Drivers' Eye Movements: An Apparatus and Calibration

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A description is given of a portable eye-marker camera and a specially designed stablization unit that may be used to record drivers' eye movements. A pilot study was conducted that showed that drivers' eye movements are closer in toward the vehicle under night driving than day driving. The pilot study also pointed to the need to examine the calibration accuracy of the system. In Phase I of the calibration experiment, seven drivers served in a 2 × 2 × 2 within-subjects design. The three independent variables were head movements (calibration before vs calibration after), distance (30 vs 60 ft), and sessions (Day 1 vs Day 2). Sessions were investigated to see if subjects can be calibrated with the same accuracy on different days. In Phase II of the experiment, calibration accuracy was measured before and after the subjects drove an automobile. Calibration accuracy was measured by having the drivers trace a matrix of targets that covered the field of view of the camera. Error was defined as the distance from the center of the target to the center of the eyespot. Analyses of variance showed that head movements, distance, and sessions had no significant effect on calibration accuracy. The effect of driving on calibration accuracy was small. The average calibration error for all subjects under all conditions was ±1 degree. Potential uses of the eye-marker camera in driving research are discussed.

•AN automobile driver receives more information from his eyes than through any other sensory modality. Knowledge of the visual behavior of drivers may lead to the identification of stimulus cues used in driving, promote the development of measures of driver work-load and fatigue, and provide data for the design of driver aids and route information systems. Although eye-marker cameras have been used in laboratory situations for many years, their use in dynamic environments has been hindered by equipment and calibration difficulties. The recent development of portable head-mounted units and a new stabilization technique has overcome these difficulties.

APPARATUS

The apparatus for recording drivers' eye movements consists of a Polymetric Products eye-marker camera (model V-0165-1L4) used in conjunction with a stabilization unit developed by the Systems Research Group (Fig. 1). The input system (Fig. 2) consists of a scene lens, an eye lens, and a light source. The light source is a 6-volt, 0.3-amp miniature bulb powered by a 9-volt battery. The eye lens monitors the corneal reflection of the light source and reflects it into a fiber optic cable. The scene lens has a 20 deg field of view in both the horizontal and vertical planes. The field-of-view is reflected into a second fiber optic cable. The image-transmitting fiber optic cables are 4 ft in length and have a resolution of 40 lines per mm.

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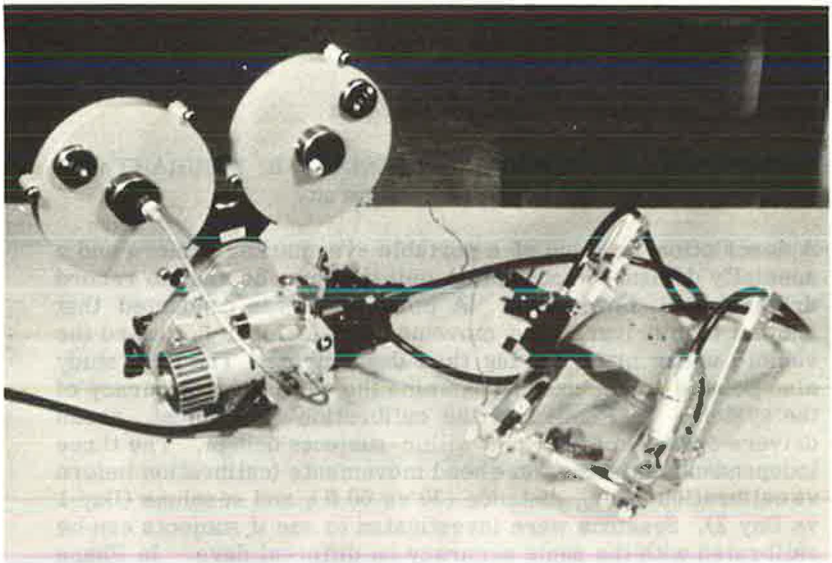


Figure 1. Eye-marker camera and stabilization unit.

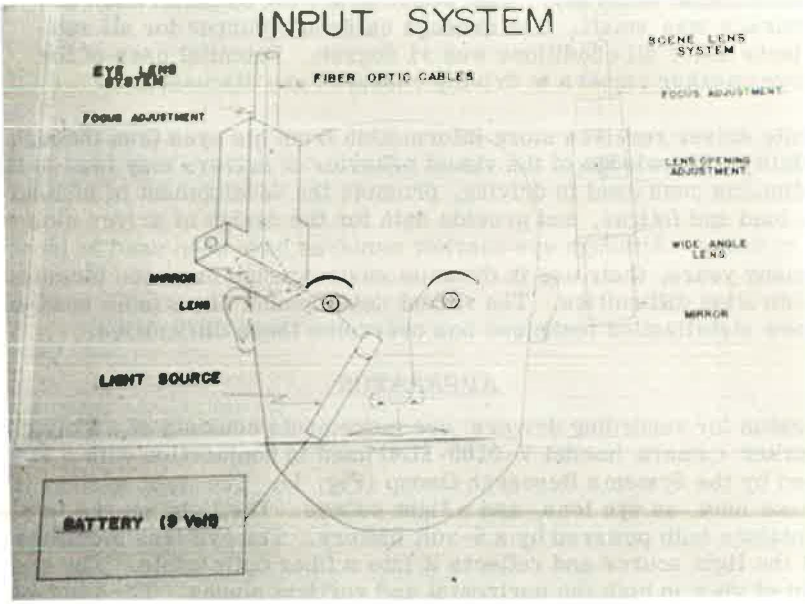


Figure 2. Input system.

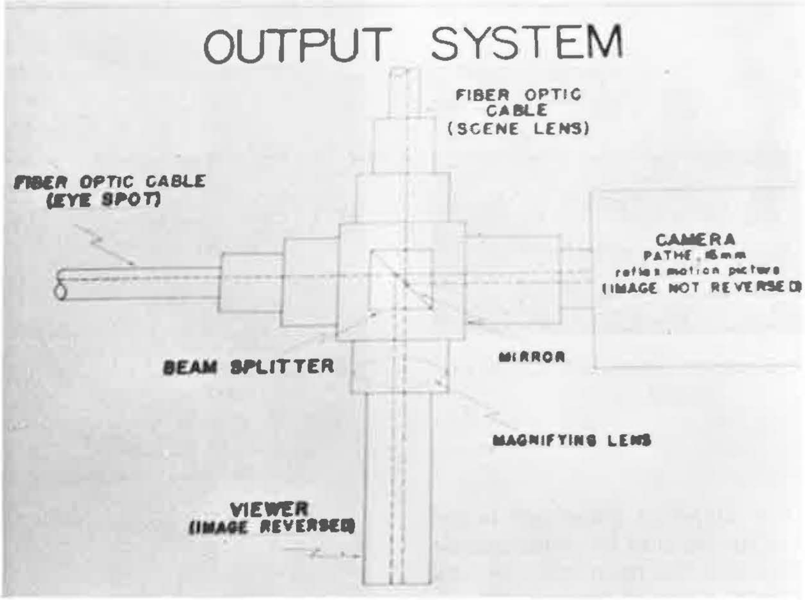


Figure 3. Output system.

The output system (Fig. 3) consists of a beam-splitter, a 16-mm Pathé camera with associated electric motor drive, and an auxiliary viewing device. The beam-splitter optically combines the images from the fiber optics cables that come from the scene lens and the eye lens. This enables the camera to photograph the eyespot when it is superimposed on the field of view. Since the fiber optic cables have a light loss of about 80 percent, Kodak Tri-X Reversal Film (type 7278) was used for daylight photography. A high-speed film, Kodak No. 2475, was used for night photography.

The stabilization unit (Fig. 4) consists of an individually fitted helmet, side-support brackets, a pressure bar that extends between the brackets, and a mouthpiece that fits against the upper teeth only. Four adjusting screws between the brackets and the pressure bar permit the subject to adjust the pressure of the unit between his upper teeth

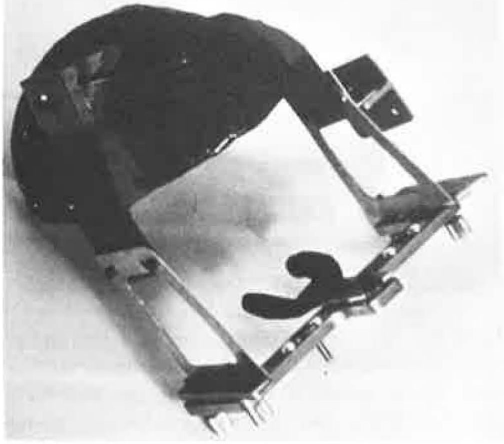


Figure 4. Stabilization unit.

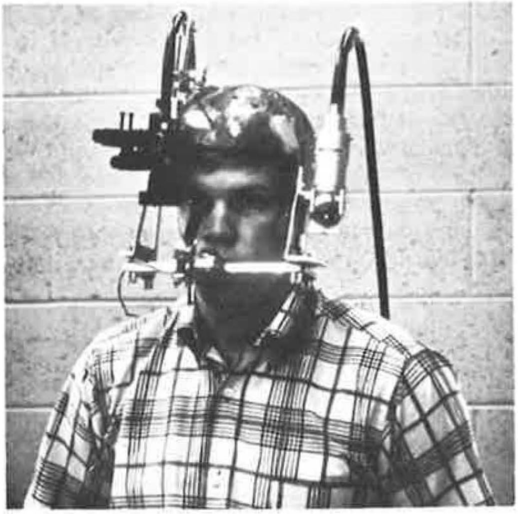


Figure 5. Subject with apparatus.

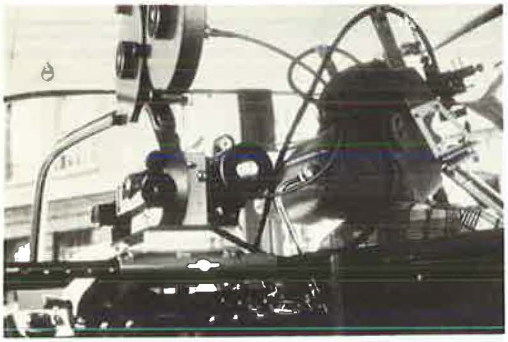


Figure 6. Eye-marker camera and subject in vehicle.

and head. The subject's lower jaw is unconstrained, allowing him to communicate verbally. The unit has been worn as long as 3 hr with little signs of discomfort.

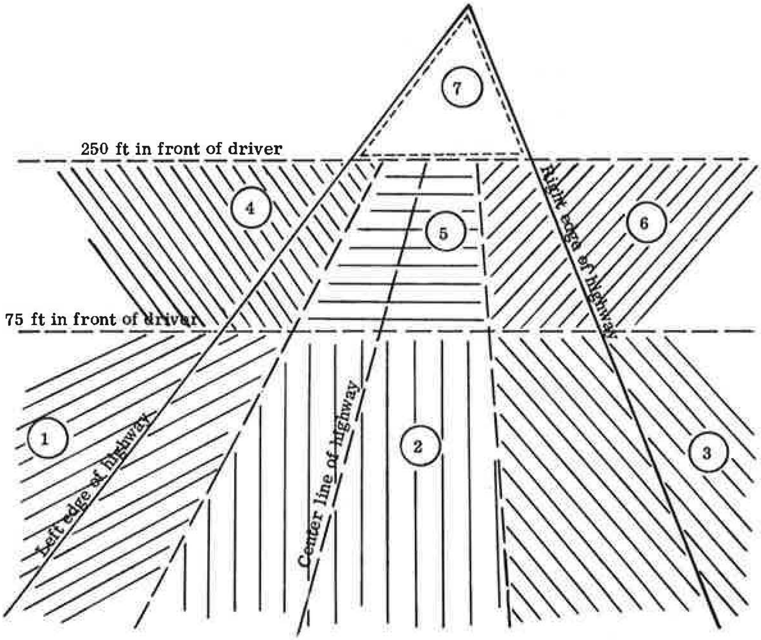
A subject with the apparatus on is shown in Figure 5. The subject and the eye-marker camera mounted in the test vehicle are shown in Figure 6.

PILOT STUDY

The first pilot study using the Polymetric eye-marker camera studied driver eye movements on two highway test sections under both day and night conditions. One highway test section was a 22-ft rural two-lane highway (Ohio 315) having a painted dashed centerline but no white edge line. The other section was a four-lane divided highway (US 23) having an ample median strip and a white edge line.

In order to better relate the eyespot to highway detail at night, two fixed reference lights were placed on the automobile for both the day and night data runs. Knowing the spatial location of these lights and the position of the driver's eyes, it was possible to approximately project the eyespot to a particular highway feature even though road features were not visible on night film. A sample of the data collected is shown in Figure 7. To facilitate data analysis, part of the driver's visual field was divided into seven sections, as indicated in Figure 8. These seven sections were chosen so as to contain prominent highway features that were believed to be significant sources of information for the driver in controlling his vehicle.

Figure 7. Six frames from 16mm data film taken under day conditions. The two bright spots spaced about ½ in. apart in each frame are the hood reference lights; the relatively unfocused larger white spot near the right hood light is the eyespot.



Driver's Visual Field

Figure 8. The seven areas used in data analysis.

One aspect of this study concerned the percent of time the eyespot was in each of the seven sections. The results indicated that for both highway test sections the areas of fixation for night driving are closer in front of the vehicle than for day driving. Table 1 gives percent of fixation duration as a function of the distance in front of the vehicle for day and night driving and for two-lane and four-lane highways.

It was found that the areas of fixation for the rural two-lane highway are closer in front of the vehicle than for the four-lane divided highway. The film also indicated that the center and edge road markings are used differently by drivers in day and night conditions. At night, more use is made of the right edge marking and at distances closer to the vehicle than in daylight driving. Thus, the data suggest that highway marking systems are a greater aid in controlling a vehicle under poor visibility conditions than in normal daylight driving.

Because this was a pilot study and data were collected for only two subjects, no statistical analyses were made on the results. However, the study made it clear that driver eye movements are reflectors of different driving situations. This study also brought out the need to determine the calibration accuracy of the eye-marker camera.

TABLE 1

PERCENT FIXATION DURATION AS A FUNCTION OF DISTANCE FOR DAY AND NIGHT DRIVING AND FOR TWO-LANE AND FOUR-LANE HIGHWAYS

Distance	Day Driving	Night Driving	Rural Two-Lane	Divided Four-Lane
0-75 ft	0	9.5	0.5	1.3
75-250 ft	9.2	17.9	19.9	8.0
>250 ft	70.0	25.4	53.6	44.8
Other	21.8	52.8	25.0	45.9

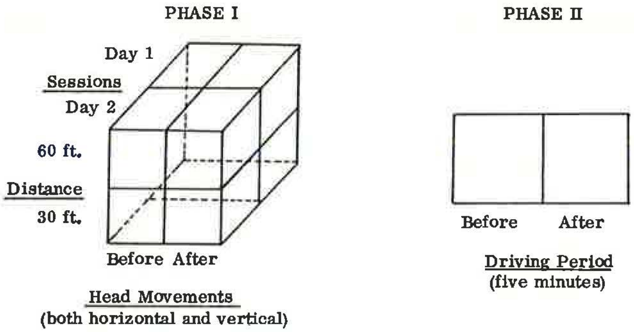


Figure 9. Experimental design of the calibration study.

CALIBRATION STUDY

Recently, Mackworth (2) reported the registration accuracy of a stand-mounted corneal-reflection eye-camera to be ±1 deg. Registration accuracy is the precision with which the eyespot (the reflection of the light source off the cornea) corresponds with where the subject is actually looking. An eye-camera is calibrated when the registration accuracy for any point in the visual field is less than ±1 deg. Other investigations (1, 3) have reported that subject head movements caused loss of calibration accuracy. Williamson and Barrett (3) also reported that registration accuracy varied as a function of the distance of the target to the subject's eye. The experimental design of the calibration study is shown in Figure 9.

In both Phase I and II all subjects served in all conditions. The subjects were seven male Ohio State University students ranging in age from 19 to 29. They were given a vision examination by the School of Optometry, and all were found to have normal visual health and at least 20-30 uncorrected vision.

At the beginning of each session the eye-camera was calibrated on the subject in the laboratory. The subject drove the vehicle (1963 Chevrolet) to the test site where he positioned it in front of a 2 × 3 target array (Fig. 10). The distance between target centers in the horizontal plane spanned 17 deg and in the vertical plane 8 deg, 30 min. Since the vehicle's hood prohibits the driver from looking down at this angle, it was impossible to span 17 deg in the vertical plane. Therefore, only a two-row target array was used. Film was collected while the subject's eyes traced the matrix twice for each experimental condition in each session.

Registration error was defined as the vertical and horizontal components of the distance from the center of a target to the center of the eyespot. Sign conventions for the scoring of errors are shown in Figure 11.

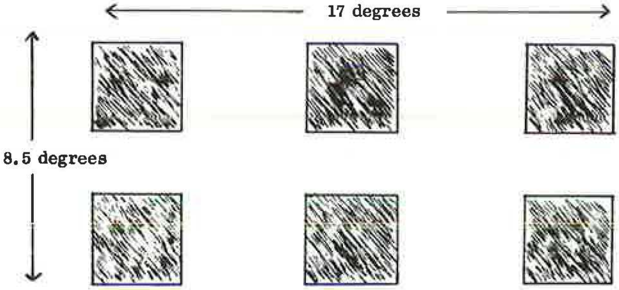


Figure 10. Target array.

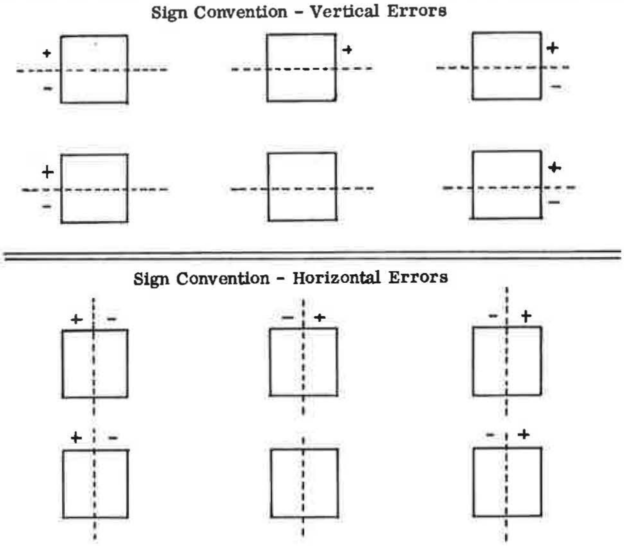


Figure 11. Sign conventions.

Errors were measured by examining the film frame by frame. A computer program converted the error measured in inches into degrees in order to make comparisons between the two distances and all targets.

Pearson product-moment correlations between the vertical and horizontal errors for each target were not significant, indicating that the horizontal and vertical errors may be analyzed separately.

Calibration Results

The mean vertical and horizontal errors are a function of target location. When summed over all experimental conditions, they are an indication of the calibration accuracy of the eye-camera. In Figure 12, the mean vertical and horizontal errors are

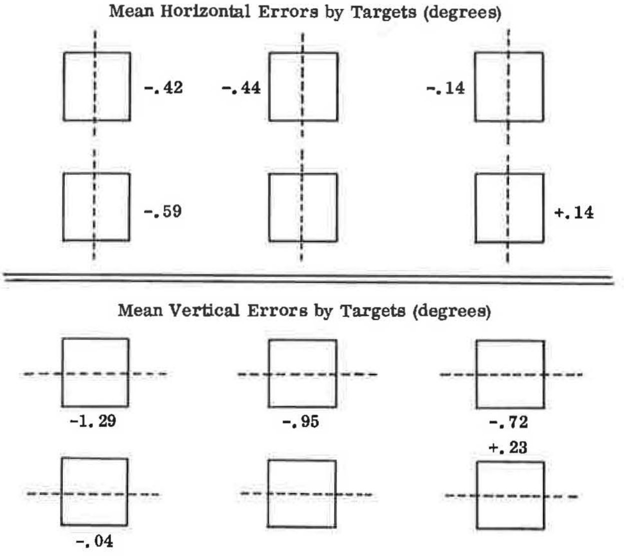


Figure 12. Mean vertical and horizontal errors of calibration—Phase I.

TABLE 2

MEAN HORIZONTAL AND VERTICAL ERRORS—PHASE I

Variable	Horizontal Error (deg)	Vertical Error (deg)
Subjects		
1	-0.52	-0.93
2	-0.27	0.08
3	-0.20	-0.54
4	0.20	-0.85
5	-0.60	-0.64
6	-0.29	-0.47
7	-0.33	-0.52
Sessions		
Day 1	-0.29	-0.52
Day 2	-0.28	-0.59
Distances		
30 ft	-0.26	-0.57
60 ft	-0.32	-0.53
Head movements		
Before	-0.31	-0.51
After	-0.26	-0.59

TABLE 3

MEAN HORIZONTAL AND VERTICAL ERRORS—PHASE II

Variable	Horizontal Error (deg)	Vertical Error (deg)
Subjects		
1	-0.63	-0.94
2	-0.23	-0.85
3	-0.32	-0.56
4	-0.03	-0.42
5	-0.57	-1.19
6	-0.28	-1.02
7	-0.41	-0.57
Driving		
Before	-0.26	-0.63
After	-0.44	-0.96
Targets		
Lower left	-0.59	-0.11
Upper left	-0.31	-1.53
Upper center	-0.56	-1.22
Upper right	-0.31	-1.03
Lower right	0.02	-0.08

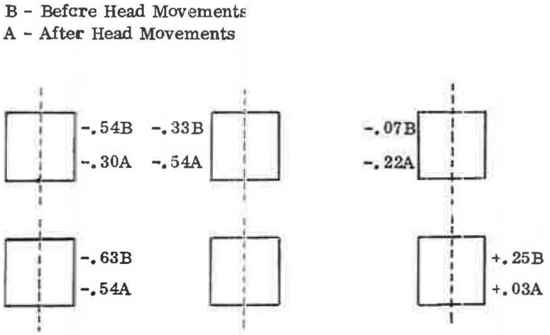


Figure 13. Interaction of head movements and targets.

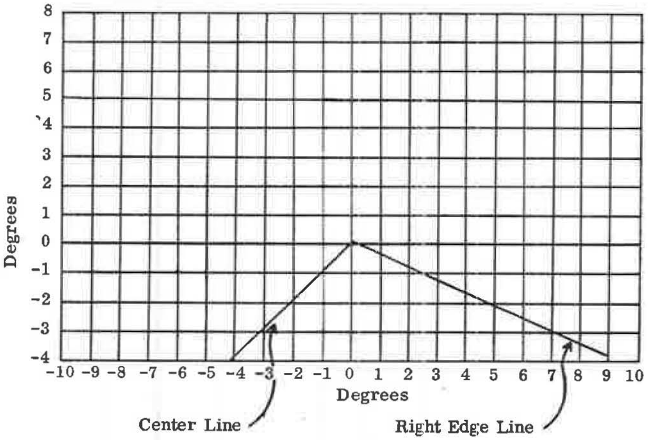


Figure 14. Data-reduction grid.

shown as a function of targets. Except for one target all the horizontal errors were less than 0.50 deg. Mean vertical errors for the two targets at the driver's eye level were less than 0.25 deg. Table 2 gives the mean horizontal and vertical errors for subjects, sessions, distances, and before and after head movements.

An analysis of variance of the horizontal errors showed that the targets by head movements interaction were significant ($p < 0.01$). The main effects of sessions, distances, and head movements were not significant. The interaction of targets and head movements is shown in Figure 13. Head movements caused calibration accuracy to move slightly to the left on all targets. This effect was small and of no practical significance.

In the analysis of variance of vertical errors, targets were significant ($p < 0.01$). Sessions, distances, and head movements were not significant. The errors of the targets in the upper row were much larger than the errors of the targets at the driver's eye level.

Table 3 gives the mean horizontal and vertical errors for Phase II. The analysis of variance for horizontal errors showed no significant effects. The only significant effect in the analysis of variance of vertical errors was targets ($p < 0.01$).

In summary, head movements, distances, sessions, and driving had very little effect on calibration accuracy. In the horizontal plane, calibration error was half that in the vertical plane. Even though the subjects were in a dynamic environment, and their heads were unconstrained, the calibration accuracy of the eye-camera system was comparable to that found in most laboratories where the subject's head is held stationary. The results may partially be attributed to the stabilization unit developed by the Systems Research Group.

RESEARCH POTENTIAL

Following the calibration study, the Systems Research Group collected eye movement data of drivers in car-following, open road, traffic, and overtaking situations. Figure 14 shows the data-reduction grid used for this experiment. The system is based on

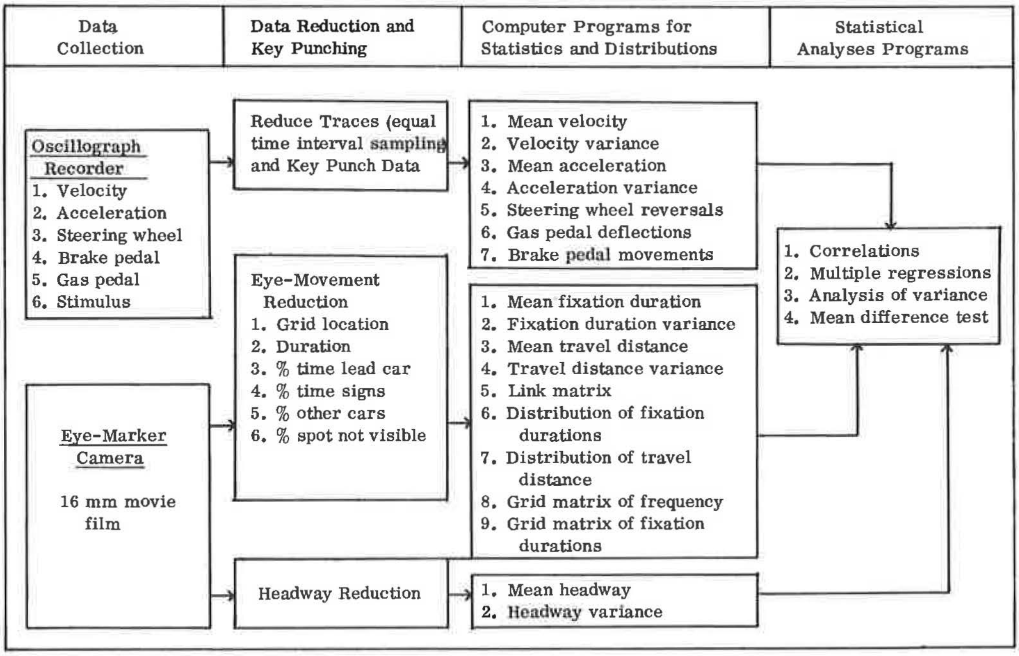


Figure 15. Data-reduction system.

lining the road geometry (the middle and right-hand marker lines) on the film with the road geometry on the data-reduction grid. This procedure eliminates the effects of driver head movements and vehicle dynamics from data reduction.

The total data-reduction system is shown in Figure 15. The reduction of eye movements from film is accomplished by using a Kodak Data Analyzer Projector. After the data are keypunched, computer programs calculate the statistics and distributions, and perform statistical analyses.

This study will provide eye-movement data that will serve as a standard for data collected in various stressful situations. Eye-movement data collected during fatigue and glare driving conditions may provide insights for the development of aids and techniques to combat these situations. In addition, the changes in eye-movement patterns while a person is learning to drive may lead to the teaching of optimal search and scan patterns for driving an automobile.

ACKNOWLEDGMENT

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Discussion

DONALD A. GORDON, U.S. Bureau of Public Roads—Rockwell and his collaborators are to be congratulated on their achievement in registering driver's eye movements. All of us who have attempted such measurements are aware of the difficulties that must be overcome. First there is the jounce of the moving vehicle, which throws measurements off-calibration. This problem was solved by use of a specially designed stabilization unit that was fitted against the upper teeth. Then there is the problem of precision. An error of 0.25 deg in the vertical dimension, which is the experimental accuracy achieved by Rockell et al, covers a distance from 75 to 99.4 ft ahead of the car. This precision is adequate for many purposes. The problem of field calibration was met by the development of a special device. We would like to know where the calibration array was placed and how the driver's eye was held steady during the calibration process. We have questions, too, about the use of illuminated reference spots as a substitute for night highway features. The angle of these lights relative to the road varies as the driver moves his head. But these are minor points which detract in no way from Rockwell's achievement.

With regard to driving, the traditional role assigned to eye-fixation data is that of indicating the object on the highway responded to when the driver steers, brakes, or accelerates the car. This stimulus-object stands in causal relation to the driver's response. Those of us who have attempted to identify the driver's visual stimuli have encountered several difficulties.

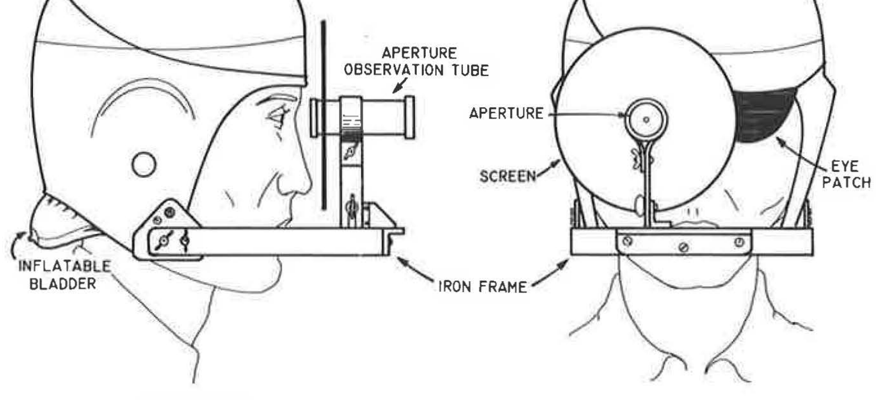
In the highway situation, the driver often responds to a general situation, rather than to an object in the center of his fixation. For example, he may slow up in urban traffic without leaving an indication of the cause on the eye record. It is also clear that the response may be to the driver's intention, desire, set, or to what psychologists call the organismic state. Let us suppose that the driver intends to leave a multilane highway and moves over to the right lane. In this case, the stimulus, if it can properly be called such, would be in the driver's mind, and not on the road.

As has often been pointed out, the driver can look without seeing, and conversely, he can see without looking. An object may be focused directly on the fovea, but that does not guarantee that it will be registered by the brain. Considerable evidence exists to indicate the importance of peripheral vision in driving. Unfortunately, we do not have a direct communication channel to the driver's brain to tell us what objects in the central or peripheral vision are being registered.

These difficulties have tended to discourage the interpretation of eye-fixation records. As we view the driver's eye, directly or on a film record, it darts back and forth, lighting in seemingly random fashion on conspicuous objects in the field ahead. The confusion is compounded when we remember that while the eye is roving ahead, the driver's hand is controlling the vehicle in relation to a different, and past situation. For example, the hand may be guiding the car out of a curve, while the eye is running ahead and exploring the next curve.

This situation is not as discouraging as it appears; eye fixation data have a clear meaning, based on the role of vision in the highway situation. Despite the apparent confusion, a very well-organized operation is taking place. The movements of the eye serve the driver's need to obtain information required to deal with the situation. Under conditions of limited visibility, as in rain, fog, or lowered illumination, every fixation counts, and if the essential information is not obtained, the driver will slow down or halt. Under daylight illumination, on a straight, uncluttered road, the required information is easy to obtain. In this situation, the eye may become lazy and spend considerable time on irrelevant objects, and may even indulge in looking without seeing.

The position that the eye's role is to gather essential information is quite different from the old visual stimulus interpretation. The driver is not to be regarded as a football kicked about by stimuli in the visual field. Rather, he is the executive who actively directs the search for information required for planning ahead. The relevant research



SIDE VIEW

FRONT VIEW

Figure 16. The apperture device. The apperture is fastened to a helmet with camera on top. The other eye is occluded with a patch. An inflatable bladder fills the space between the head and helmet.

questions then become: What is the essential information required for various maneuvers? What are the typical modes of information-gathering used by the driver? Under what conditions is essential information missed and an accident-prone situation created? We are led to develop techniques for quantifying information and to study problems of information-processing and overload.

For indicating essential information, techniques other than eye-movement recordings may be used. In a previous paper (4), I have discussed a technique for isolating the driver's essential information. The method involves having the driver guide the car while looking through a device containing a small aperture (Fig. 16). By decreasing the visual field, the essential information, whatever it is, cannot be seen at once; i.e., the driver is forced to obtain this information in separate visual fixations. A continuous film record is made of his visual aim and the content of each fixation. The essential information he is using is easily identified in each separate restricted fixation. The stimulus to driving may also be studied by formal experimentation. For example, Michaels and Cozan showed that the sideways angular velocity of an approaching object in the field of view could logically be considered a stimulus to lateral displacement of the vehicle by the driver. Introspective data should not be neglected. Information becomes essential only in relation to the intentions and purposes of the driver. To the extent that the driver is aware of what he is looking at and trying to do, introspective data may explain his response.

Eye-fixation data are likely to have their most important application regarding the question of how the eye secures essential information. In maneuvers such as overtaking and passing, lateral displacement to a road obstacle, merging, and braking, we can often designate the relevant stimulus, but the details of visual performance require clarification. Eye-movement data tell us when the driver starts to look, how long he looks, and in what direction. For example, in the merging maneuver, where the driver must find a gap in the main stream, eye-movement records tell us how far he looks to the side of the road and assist us to assess the danger of the task. The essential information is apparent from the logic of the situation.

Finally, in discussing the contributions of eye-movement techniques, it should be mentioned that these records have always had something special and surprising about them. Ninety years ago, Javal, an optometrist, watched the eye of a reader and found that it proceeded in jumps rather than moving smoothly across the page. Javal called these movements "saccades," which is French for "jerks." The term is still in use. The subsequent history of eye movement research has revealed many other interesting facts of visual behavior. It is to be hoped that the typical patterns of eye fixation will indicate much concerning the dynamics of the driving process. We look forward to further contributions from the Systems Research Group of the Ohio State University, now that the basic techniques have been mastered.

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T. W. FORBES, Department of Psychology and Highway Traffic Center, Michigan State University—The study of head and eye movements in driving is of considerable importance and has not been given sufficient research attention. The authors are to be complimented on developing a new combination of camera, head-mounting frame, and fiber optics for transmitting a picture, using some "off the shelf" equipment and adding or modifying it. This apparatus offers the advantage of a relatively light head-mounted unit compared with others on which the camera itself is mounted on the head frame.

The authors' combination of a pilot study using the camera in actual driving and also a calibration study to determine the recording accuracy is a desirable approach. It would seem that good accuracy was achieved.

Accuracy of calibration was not significantly disturbed when checked before and after head movements and the lateral range of eye movements was about 17 deg. This represents about one lane width either side of the median at 100 ft. If so, this appears to limit eye-movement recording to open-road driving, and information of this type is certainly needed for studying the detail of open-road driving performance.

The report does not mention the procedure for measuring eye movements when combined with head movements. Such measurements would seem to be possible with the equipment, and perhaps discussion of them was omitted for simplicity in the description. Measurement of extent and time duration of head and eye movements separately and together is highly desirable.

Important as it is, the study of detailed head and eye movements in open-road, straight-ahead driving is only the beginning of a broad area that needs to be studied.

When the 20-deg cone of clearest vision (10 deg either side of center of the fovea) is diverted off the road, the driver momentarily loses clear vision of what is ahead. During eye movements from one fixation point to another, clear vision is also lost. Furthermore, attention is usually given to the clear vision field and is less often given to stimulus objects in the remaining blurred vision areas. Thus, drivers are effectively blind or partially blind to areas out of the field of clear vision. A pilot study some years ago at UCLA indicated that drivers may be "flying blind" for significant time intervals and that these occurred not singly but in a continuous series. Times were long enough for serious things to happen. Car instrumentation and photographic recording was used. The equipment did not allow completely satisfactory measurement, but records on five subjects did indicate head movements of as much as 45 to 65 deg and a continuing series of "blind" intervals of 1.0 to 2.5 sec and more. This is an area of important information needed to understand and reduce driving hazards. The type of equipment described by the authors may well contribute in an important way to research in this area.

THOMAS H. ROCKWELL, C. OVERBY, and R. R. MOURANT, Closure—As pointed out by Dr. Forbes, the apparatus does not measure head movements. However, it does record where a subject is looking regardless of his head position. For example, if the driver is looking at the car in front of him and then turns his head 5 deg and continues to look at the car, the system can record this. There is little doubt that the measurement of head movements, in addition to eye movements, is an important goal. Dr. Gordon's question as to the use of illuminated reference spots as a substitute for night highway features is well founded. Since the angle between the subject's head and the reference lights changes with head movements, error is introduced into the determination of the eyespot location. Because of this, we have decided to use the middle and right-hand edge markers as reference lines. The location of the eyespot with respect to the edge markers is independent of the position of the vehicle and the driver's head.

The driver's eye was not held steady during the calibration process. He was instructed to fixate on the center of each target. This means that small saccadic movements of about 2-10 min of arc may have influenced the measurements. The calibration array was placed on a blank outside wall of a building.

The question of looking without seeing has been of interest for many years. Gaarder (5) reported that eye movements patterns are dependent on whether or not the subject is paying attention. Eye movements during inattention are characterized by infrequent saccades and shifting phase relationships between horizontal and vertical movements. During attention, eye movements contain about 0.3 saccades per sec with no shifting phase relationship between horizontal and vertical movements. Thus, there is hope that eye-movement patterns are reflective of the attention-inattention continuum.

Both reviewers have addressed themselves to the problem of interpretation of eye-marker data. In a study currently being conducted at Ohio State University, preliminary results show that mean duration of eye fixations in the traffic condition is lower than in the open-road driving condition. This indicates that statistics from eye-marker data may be a measure of driver work load.

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