Driver Eye-Movement Patterns Under Conditions of Prolonged Driving and Sleep Deprivation

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This study investigated the changes in eye-movement patterns of 3 drivers after prolonged driving and sleep deprivation. In the first experimental condition, subjects drove for approximately 9 hours with only minor stops for equipment setup and calibration on refueling. Prior to the second 9-hour driving task, the same subjects were deprived of sleep for 24 hours. Eye movements were filmed under open-road conditions (no traffic in the visual field) at 3 speeds: 40 to 50 mph, 60 to 70 mph, and 75 mph exact velocity maintenance. The eye movements were examined both spatially and temporally, and a new index—pursuit eye movements—was investigated.

•DRIVING has become a much easier task to perform due to a host of improvements, including smoother vehicle performance and better highway design. While driving at control speed on a modern freeway, the driver has less need to accelerate or brake. The driver still must steer continuously, but he is not confronted with many large turns. In short, the driver's primary function has become that of a monitor.

A survey of the National Safety Council shows that the percentage of all accidents that might be categorized as open-road accidents increased from 27.4 percent in 1946 to 35.8 percent in 1966 (1). The inherent boredom and fatigue associated with monitor or vigilance tasks might partially explain why these accidents have proportionately increased on freeways while other types have proportionately decreased (8). The similarity between low-demand vigilance tasks and long-term freeway driving has been discussed elsewhere by Safford (8). He proposed that many of the results of vigilance research could be applied to the turnpike driving problem. The development of the portable eye-movement system by Whalen, Rockwell, and Mourant (15) has provided the means of studying this problem through analysis of drivers' eye movements.

THE VISUAL TASK AS IT APPLIES TO DRIVING

The driving situation places the driver in an environment that is essentially dynamic. Although the physical position of the driver in relation to the vehicle is relatively unchanging over time due to the motion of the vehicle, he is monitoring signals that are many and varied and that evolve from a constantly changing background.

The driver's entire visual field contains information that can be classified into signals and nonsignals. Signals are meaningful information that require the driver to make a decision concerning the operation of his vehicle. Nonsignals, conversely, do not require a decision concerning the operation of the vehicle; they constitute a noise environment in which signals are interspersed.

According to Yarbus (17), "The order in which the observer's attention moves from one point of fixation to another, the duration of the fixations, the distinctive cyclic pat-

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Paper sponsored by Committee on Road User Characteristics and presented at the 49th Annual Meeting.

tern of examination, and so on are determined by the nature of the object and the problem facing the observer at the moment of perception." Later he states that "foveal vision is reserved mainly for these elements containing essential information needed by the observer during perception."

The classical concepts of spatial and temporal expectancy are important to this problem. Spatial expectancy would entail consideration of the "expected values" of observing at various times. For example, if the expected value of information to be gained is greater for an area on the right side of the road than an area on the left side, the relative observing rate would be greater in the area to the right than the area to the left. A similar example could be described for temporal expectancy. Mackworth's statement (5) relating the two has been widely accepted: "...spatial expectancy is the dominant factor, but when it is not present temporal expectancy can begin to influence performance to some extent."

Senders' model of visual sampling behavior (10) provides some additional insight. Senders proposes that the time of the next observation can be extended until the probability of occurrence of a critical event within that interval exceeds some limit. When this "limit of safe operation" is exceeded, a new observation is taken. This describes a system that would respond to changes in the perceived environment by initiating a compensatory change in the time distribution of eye movements.

EFFECT OF STRESS

The degree to which the visual areas are spatially affected by stress is of considerable interest. It is reasonable to expect that stresses resulting from long-term vigilance would, in general, depress the expected values associated with spatial and temporal expectancies. This could result in a change in the eye movements alloted to spatial areas and temporal zones.

An article by Weltman and Egstrom (13) reveals that the ability to monitor a peripheral task becomes greatly impaired under stress, while the ability to control the central or frontal tasks is not significantly reduced. The subjects involved in Weltman's experiment were underwater divers and the stress was induced by fear. Weltman and Egstrom cite the work of Teichner (12) who reported that detection of a light signal in the visual perhiphery was adversely affected by sleep deprivation. The obvious conclusion is that signals reaching different retinal areas are not uniformly affected by stress. Weltman concluded that "whatever the genesis of this phenomenon, it seemingly occurs under varied conditions of psychological stress...."

In a somewhat different experiment, Mackworth (5) demonstrates that visual noise (i.e., incorrect signals similar to correct ones) causes "tunnel vision." He explains that the periphery of the retina could no longer accurately detect at a glance whether items were similar. Foveal performance was also affected to some extent by extra items in the periphery of the retina. Mackworth explains that, in order to reduce random search, eye movements must often be planned from data acquired by the peripheral retina. His main contention is that the addition of visual noise in the form of unwanted signals can destroy this vital peripheral matching.

Whatever the cause, sleep deprivation, fear, or visual noise, it seems apparent that the ability to detect signals on the peripheral retina is hindered to a greater degree than is the ability to detect foveal signals.

ACQUISITION OF INFORMATION

Unlike the stationary observer, the driver must sense his velocity and position in relation to the outside environment. The same stimuli that provide information relating to the decision aspects of the driving task also provide the information relating to velocity and position.

In terms of the visual field available to the driver, the linear motion of the vehicle is best translated into angular velocity. Gordon (2) accomplished the mathematical description of a moving ground plane. In general, the angular velocity of any point of the plane is directly proportional to the linear speed. In addition, angular velocity

values are at a minimum in the foveal visual field along the direction of motion and at a maximum in the peripheral visual field close to the vehicle.

Salvatore (9) succeeded in demonstrating that velocity estimation is much more accurate when based on stimulation to the peripheral field rather than stimulation to the frontal field. According to Salvatore, frontal field refers to 25 deg centered on the direction of motion and peripheral field refers to the field subtended from 65 to 90 deg from the direction of motion.

In an effort to explain his results, Salvatore offered that linear velocity information is acquired peripherally because of the larger angular velocity information available in that area. For example, at a vehicular speed of 60 mph, a distant road sign 12.5 deg from the center of the vehicle's path has an angular velocity of 81 deg/sec; however, by the time the vehicle passes the road sign it has attained an angular velocity of 1,080 deg/sec. The results of his study show that velocity estimates, in addition to being poorer, were also lower when based on frontal information alone. Thus, a fatigued driver whose periphery has become "clouded," may tend to substitute frontal velocity information for peripheral velocity information. Salvatore states, "This may underlie the phenomenon of highway hypnosis which results in gross under-estimation of high speeds. The attention, after prolonged driving, may become restricted to the area normally fixated: the frontal field."

Furthermore, Salvatore believes that "perception of motion in the frontal field is detrimental to steering or tracking performance and would tend to be ignored in driving." Michaels (6) shows that acquisition of lateral position information is necessary in order to maintain the vehicle's position on the roadway. To determine the relative position of stimuli to each other and to the vehicle and its axis of direction, it would be advantageous to perceive them as stationary, which, of course, they are not. However, as compared with stimuli in the peripheral fields, stimuli in the frontal field are relatively stationary. It is believed that perception of the stable relationship of objects when they are frontal enables the driver to "aim" his vehicle on the roadway. Perhaps the passing of this stimulus by the vehicle provides, in addition to velocity information, a continuous feedback of performance of this tracking task. Subsequently, a peripheral detection deficiency caused by fatigue could lead to an impairment of this feedback loop, resulting in an inability to maintain lateral position.

PURSUIT EYE MOVEMENT

Pursuit movements provide a stationary retinal image for resolution when the object of resolution is in motion. This type of movement, however, is impossible without the presence of a moving object. Shakhnovich, Dzhanelidze, and Inauri (11) state that "the floating tracking motions of the eyeball are possible only when there is a moving object in the field of vision, the velocity of which exceeds the velocity of spontaneous drift of the eye." It is known that, when fixating on a still point, the micromovements of the eyeball consists of tremor, drift, and small jumps that return the images of the point on the retina to the center of the fixation zone. Past vehicular eye-movement studies (14, 18, 1) have shown that the majority of the receiving time is spent in the frontal area of minimal angular velocity. It is doubtful that fixations on objects in this area result in pursuit movements because the velocity of spontaneous drift was probably not often exceeded.

Woodworth and Schlosberg (16) mention the alternating pursuit movements and return saccades that occur with regularity when one is fixating on objects while riding a train or bus. Train and bus passengers are fixating out of side windows on environmental features that have attained angular velocities that undoubtedly exceed the spontaneous drift velocity of the eye. Drivers do not normally fixate in these nonfrontal areas. If they did, the tendency to make pursuit eye movements could be expected to increase.

EXPERIMENTAL METHODOLOGY AND DESIGN

The objective of this experiment was to study the effects of (a) sleep deprivation, and (b) prolonged driving on drivers' performance and drivers' eye-movement patterns.

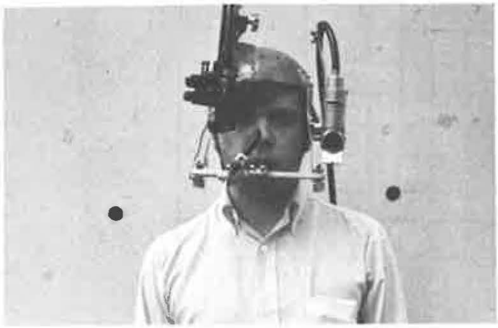


Figure 1. Subject wearing eye-marker equipment.

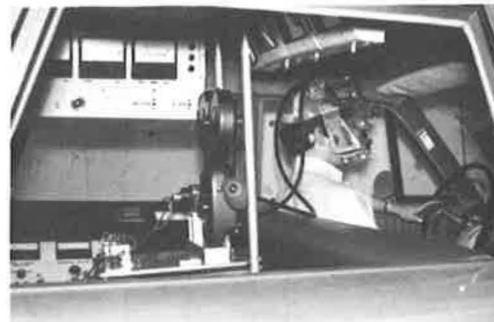


Figure 2. Experimental vehicle with mounted camera.

Eye-Marker Apparatus

The eye-marker apparatus is described in detail in a previous study by Whalen (14). In the system, the eyespot from the subject's right eye and the scene from the scene lens are superimposed by a beamsplitter. This picture is then recorded by a 16-mm Beaulieu motion picture camera. Figure 1 shows a subject wearing the eye-marker equipment. Figure 2 shows a subject in the experimental vehicle with the camera mounted on a platform in the rear seat compartment.

Experimental Design

The experimental design is shown in Figure 3. The pre-experimental preparation of the subjects was, of course, the primary control variable. For ease of reference, the treatments are designated as Run 1 and Run 2. Prior to Run 1 the subjects were instructed to obtain a normal night's rest at home. Prior to Run 2 the subjects were required to remain awake throughout the night at the Systems Engineering Building under the observation of a research assistant.

On each run, subjects drove three 150-mile laps. Each lap consisted of a predetermined section of Interstate highway. The travel time per lap was between 3 and 3½ hours. A special treatment occurred at the end of lap 3 during Run 2. The data, designated 3*, were collected following a rest stop during which the subjects were permitted normal "revival" activities. Within practical limitations, all experimentation was duplicated for each lap, permitting time behind the wheel to be treated in a discrete manner.

The eye-movement records that were taken included filming of 3 maneuvers: (a) open-road driving, 60 to 70 mph; (b) open-road driving, 40 to 50 mph; and (c) open-

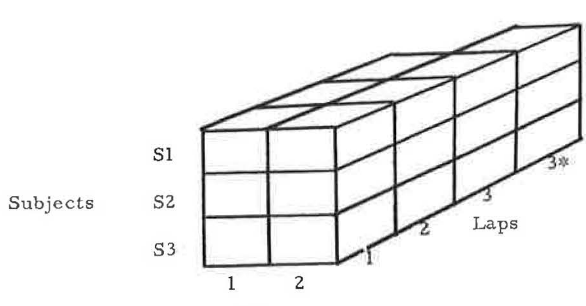


Figure 3. Experimental design.

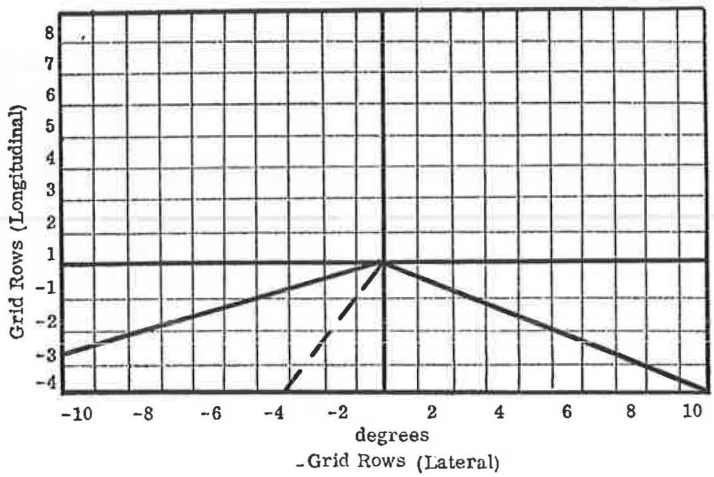


Figure 4. Film data reduction grid of 1-deg squares.

road driving, 75 mph velocity production. At least one 60-sec sample of eye-movement patterns during these maneuvers was filmed during each lap.

Because of inherent individual subject differences that have been observed in past eye-movement studies, subjects were treated as a separate factor. The 3 subjects were male studies at Ohio State University. The subjects selected were all experienced subjects and all had driven the test vehicle previously.

Data Reduction Procedures

The grid shown in Figure 4 was used to relate the eye-movement data directly to the highway. The 2 slanting lines were used to align the centerline and the right-edge line delineating the right lane for each frame of film. Thus, fixations were located relative to the environment despite head and trunk movements and changes of vehicle position. The grid squares measured 1 deg and were coded by the letters and numbers shown in

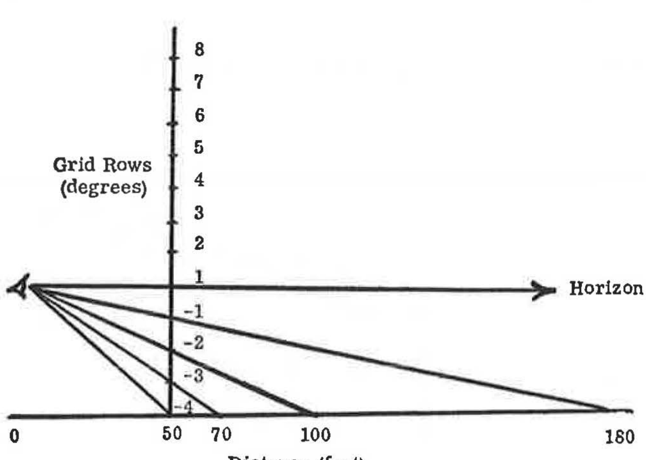


Figure 5. Relation of the grid to the driver's eye.

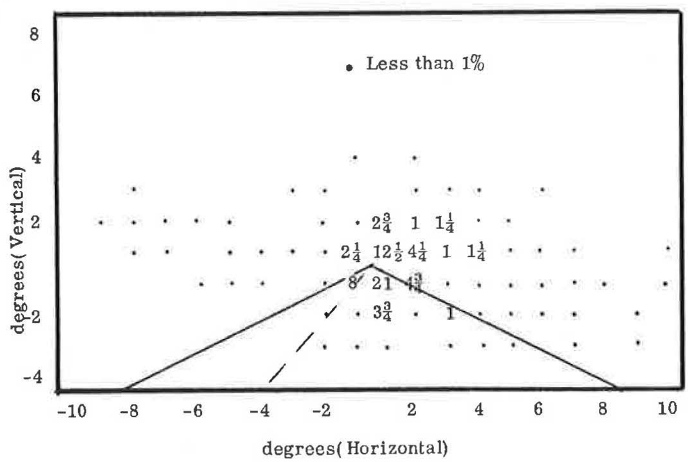
the vertical and horizontal directions. In addition to the locating of fixations by grid square, the feature in the environment that the eyespot intersected was recorded. These features include highway lane markers, signs, and bridges. Frames that did not contain an eyespot were tallied collectively as "out-of-view." This category includes blinking, fixations on the rear view mirror or speedometer, and fixations outside the field of view of the scene lens. Figure 5 shows the relation of the grid to the driver's eyes.

RESULTS

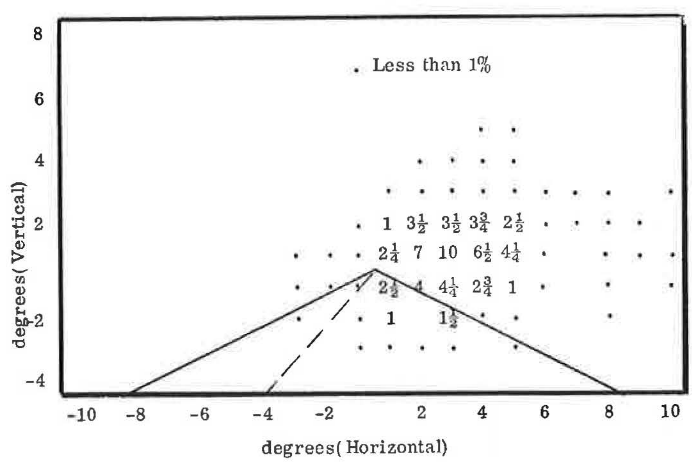
Eye-Movement Data

The analysis was conducted in 4 parts: spatial analysis of eye-movement data, temporal analysis of eye-movement data, analysis of special film segments, and microscopic analysis.

Occasionally during the filming sessions on Run 2, the subjects would become extremely drowsy. As a result, eyelids would lower and much of the corneal reflection was lost. Because this seemed to signify a finite change in state compared with the



RUN 1-Lap 1- 60-70 mph



RUN 2-Lap 1- 60-70 mph

Figure 6. Percentage of total fixation time per 1-deg square—all subjects combined.

rest of the Run 2 data, these "special" film segments were removed from the remainder of the Run 2 data and analyzed separately.

Because film sessions during Run 1 were duplicated during Run 2, paired comparisons of the eye-movement parameters were the most convenient form of analysis. The paired-t statistic was chosen as it requires neither independence nor equal variances.

Spatial Analysis of Eye-Movement Data—Figure 6 shows fixation density maps for combined subjects on lap 1, Run 1 and Run 2, under 60 to 70 mph open-road driving conditions. A fixation density map is, in reality, a 2-demensional representation of a 3-dimensional world, viewed through the windshield of an automobile. The numbers inside the 1-deg squares represent the percentage of fixation time spent in the square, and the dots designate squares that contain less than 1 percent of the total fixation time.

Longitudinal Analysis—The vertical, time-weighted, mean grid location (Fig. 7) is a measure of central tendency that indicates the relative height above the roadway or the viewing distance ahead of the vehicle. Figure 8 shows the results of this measure for combined subjects on Run 1 and Run 2 for the 3 open-road driving conditions. There is no significant difference (paired-t test, 8 degrees of freedom) between runs; however, a downward trend over both runs is evidenced. This trend indicates that, as time on the road progresses, subjects tend to look closer to the car. The trend is statistically significant for Run 2 and not for Run 1. The subjects exhibited a recovery of this measure after the rest break at the end of L3 of Run 2 (Fig. 8, L3*). A paired-t test (vertical mean at L3* - vertical mean at L3) revealed significance beyond the 99.5 percent level. This indicates that after the rest break the subjects again looked farther down the roadway.

Lateral Analysis—The horizontal, time-weighted, mean grid location (Fig. 7) is a measure of central tendency that indicates the relative location of eye fixations to the right or left of an imaginary vertical plane passing through the point of intersection of

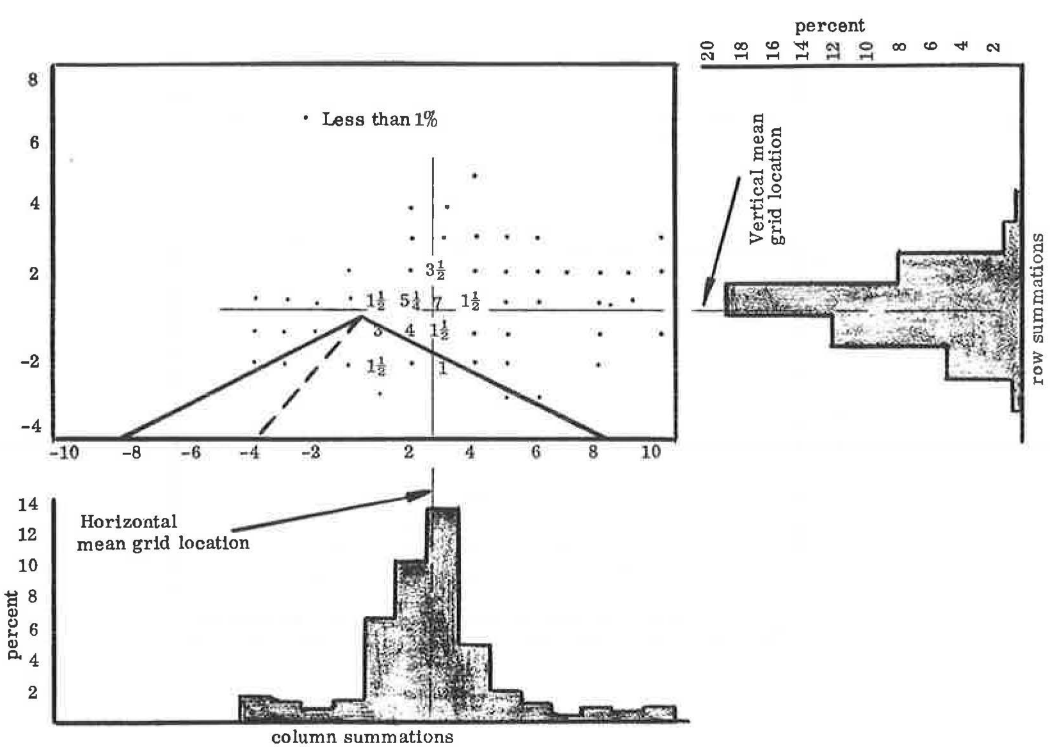


Figure 7. Mean grid location—a graphical interpretation.

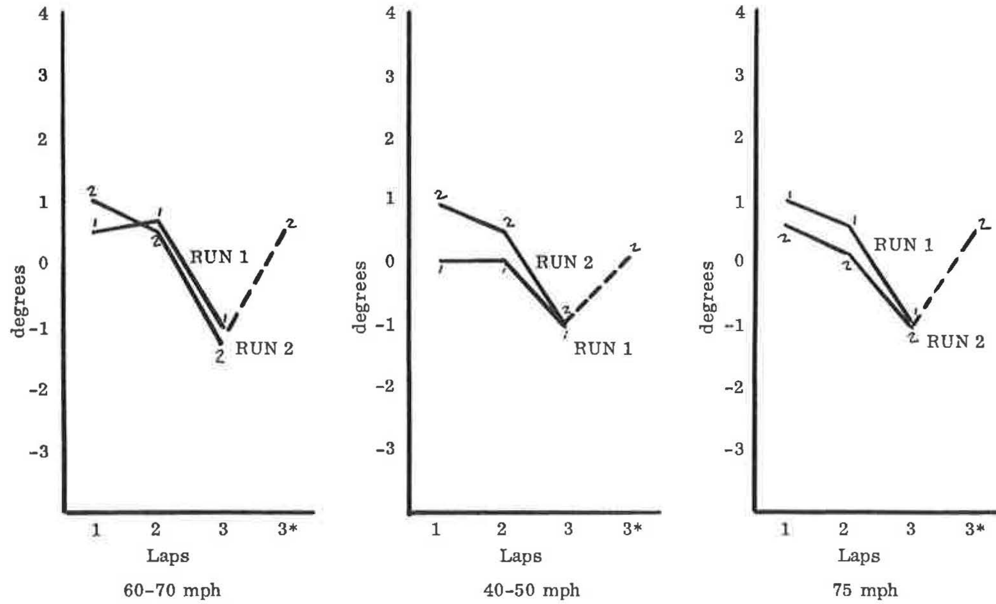


Figure 8. Vertical mean grid location—all subjects combined.

the horizon and roadway. Figure 9 shows the results of this measure for combined subjects on Run 1 and Run 2 for the 3 open-road driving conditions. The horizontal mean for Run 2 is significantly greater than that for Run 1 for the 60 to 70 mph and 40 to 50 mph open-road conditions. Statistically, this is significant beyond the 97.5 percent level (paired-t test, 8 degrees of freedom). This indicates a shift in the eye-movement patterns away from the center of the roadway to the right side of the road. Although numerically in the same direction, the shift for the 75 mph, velocity production, open-road condition is not significant.

As with the vertical mean, the subjects exhibited a recovery of the horizontal mean grid location after the rest break at the end of L3 of Run 2 (Fig. 9, L3*). A paired-t test (horizontal mean at L3 - horizontal mean at L3*) was significant at the 99 percent level. This indicates that, after the rest break, the subjects' eye-movement patterns shifted away from the extreme right side of the roadway back toward the center of the roadway.

As was indicated earlier, the area of minimal angular velocity is along the line of direction of the vehicle. In order to determine the amount of time the subjects spent fixating in these minimal angular velocity areas, the percentage of total time they spent fixating in the 2 center grid columns was calculated. These 2 columns contain the road straight ahead and the intersection point of the road and the horizon. Figure 10 shows these calculations for combined subjects on Run 1 and Run 2 for the 3 open-road driving conditions. Under the 60 to 70 and 40 to 50 mph open-road conditions, the paired-t tests (8 degrees of freedom) indicate that the amount of time spent in the 2 center grid columns during Run 1 is significantly greater than that for Run 2. These values are significant at the 99.5 and 95 percent levels respectively. The results for the 75 mph condition were not significant, although again the shift occurred in the same direction. This finding indicates that during Run 2, the subjects devoted significantly more of their total fixation time to areas containing greater angular velocity information.

A paired-t test revealed a recovery of this measure, significant beyond the 95 percent level, following the rest break. Therefore, after the break, the subjects again spent a lesser percentage of time fixating in the areas with maximal angular velocity information.

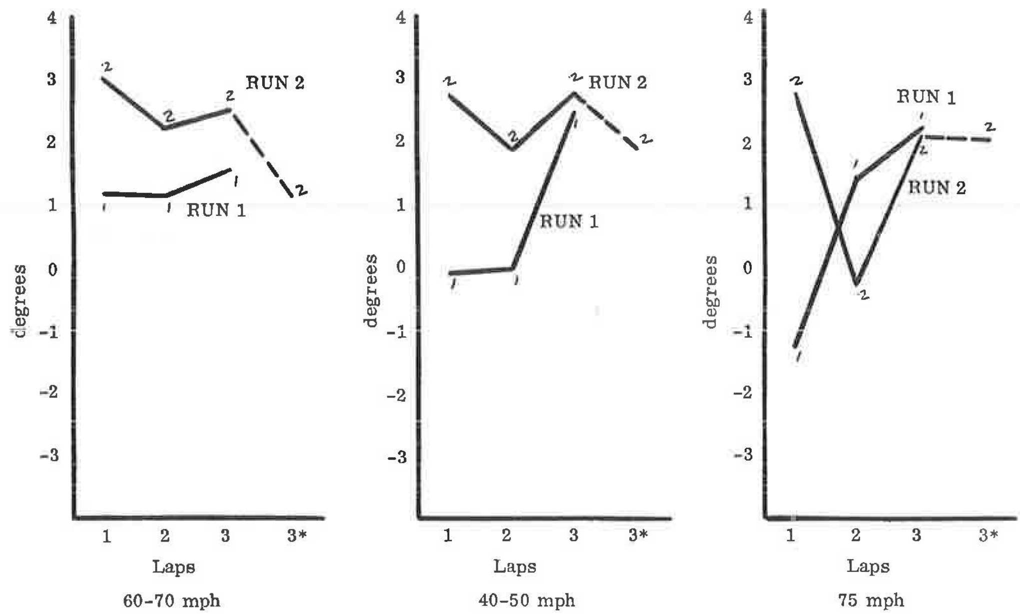


Figure 9. Horizontal mean grid location—all subjects combined.

Additional Analysis—In order to measure the dispersion of the fixation density diagrams in the vertical and horizontal direction simultaneously, Belt (1) developed the concentration index ratio (CIR):

$$\mathrm{CIR} = \frac{\text{total fixation time outside the most densely populated 3- by 3-deg square}}{\text{total fixation time over the entire grid}} \times 100 \text{ percent}$$

Because this measure seeks the most densely populated area, the effects of vertical or horizontal shifts in the density maps are neutralized.

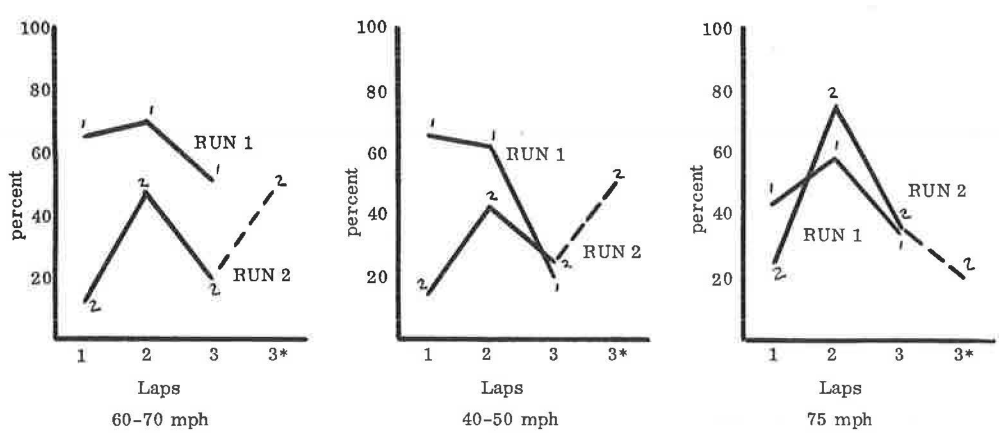


Figure 10. Percentage of fixation time in 2 center grid columns—all subjects combined.

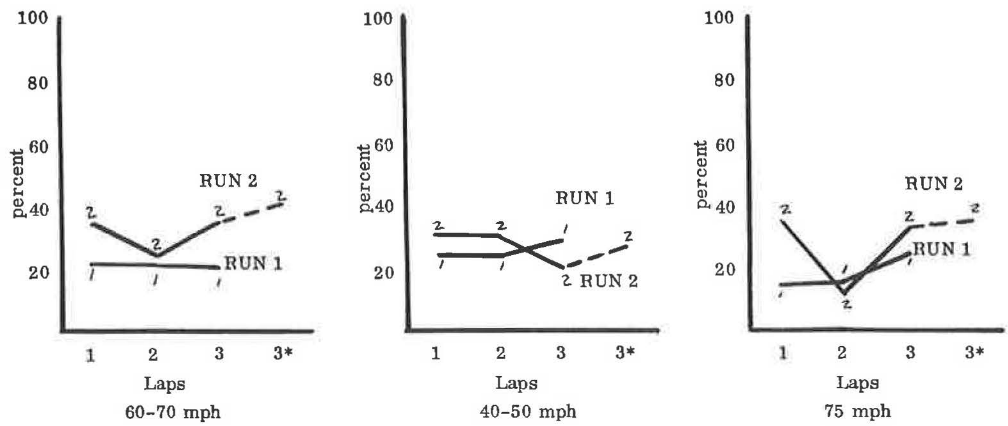


Figure 11. Percentage of total fixation time outside the most densely populated 3- by 3-deg grid square—all subjects combined.

Figure 11 shows the results of this measure. For the 60 to 70 mph open-road driving condition, the paired-t analysis revealed an increase from Run 1 to Run 2 significant beyond the 99 percent level. For the 75 mph open-road condition, the increase was significant beyond the 90 percent level. For the 40 to 50 mph condition the observed shift was also positive. However, because of subject variability, this shift was not statistically significant. These analyses for the 3 open-road conditions are interpreted to indicate that the dispersion of fixation durations increases between Run 1 and Run 2.

A paired-t analysis of these data between L3 and L3* shows (Fig. 11) that no significant changes occurred after the rest break. It appears from the spatial analysis, for the 3 subjects tested, that the eye patterns shifted to the right between Run 1 and Run 2 and shifted downward over the course of both Run 1 and Run 2. Also, after the rest break at the end of L3 of Run 2, the eye patterns moved back toward the left and upward. While the mean shifted between Run 1 and Run 2, the eye patterns also enlarged with respect to their 2-dimensional representation. Also, the amount of time spent fixating outside the areas containing minimal angular velocity information increased from Run 1 to Run 2 and decreased after the rest break at the end of L3 and Run 2.

Temporal Analysis of Eye-Movement Data—Analysis of the amount of time subjects spent foveally pursuing environmental features was revealing. Because of the rarity of pursuit of eye movements in driving, the data were combined for the various open-road driving conditions to obtain large enough samples to test for significance. Figure 12 shows mean pursuit eye-movement time for all subjects combined on Run 1 and Run 2. The increase in mean pursuit duration from Run 1 to Run 2 is significant beyond the 99 percent level (paired-t test, 8 degrees of freedom).

Figure 13 shows the percentage of total film time due to pursuit eye movements for all subjects combined on Run 1 and Run 2. The increase in this measure from Run 1 to Run 2 is significant beyond the 97.5 percent level (paired-t test, 8 degree of freedom). Interestingly, this percentage increased after the rest break (Fig. 13, L3*, for each subject). However, because of the lack of paired samples, one for each subject, this was not tested statistically. For the 3 subjects tested, it appears that the tendency to make more and longer following eye movements increases from Run 1 to Run 2.

Table 1 gives the environmental feature that the following eye movements intersected. Scenery on the right included poles, guardrails, trees, or any feature in that area that could not be determined from the film. Category "other" included the left edge marker, bridges, center of subject's own lane, and scenery on the left. Most important from this figure is that at no time during the film sessions of Run 1 did any of the subjects make a pursuit eye movement in the area of the scenery on the right.

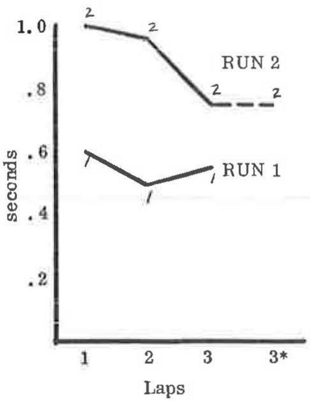


Figure 12. Duration of mean pursuit eye movements—all subjects and maneuvers combined.

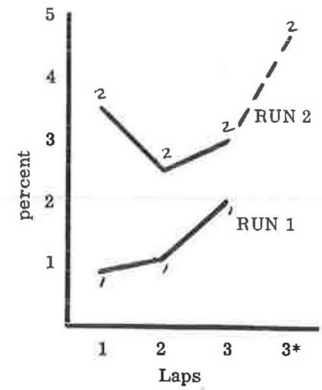


Figure 13. Percentage of total film time due to pursuit eye movements—all subjects and maneuvers combined.

TABLE 1

PRINCIPAL FEATURES INTERSECTED BY PURSUIT EYE MOVEMENTS

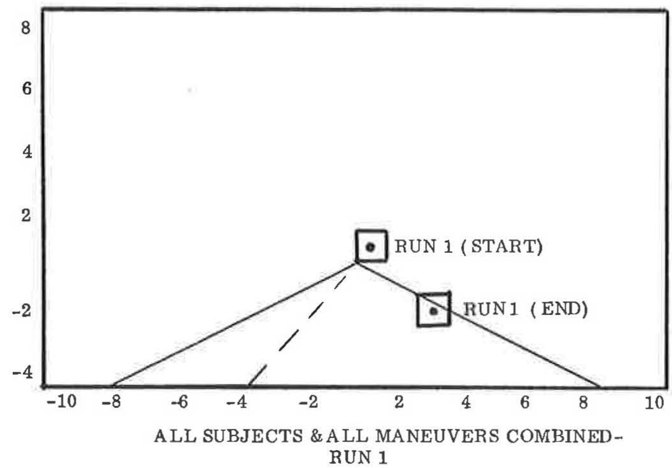
Subject	Run	Mean Pursuit Time: Center Lane Marker	Road Sign	Scenery on the Right	Right Edge Marker	Other	Percent of Total Pursuit Time: Center Lane Marker	Road Sign	Scenery on the Right	Right Edge Marker	Other
1	1	0.450	0.719	–	0.625	–	57.7	36.9	0.0	5.4	0.0
	2	0.438	1.056	0.786	0.688	–	1.4	64.0	30.1	4.5	0.0
2	1	0.552	0.799	–	0.500	–	34.7	58.7	0.0	2.6	4.0
	2	0.435	0.988	1.593	0.813	–	31.7	42.6	8.6	4.4	12.7
3	1	0.493	0.524	–	0.915	–	41.4	37.6	0.0	11.0	10.0
	2	–	1.076	0.992	0.313	–	0.0	48.7	39.9	1.6	9.8

DISCUSSION OF RESULTS

The spatial analysis of the eye-movement data yielded several measurable results. In general, the mean locus of the eye-movement patterns shifted to the right (Fig. 9) and down (Fig. 8) approximately 2 deg in each direction over the course of Run 1. During Run 2 the vertical shift repeated its pattern, while the horizontal tended to remain approximately 2 deg to the right over the course of the run. Therefore, regardless of the amount of sleep, the subjects exhibited the same downward shift over "time behind the wheel." The shift to the right occurs over time behind the wheel for Run 1, but the effect of no sleep, Run 2, causes the shift to the right at the outset of Run 2.

Figure 14 shows the shifts in terms of roadway geometry. The shift does not seem large when expressed in degrees. In terms of margin of safety, however, time to overtake the "higher" point is approximately 5 or more seconds; time to overtake the "lower" point is approximately 2 or less seconds.

The analysis of the amount of time the subjects spent viewing in the 2 center columns (Fig. 10) helps to confirm that fact that the eye-movement patterns had shifted to the right. Figure 14 shows the center columns in relation to the roadway. For the 60 to 70 and 40 to 50 mph maneuvers, the amount of time spent viewing in the 2 columns was significantly less for Run 2. The difference, although not significant, was in the same direction for the 75 mph velocity production task.



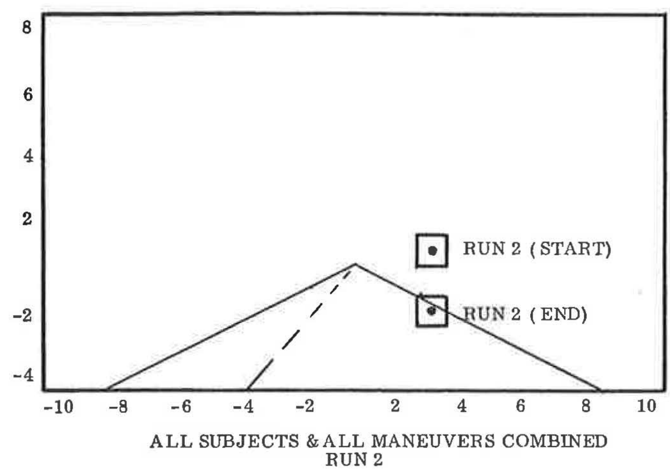


Figure 14. Approximate position of locus points at the start and the end of Run 1 and Run 2.

Analysis of the eye-movement data from lap 3* of Run 2 revealed that the locus point had returned to its Run 1 position following the rest break. At this point it appears that, with respect to eye movements, the subjects had successfully revived.

The concentration density graphs (Fig. 11) reveal that on the average the eye-movement patterns were less concentrated during Run 2. Therefore, it appears that more foveal viewing time was allocated to areas normally monitored primarily by the peripheral retina. This implies that some decrement in peripheral sensitivity had occurred.

In Mackworth's static laboratory setting (5), impairment resulted in a tighter foveal concentration (i.e., fixations were more central). In the dynamic freeway setting, the change in the observed fixation pattern was the opposite of Mackworth's findings.

Earlier it was argued that drivers sense velocity by stimulation from the peripheral fields. According to both Yarbus and Senders (17, 10), then, sensitivity decrement to the peripheral retina, coupled with a need to sense velocity, should result in more foveal excursions to areas of greater angular velocity. This would predict greater

dispersion in the eye-movement patterns. Furthermore, it would explain the overall drift of the eye-movement patterns to the right and down (Fig. 14). Such a shift is toward an area of greater angular velocity information. It is thus suggested that this effect is consistent with the principle of perceptual narrowing.

When combined with the experimental results reported by Jarboe (3), these findings provide special insight into a possible cause of open-road accidents. Jarboe showed that an additional effect of fatigue in driving is an increase in the speed the subject maintains when denied use of a speedometer. The increased speed and reduced viewing distance ahead of the car combine to make it extremely difficult or impossible for the driver to take the actions necessary to maintain complete control of his vehicle.

Shifting and increased dispersion of the eye patterns were, in fact, evident in this study. Under the strict control exercised during the filming sessions, the measures appear to be reasonable and valid. However, changes in traffic patterns or roadway environment could substantially change these observed phenomena. Therefore, another measure of impaired driver performance, which might be appropriate to a wider variety of traffic patterns and roadway environment, was sought.

In the results previously cited (Figs. 12 and 13), both the mean pursuit duration and the percentage of total film time due to pursuit eye movements (volume of pursuit movements) were significantly larger for Run 2. Because spatial analysis revealed that the eye-movement patterns had shifted to an area where the angular velocity of environment features was greater, it is suggested that the tendency to fixate on faster moving objects might result in more pursuit movements (16). Analysis of the lap 3* data, after the rest break, revealed the locus of the eye-movement patterns had shifted back to the Run 1 position, while the mean pursuit time remained the same and the percentage of total film time due to pursuit movements actually increased. Therefore, for the 3 subjects tested, it appears that, regardless of whether the locus of eye-movement patterns is near areas of large angular velocity, the tendency to make more and longer pursuit eye movements is affected by sleep deprivation.

To probe this phenomenon in detail, the area to the right (categorized as scenery on the right for reduction purposes) was examined. The data given in Table 1 reveal that no pursuit eye movements in that area were found for any of the subjects over Run 1. For Run 2, however, a large percentage of the total volume of pursuit movements for each subject was found in this area. Rested subjects made no pursuit eye movements in this area of large angular velocity, although they did fixate in that area occasionally. This implies that a rested subject is capable of obtaining the necessary information from a moving roadside feature without having to pursue that feature by making the appropriate pursuit eye movement.

At this point it appears that the increase in pursuit eye movements are induced by sleep deprivation. It is possible that the effect is due to either sensory impairment or a regression of learning. In order to examine this dilemma, eye-movement film from Zell's study (18) was examined. Film of the 4 inexperienced subjects for the 60 to 70 and 40 to 50 mph open-road conditions on the first test were reexamined. These film samples theoretically depict the condition of least experience. The combined pursuit eye movements from these 2 maneuvers were contrasted to the combined pursuit movements from the 2 maneuvers for 2 experienced drivers. Table 2 gives the individual values obtained.

TABLE 2

COMPARISON OF PURSUIT EYE MOVEMENTS OF EXPERIENCED AND INEXPERIENCED SUBJECTS

Subject	Mean Pursuit Duration	Volume of Pursuit Eye Movements (percent)
Inexperienced		
S1	0.30	7.6
S2	0.52	4.0
S3	0.43	1.3
S4	0.71	3.7
Avg	0.49	4.15
Experienced		
SA	0.47	2.1
SB	0.42	0.006
Avg	0.45	1.05

Salvatore (9) argued that, in driving, the foveal area is allocated the task of detection and discrimination, while the periphery is allocated the task of motion

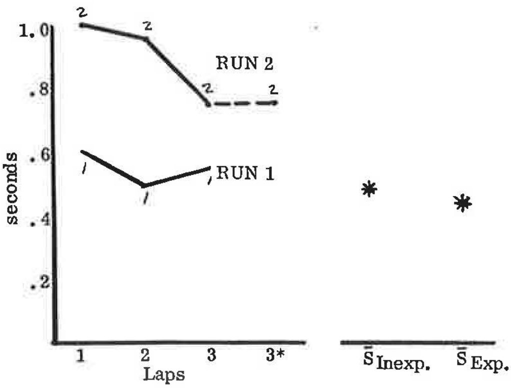


Figure 15. Duration of mean pursuit eye movements and comparison of experienced and inexperienced subjects—all subjects and maneuvers combined.

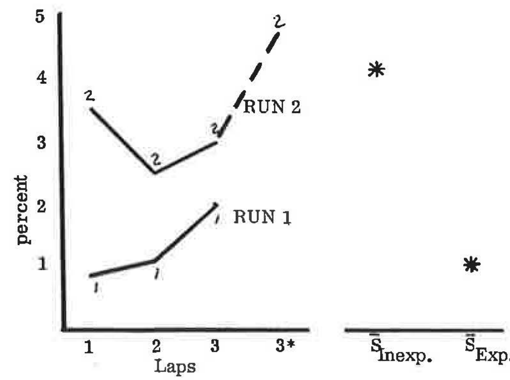


Figure 16. Percentage of total film time due to pursuit eye movements and comparison of experienced and inexperienced subjects—all subjects and maneuvers combined.

perception. This represents a rather sophisticated time-sharing task in the information processing chain, especially in the context of single channel theory. It appears that at least three out of four of Zell's inexperienced subjects had not yet learned the time-sharing task. However, as their experience increased, their eye-movement patterns became more like those of the experienced driver.

Figure 15 shows the average value of Zell's subjects for mean pursuit duration compared with the previously cited results of this study. Figure 16 shows the average value of Zell's subjects for volume of pursuit movements plotted next to the comparable results from this study. The data in Table 2 suggest that mean pursuit duration may be an index of impairment independent of experience. Figure 16 suggests that the volume of pursuit eye movements is an index of impairment that shows a regression toward behavior characteristic of inexperienced subjects. This conclusion is based on the observation that sleep-deprived subjects and inexperienced subjects exhibit similar behavior. The possibility of using pursuit eye movements as correlates of performance is suggested here for the first time. Additional research will be necessary to confirm their validity and suitability as performance indexes in driving research.

SUMMARY

The intent of this research was to investigate the changes in eye-movement patterns that occur under conditions of prolonged driving and sleep deprivation. The eye-movement data were examined spatially and temporally. The major results are listed as follows:

1. The mean locus of the eye-movement patterns shifted 2 deg to the right and 2 deg down over the course of Run 1. At the outset of Run 2, after sleep deprivation, the horizontal mean had already shifted approximately 2 deg to the right. The vertical mean exhibited the same downward shift over time that had been observed during Run 1. In terms of time-headway, subjects would overtake the locus of the "fatigued" eye pattern approximately 3 sec sooner than they would overtake the "rested" patterns.
2. On the average, the patterns were less concentrated during Run 2. This finding in conjunction with the discovery of the mean locus shift indicates that more foveal viewing time was allocated to areas normally monitored peripherally. This finding is consistent with the expected behavior in a dynamic control situation and indicates a decrement in peripheral sensitivity, i.e., perceptual narrowing.

3. Both the mean pursuit eye-movement duration and the volume of pursuit eye movements (the percentage of total film time due to pursuit eye movements) were significantly larger for Run 2. Thus, the tendency to make more and longer pursuit eye movements is affected by sleep deprivation.

4. Comparison with eye movements of inexperienced and experienced drivers indicates that mean pursuit duration may be an index of sensory impairment, and that volume of pursuit eye movements may be an index of regression toward behavior that is characteristic of inexperienced subjects.

5. There were no discernible differences in any of the significant measures due to differences in velocity.

ACKNOWLEDGMENT

This research was conducted by using the facilities of the Driving Research Laboratory of the Systems Research Group and was supported, in part, by grants from the Federal Highway Administration and the Ohio Department of Highways.

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