1°) were not significantly different for the approach and curve. This lack of difference suggests that visually the curve negotiation process starts well in advance of the curve, i.e., in the approach, as evident in

Figure 2. With regard to the areas of fixation in the visual field (See Figure 1.), in the approach zone drivers divided their viewing time equally between the road and the adjoining scenery (23% each), while in the curve they spent significantly more time viewing the scenery (27%) than the road (23%) ($F(1, 4) = 7.23, p < .05$). this counterintuitive result may be indicative of the importance of contiguous road scenery to the assessment of curvature since, once in the curve, the road

itself is not as visible as in the approach zone.

Direction: right vs. left. As might be expected, the direction of the road ahead appears to be the primary determinant of drivers' visual search patterns. Mean fixation location was 3.6° to the right on right curves and almost straight ahead (0.3° to the left) on left curves ($F(1, 4) = 17.28, p < .05$). This is consistent with the finding that drivers spent significantly more time fixating on the road on right curves (55%) than in left curves (38%), ($F(1, 4) = 22.38, p < .01$). In general, drivers concentrated their fixations on the relevant side of the visual scene; in right curves they fixated the left side of the visual scene (road left, scenery left) only 5% of the time, and in left curves they sampled the right side only 24% of the time ($F(1, 4) = 34.93, p < .01$).

Accident rate. To provide a counterbalanced design, four curves of similar geometry (.05-.07 km long, $9-10^\circ$ central angle) were selected for this analysis. The curves were a high-accident right turn, a high-accident left turn, a no-accident right turn, and a no-accident left turn. The results revealed that the high-accident curves elicited significantly longer fixation durations (.48 s) than no-accident curves (.39 s) ($F(1, 4) = 8.50, p < .05$). In addition, the three-way interaction among accidents, zone, and direction on the standard deviation of fixation durations was marginally significant ($F(1, 4) = 5.06, p = .10$). This interaction is represented in Table 1, where it can be seen that for the left curves, the high-accident rate is associated with greater variability of fixation durations in the approach zone, while for the right curves the increase in variability is in the curve zone itself. In general, it appears that eye fixation behavior may be a useful indicator of curves' accident liability. The road zone where this is apparent differs, however, for right and left curves; in left curves the approach zone is the critical one, while in right curves it is the curve zone. This difference may be because in

TABLE 1

Effects of Curve Zone, Curve Direction, and Accidents on the Mean Intra-Subject Variability (Standard Deviation) of Fixation Durations.

Accidents	Approach Zone		Curve Zone	
	Right Curve	Left Curve	Right	Left
High	.17	.49	.40	.28
Low	.17	.23	.19	.27

left curves the driver can view the right lane while he is still in the approach zone, whereas in right curves, the right lane is often hidden from view until the driver enters the curve.

To test further for a possible relationship between accidents and fixation duration, the mean and standard deviation of fixation durations were tabulated for all the curves studied as a function of the number of accidents recorded, when the car causing the accident traveled in the same direction as the test drivers. This was done separately for left curves in the approach zone and right curves in the curve zone. The results are presented in Table 2. Note that the same relationship observed above for the four matched curves holds for the total sample of curves studied. On the average, mean and standard deviation of fixation duration are less than .45 s on low-accident curves and longer than .45 s on

TABLE 2

Mean and Standard Deviation of Fixation Durations in the Approach Zone of Left Curves and the Curve Zone of Right Curves as a Function of Accidents in the Same Direction of Travel.

Number of Accidents in Direction of Travel	Left Curves Approach Zones		Right Curves Curve Zone	
	Mean	S.D.	Mean	S.D.
0-1	.41 (11)	.30 (11)	.39 (8)	.25 (8)
2-3	.50 (2)	.60 (2)	.52 (1)	.46 (1)

The numbers in parentheses represent the number of curves in which each estimate is based.

all high-accident curves. If one assumes that longer fixation durations reflect greater uncertainty, then the results suggest that high-accident curves are associated with a more difficult information acquisition task than low-accident curves.

Straight road. As noted above, straight road eye movements were recorded on only two straight road segments. However, since the straight road data presented here are consistent with eye movements in straight roads (see Rockwell, 1972a, for a review), it is felt that comparisons in visual search behavior between straight- and curved-road segments are still meaningful. Mean fixation location in the straight road was 1.6° to the right and 0.7° above the focus of expansion, i.e., similar to that observed for the approach zone prior to the curve (1.7° , 1.2°). In all other respects, the straight road was different from the curved road. Results of *t*-tests for differences between related measures indicated that on the straight road, fixation durations were longer (.60 s vs. .41 s, $p < .05$), travel distance between fixations was shorter (2.6° vs. 3.1° , $p = .09$), and the concentration index was higher (.62 vs. .27). All of these differences reflect the greater amount of visual search activity involved in curve driving than in straight-road driving. This difference was also reflected in the finding that on the straight road drivers could afford to devote more time to non-control operations. They looked more (4.1% vs. 1.8% of total time, $p < .01$), appeared to spend more time fixating the speedometer (6.7% vs. 3.0%, $p = .07$) and the rear view mirrors (3.7% vs. 2.0%, $p > .10$) on the one hand, and less time on contiguous scenery (14% vs. 23%). The last comparison was made at a later stage. Unfortunately, the original subjects' data could not be located to allow a statistical test of significance. The results are presented nonetheless, since they appear to be consistent with the statistically significant comparisons.

DISCUSSION

The results of this study point to some important differences between the visual search patterns on straight and curved roads and provide empirical support for theoretically derived arguments previously made by Gordon (1966) and Fry (1968).

Instead of concentrating his fixations—and presumably his attention—close to the focus of expansion as he does on the straight road, on a curved road the driver concentrates intermittently on the position of the road ahead and the road edge (or lane markings) closer to the car. Since the direction of the car relative to the focus of expansion is not constant in the approach and curve zones, the driver must rely on other cues for the car's lateral position in the lane. The reasoning behind this argument is that on the straight road the driver can (Gordon, 1966) and does (Mourant and Rockwell, 1972) maintain his fixations close to the focus of expansion and monitors his lateral position peripherally by simply responding to a change in the relative position of the edge line or lane markers in his peripheral visual field. If the driver were to attempt to do the same on a curved road, he would very quickly go off the road due to the rapid changes in the relationship between the direction of the road and the focus of expansion. This is especially true because most curves are parabolic rather than arcs of a constant radius. In order to respond in time to changes in the directionality of the road, the driver must preview the information ahead of his present position. The data obtained here and previously obtained data (Rockwell, 1972b) suggest that, when possible, the driver attempts to maintain a preview distance of 2.5 to 3.5 seconds. All these considerations result in an in-and-out visual scanning pattern in which the driver intermittently looks ahead (out) on the road and down (in) close to the car (Figure 2). If we

assume that the foveal fixations correspond to the cues to which the driver is attending at any given moment, then it appears that under conditions of stress, e.g., high speed curve negotiation, the driver acts as a single channel processor selectively attending to either directional or positional cues.

The second point that should be noted is that the inadequacy of the focus of expansion to provide directional cues is exhibited even before the car enters the curve. The greater similarity of the scan pattern in the approach zone to the search pattern in the curve zone rather than the straight road, suggests that the curve negotiation process perceptually starts well in advance of the curve itself. Thus, the eye movements appear to reflect an anticipatory mechanisms in which the scanning of the curve may serve to construct a scheme of the curve that can be assessed and responded to in terms of curvature, length, superelevation, etc. The possibility remains, however, that actual longitudinal and lateral corrections are made in response to gravitational and vestibular sensations that the driver experiences during the turn (Herrin and Neuhardt, 1974) and that the primary function of the visual cues is to provide preview information before entering the curve and reinforce his awareness of other cues once he is in the curve (Fry, 1968).

In the search for eye movement parameters related to the accident rate in a curve, the data are only suggestive. The observed increase in the mean and variance of fixation durations may be indicative of greater confusion or difficulty in extracting the relevant directional information. The fact that this is manifested at different zones for right and left curves fits well with other asymmetries observed in eye movement behavior and right and left curves. In general, drivers tend to fixate more on the right side than the left side of the road (Mourant and Rockwell, 1972), i.e., their driving lane. This tendency may be

the determining habit that elicits shorter excursions to the left on left curves than to the right on right curves. Thus it is possible that drivers process curve information for left curves mostly in the approach zone, while visual acquisition of information continues well into the curve on right curves. These, however, are only hypotheses that should be further tested on a more representative set of curves.

CONCLUSIONS AND DESIGN IMPLICATION

This study suggests that drivers rely on different visual cues, for directional and lateral control, on curves than on straight roads. Drivers start scanning curves for directional cues as they approach them and resort to direct foveal fixations of roadway close to the car for lateral placement cues. To the extent that the results warrant these conclusions, several recommendations can be made:

- (1) On curved roads, the approach zone—sight distance—to the curve should be maximized so that drivers may have more time to assess the curve prior to entry. This is especially critical on roads designed for high speeds.
- (2) To warn drivers to switch their visual search strategy and thus maximize the curve scanning time prior to entry, the optimal placement for advisory curve signs may be just prior to the beginning of the approach zone. In any case, the signs should not be in the beginning of the curve itself since at that point the driver is already occupied in fixating the roadway itself for proper directional guidance and lateral placement cues.
- (3) If further research that is presently underway supports the tentative findings here relating accidents to fixation duration, then eye movement measurements may be a useful tool for both the identification of potentially dangerous curves, and the assessment of safety-related curve modifications.

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Requests for reprints should be sent to David Shinar.

Institute for Research in Public Safety, School of Public and Environmental Affairs, 400 E. Seventh Street, Indiana University, Bloomington, Indiana, 47401.

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