Because the rates of nighttime accidents are higher than daytime accidents, much research has been directed to the unique problems of night driving. Many researchers concur that the driver receives most of his or her information through the visual system. During night driving, the visual cues normally available during daytime are reduced. Whether this paucity of visual information is related to the higher night accident rate is not known. A basic approach to the problem is to identify through visual search patterns the driver's use of night driving cues. Identification of driver visual needs in night driving can eventually lead to improved night driving safety. This paper discusses and presents the results of two studies to investigate drivers' visual search patterns in night driving. The first study compares nighttime visual search behavior to daytime behavior on freeways and rural highways. The second study develops methods of using driver visual search data to evaluate illumination at rural highway intersections, which have high rates of nighttime accidents.

DRIVER SEARCH AND SCAN PATTERNS IN NIGHT DRIVING

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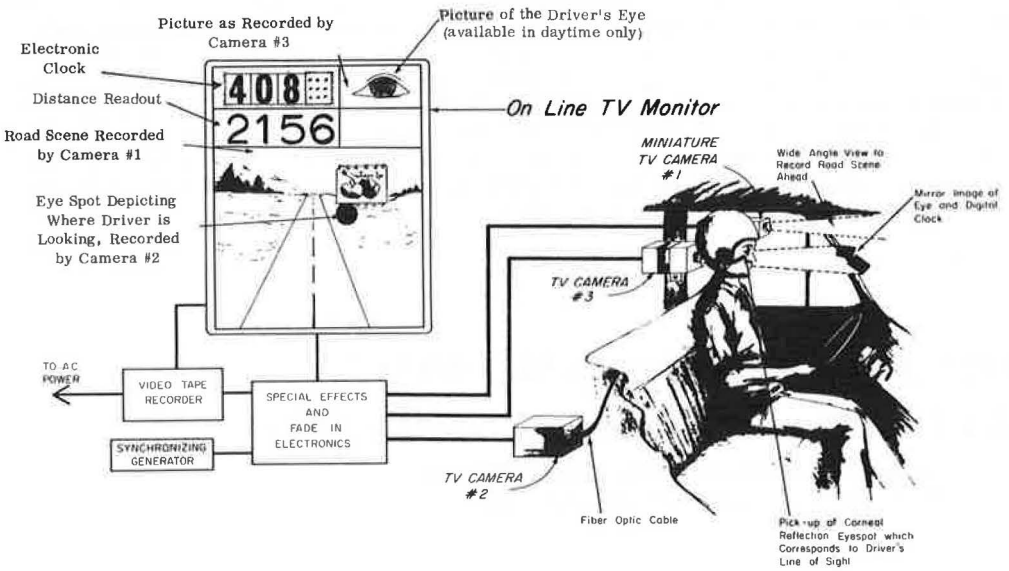
An essential step to the identification of driver visual needs is the understanding of where drivers visually search the environment. With the support of the Ohio Department of Transportation and the Federal Highway Administration, the Driving Performance Laboratory (DPL) of the Ohio State University has developed a method for measuring drivers' visual search behavior during night driving and has conducted several studies of this search behavior at night.

The system developed is a vehicle-based television system that records drivers' eye movements. The system continuously records on video tape the driver's direction of gaze while he is driving an instrumented car. The record contains a small light spot on the moving picture of the driving scene corresponding to the driver's point of fixation. This record and subsequent computer summaries of various measures enable quantitative analyses of visual search behavior (e.g., percentage of time viewing specific areas, fixation times, spatial distribution of fixation locations, eye travel distances).

THE RECORDING SYSTEM

The television system used in this study to record eye movement has been described in detail in another paper (2) and is shown in Figure 1. The driver wears a helmet that is securely located on the head by means of 16 separately adjusted pads on the helmet. In addition, an individually molded bite bar is fitted to the upper teeth and also fastened to the helmet by support brackets. When clamped, the helmet provides a stable unit for supporting the scene camera, light source, and reflection pickup lens. The scene camera provides a 54 by 41-deg view of the road scene ahead. For the night system, this camera was modified to operate at nighttime illumination levels. The light source shines a narrow beam of infrared light onto the driver's cornea, which then reflects from the cornea. As the eye moves this reflection also moves and is received by a pickup lens. This eye spot image is transmitted to a television camera via a high-resolution 3-ft fiber optic cable. The image of the moving eye from this camera is superimposed (faded) onto the driving scene depicted by the camera worn by the driver. The resulting combined image is displayed by a small television monitor in the vehicle, which permits calibration and constant checking of data quality. The resulting picture is recorded on video tape, which provides a permanent record of the data. When prop-

Figure 1. Eye movement recording system.



erly calibrated, the picture provides continuous recording of the driving scene and the driver's fixations (±1 deg) to objects within that scene. A third camera provides a picture of a digital clock, which updates every 20 msec, and a digital readout of distance along the roadway (every 5.28 ft), which is split into the top left of the TV picture to provide an accurate record of event times, durations, and road location.

Eye movement data are reduced by replaying the recorded video tape on a stop-action playback machine in the laboratory. Driver fixations are characterized by a series of discrete dwells in direction of gaze that last at least 200 msec. Each time the eye moves to a new location is a new look event. For data reduction, the tape is advanced to the instant each event begins. The following information is recorded:

1. Beginning time of the event from the digital clock;
2. Location of the vehicle on the roadway from the digital distance readout;
3. Object of fixation (i.e., road surface, road sign, edge line, scenery ahead, headlights of oncoming cars); and
4. Horizontal and vertical position in units of visual degrees (x and y) of the fixation relative to the focus of expansion.

The focus of expansion is that point on the horizon where the road edge lines of a straight road appear to meet. The information in item 4 requires the data reducer to position a transparent grid over the TV monitor screen, which is etched with 1 by 1-visual deg grid squares.

The data are transcribed onto computer coding forms and punched onto computer cards, which are processed by a computer program that provides numerous statistical summaries for each trial. In addition to measures such as mean horizontal position, percentage of time viewing objects, and travel distances, the program derives a set of measures based on the grid coordinates. The program also reduces the visual field to six major areas that appear to have different informational content and different visual cues (i.e., scene ahead 3 by 6 deg around the focus of expansion, scene right, scene left, road surface and road edge right, road left, and sky). The third camera provides data on mirror and speedometer sampling. After the system has been calibrated, registration error is about ½ deg horizontal and 1 deg vertical (18).

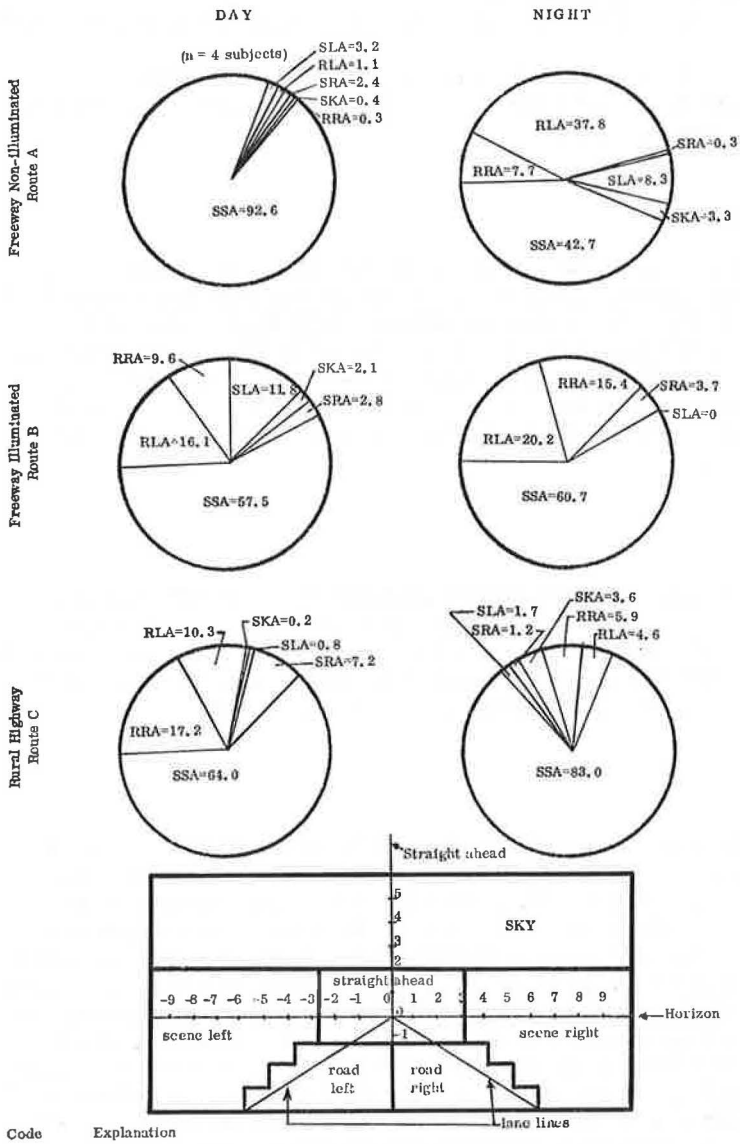
In addition to the eye movement recorder, an oscillograph recorder provides a permanent record of vehicle velocity, steering wheel and brake pedal movements, and

Table 1. Summary of eye movement data.

Route	Time	MVL[a] (deg)	MHL[b] (deg)	CI[c] (percent)	Time Viewing Oncoming Headlights (percent)
Nonilluminated freeway	Day	0.16	0.07	84.0	0.0
	Night	-0.85	-0.98	69.0	16.0
Illuminated freeway	Day	0.07	-0.60	71.1	0.0
	Night	-0.48	0.52	75.4	0.8
Rural two-lane highway	Day	-0.38	0.61	76.0	
	Night	0.41	0.02	78.0	

[a]Above horizon.
[b]To right of straight ahead.
[c]Time spent viewing most populous 3 by 3-deg area.

Figure 2. Average percentage of time viewing spatial areas.



Code	Explanation
RRA	Road Right - Includes right edge lane line and right road surface in front of driver
RLA	Road Left - Includes left edge lane line and left road surface in front of driver
SRA	Scenery right
SLA	Scenery left
SSA	Straight ahead ($3^{\circ} \times 6^{\circ}$)
SKA	Sky

vehicle longitudinal position along the roadway. Visual performance measures are given below:

1. Mean horizontal location (MHL) in visual degrees to the right of straight ahead.
2. Mean vertical location (MVL).
3. Mean travel distance between fixations in visual degrees.
4. Two-dimensional concentration index (CI), the percentage of fixation time spent in the most populous 3 × 3-deg grid square.
5. Percentage of time viewing scenery ahead.
6. Percentage of time viewing scenery to the right.
7. Percentage of time viewing scenery to the left.
8. Percentage of time viewing road surface and edge to the right.
9. Percentage of time viewing road surface and edge to the left.
10. Percentage of time viewing sky.
11. Mean look time to the scenery on the left.
12. Percentage of time viewing the combined areas straight ahead and below straight ahead.
13. Mean time per look in the combined areas straight and below straight.
14. Mean time per look away from the combined areas straight and below straight.
15. Mean time per area and out-of-view.

STUDY 1

The purpose of this study was to describe driver eye movement pattern during night driving and to compare those patterns to daytime patterns on freeways and a rural highway. A number of studies by the DPL on daytime driving (2, 20, 22, 23) showed eye movement patterns to be a useful tool in evaluating signing, designing driver information aids, assessing the effects of highway geometry, exploring the effects of instructions, and assessing the effects of alcohol, fatigue, drugs, and age on driver search patterns. A goal of this study was to extend the capability and knowledge gained in the daytime studies to night driving.

Methodology

Four college males drove the experimental vehicle on three routes in both day and night conditions (a divided four-lane rural freeway without illumination, a four-lane urban freeway with illumination, and a rural two-lane highway). The order of conditions was mixed, and subjects drove the routes several times to familiarize themselves. Eye movement data were reduced to 30-sec samples for a total of 24 trials.

Results

The results for several measures are given for the three routes in Table 1 and in Figure 2. The data in Table 2 are based on 30-sec trials and about 150 fixations. Note that, for all routes in both day and night, MVL and MHL are within 1 deg of the zero point. That is, drivers tend to fixate near the focus of expansion (i.e., that point on the scene that appears to remain stationary to the driver and is the direction in which the car is moving; it is also that point in the scene where the lane lines appear to meet). It is also important to note that most of the fixations occur within a narrow visual area. Seventy-five percent of fixations occurred within a visual area measuring about 3 by 3 visual deg. This central tendency and the concentrations shown are similar to results found in previous studies on daytime driver eye movements. Closer examination of Table 1 shows notable differences between day and night. Differences among routes are also pronounced. The major findings for this study are summarized below.

1. On the unlighted freeway, the eye movement pattern shifted down and to the left from day to night by about 1 visual deg. This shift was attributed in part to glances at headlights of oncoming cars across the median, which were viewed about 20 percent of the time at night. Drivers did not fixate on oncoming traffic in the day trials.
2. Eye movement patterns were spatially more disperse at night than during the day on the unlighted freeway.
3. On the unlighted freeway, glances to the road edge lines and road surfaces increased from 1 percent in the day to almost 45 percent at night, whereas glances straight ahead decreased at night.
4. On the illuminated route (which also had light traffic) few differences were noted between the day and night trials. The daytime trials on the illuminated route were similar to the night trials on the unilluminated freeway. Apparently, traffic balances the differences between light conditions. The effect of illumination could not be separated from the differences in traffic conditions or routes.
5. On the rural highway, drivers viewed straight ahead more at night than during the day. They were searching for targets beyond the headlight beam patterns to increase their preview.

Conclusions for Study 1

These results show that nighttime visual search behavior differs from daytime visual behavior. Some of these differences may be due to differences in time spent viewing head lamps of oncoming cars, which are sources of glare. The results for the unilluminated trials support the notion that, in the cue-poor night driving environment, drivers' eye movement patterns concentrate in the area lighted by the head lamp beams for lateral and directional control. Future studies using the night recording system can provide insight on drivers' search and scan patterns at night and the effects of factors such as illumination, traffic load, glare sources, driver aiding, and type of road on those patterns.

STUDY 2

The experiments in study 2 were directed at determining differences in visual search behavior at sites with high and low night accident rates and the effects of illumination on drivers' visual search. Many rural highway sites, particularly intersections, are known to have high rates of night accidents. One method of reducing accidents is to erect lighting. However, few sites are now lighted, and the problem is to determine priorities of which sites to light and how much lighting to erect to best use limited resources of energy and money. An outgrowth of study 2 was to develop a reliable quantitative technique for quickly evaluating the potential effectiveness of illumination design changes in reducing accidents at rural highway sites with high nighttime accident rates. Eye movements were recorded for subjects driving along sites with both high and low night accident rates and with and without illumination during day and night.

Methodology

Six college males drove a total of nine sites. Three intersections with high night accident rates were matched to three sites with low night accident rates. The matching was based on similar geometry (two lanes and no horizontal and vertical curvature), signing and signaling, traffic volume, daytime accident rates, intersection lighting, and surrounding night visual environment. Another three sites were selected that had lighting that could be turned off. Subjects were not informed of the purpose of the study, but drove a specified route that included the experimental intersections. Approximately 1,000 ft prior to the intersections, subjects were instructed to turn left. In all, 128 separate intersection passes were performed.

Three major comparisons of visual search behavior were examined:

1. Nighttime versus daytime,
2. Sites with high night accident rates versus those with low night accident rates, and
3. Illumination versus no illumination.

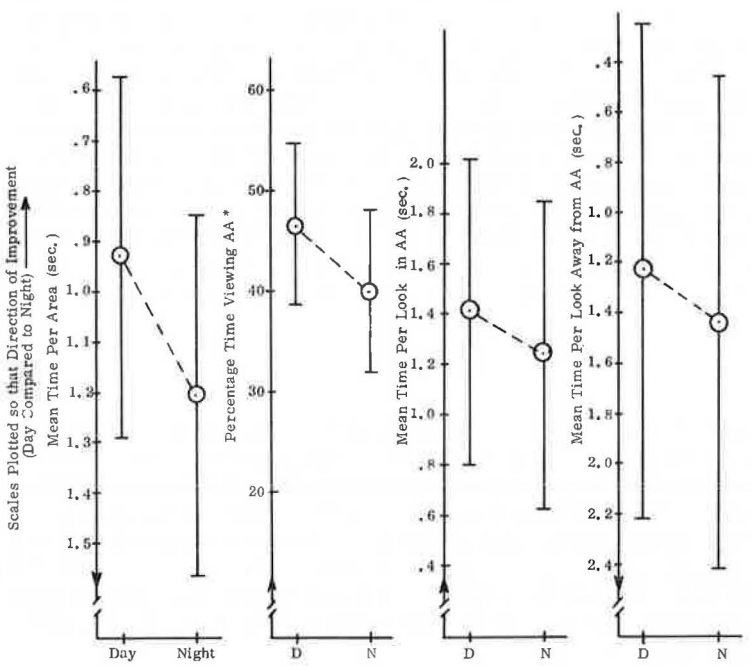
The results that follow are for visual search patterns under the instructions to turn left. Drivers' visual search patterns for left turns (on a two-lane rural highway) shifted to the left, and they spent an increased percentage of time viewing scenery left.

Results

Daytime Versus Nighttime

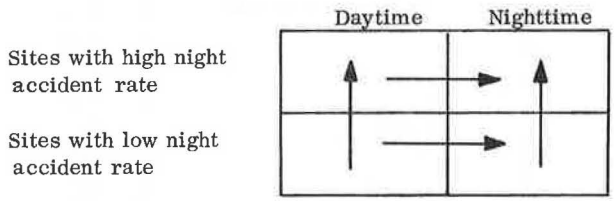
The results for gross differences between day and night for all nine sites are shown in Figure 3. An important difference between the day and night behavior is the greater mean time per look in each area for the night driving (all six areas are combined in this measure). Longer mean times possibly imply longer times on the average needed to acquire or process information. Thus, drivers' mean search time per area is lower during the day than at night; this may be interpreted as an improved search behavior in the daytime inasmuch as time to acquire information is shorter. In the day, drivers also spend more time viewing the combined scene directly ahead of the road right and road left. When looking away from this area, drivers sample in shorter times during the day than at night. Thus, several measures appear to be sensitive to day and night differences, and interpretation of the differences suggests somewhat more efficient visual search behavior in the day than at night.

Figure 3. Significant differences between day and night trials.



Sites With High Night Accident Rates Versus Those With Low Night Accident Rates

The results for the six sites are shown in Figure 4. The data should be compared in the following way:



The first comparison of interest is of sites with low and high night accident rates at night. As shown in Figure 4, only CI showed a statistically significant difference at the $p = 0.10$ level, and it was a bit higher at the high accident sites. The only other measures with possibly significant trends were (a) MHL, which was more to the right at the high accident sites, and (b) the mean time per area, which was longer at the high accident sites. On the other hand, several differences were noted between sites with low and high accident rates when daytime measures were compared. Drivers at the high night accident sites spent (a) greater percentage of time viewing the scene left, (b) more time when glancing at the scene left, and (c) more time looking away from the scene and road ahead. Thus, the general pattern of visual search results is that sites with different accident rates were very much alike at night but different in the day.

Figure 4 also shows that visual search behavior at the high accident sites was very much the same in the day and night. At the low accident sites, however, most of the measures showed changes from day to night. The results for one measure, percentage of time viewing the scene left, are particularly important, for this area is likely to contain cues for locating the intersection. The results at low accident sites suggest that at night drivers tend to rely on cues from the scene left much as they did in the day, but they require more time in this area and more time to acquire the information. At high accident sites, at night drivers rely less on the scene left; they apparently change the location of search for intersection cues.

An interpretation of the general trends suggests that these differences in the day between high and low accident rate sites indicate that cues are not equally discernible at low and high night accident rate sites in the day. The measures may indicate that visual cues are not so easily obtained even in the day at sites with high night accident rates. At night, the cues at sites with high accident rates are simply not obtained or not obtained in time for a safe smooth maneuver.

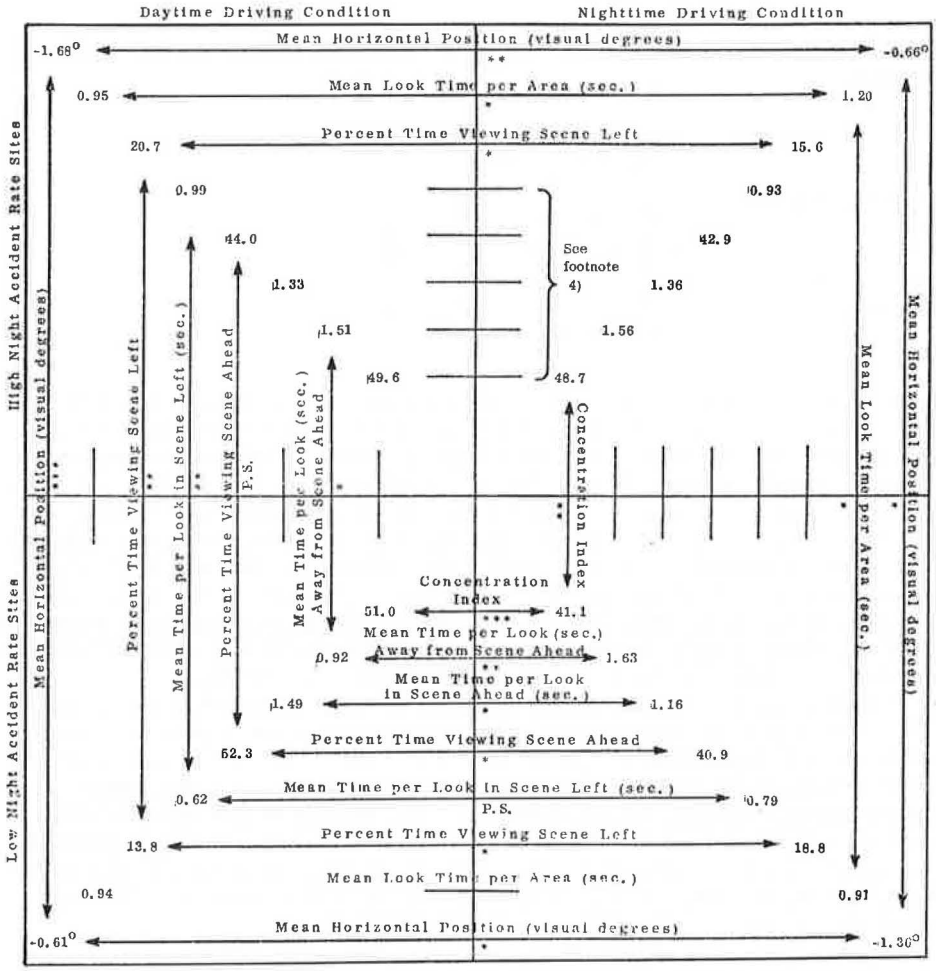
The results may be summarized as follows:

1. During daytime conditions, there are many differences in visual search behavior for sites with low and high night accident rates;
2. There are few differences in visual search patterns at night and during the day; and
3. The lower percentage of time viewing the scene left at night at sites with high night accident rates suggests that drivers search different areas for intersection cues.

In terms of the potential effects of illumination, the results point to the following:

1. Because the nighttime level of performance at high accident sites is not, in the main, different from that at low accident sites, a standard for the effect of illumination would not likely be nighttime performance at low accident sites; and
2. The fact that daytime levels at high accident sites were much different from daytime levels at low accident sites may suggest that the daytime performance level at high

Figure 4. Results of study 2.



NOTE: 1) A line drawn between two numbers indicates that the contrast between those two values was significant (from ANOVA):
*** ⇒ $p < .05$, ** ⇒ $p < .10$, * ⇒ $p < .20$,
P.S. ⇒ not statistically significant but would likely attain statistical significance with a larger sample size (in the judgment of the researchers).
2) Data shown are for six sites and six subjects at each site.
3) These scales are a repeat of the lower scales in inverse order.

accident sites may not be an appropriate standard of illumination effects.

Two possibilities remain as a standard for illumination: (a) the daytime level at low accident rate sites should serve as a standard or (b) the effects of illumination are to modify driver visual search behavior in a manner not suggested by daytime levels at either types of sites or nighttime levels at the low sites. A hint as to this possibility lies in the tendency of drivers to rely less on the scene left at night at the high accident sites than in the day. That is, drivers may be looking elsewhere than the scene left for (but perhaps unable to attain) alternate intersection cues. The role of illumination then might be to highlight these alternate cues.

The potential effect of illumination at sites with high night accident rates, as indicated above, is not clear from the preceding analyses. The experiment described below examined the effect of illumination on visual search at several (not high night accident) sites.

Illuminated Versus Nonilluminated Sites

Three sites (not having high accident rates) both with and without illumination were selected for comparison of nighttime driver behavior in the task of turning left. Figure 5 shows the results of the analyses and the effect of artificial illumination at all sites combined (and, for some measures where signalization was a significant factor, the results are shown separately for signalized sites).

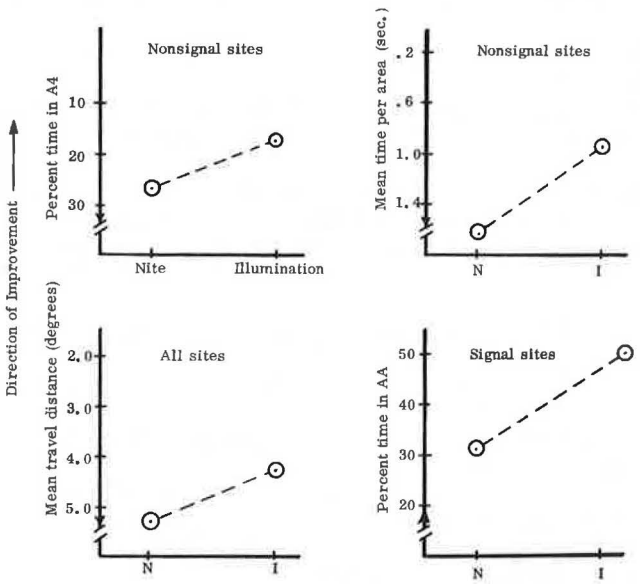
Illumination has an effect on several measures of visual search behavior. At illuminated sites drivers (a) spend less time viewing the scene left (nonsignal sites, 27 to 17 percent), (b) apparently decrease the mean look time per area (nonsignal sites, 1.6 to 0.94 sec), which may indicate shorter times to acquire information, and (c) increase the mean time viewing the scene ahead (signal sites, 31 to 50 percent), the area where guidance control information is concentrated. The mean travel distance was reduced (no differences were found in previous analyses), which indicates a reduction in spatial search activity; this can also be viewed as an improvement when compared to the standard of the lower information load condition in straight road driving (2.5 deg).

In conclusion, the results of this analysis lend encouragement to the notion that illumination can affect driver visual search performance.

Conclusions for Study 2

The results of study 2 indicate that measures of visual search are sensitive at sites with different accident rates and to day and night conditions. The changes in visual search measures due to illumination not only demonstrate that illumination can affect visual search at some sites but also show that visual search behavior can be useful in identifying the specific effects of various illumination designs on driver search patterns.

Figure 5. Significant differences in night behavior at sites with and without illumination.



CONCLUSIONS FOR STUDIES ON NIGHTTIME DRIVER EYE MOVEMENT PATTERNS

The results show that measures of driver visual search patterns are sensitive to day and night differences, to sites with different accident rates, and to illumination. The results from the highway intersections with illumination lend encouragement to using eye movement data to evaluate methods of improving nighttime driving. Illumination, which is generally believed to be of benefit in night driving, was found to affect several measures of driver visual search behavior. The methodologies developed in these studies should be extended to evaluate the effects of illumination at sites with high night accident rates. Another immediate problem to which the methodologies can be applied is evaluation of alternate methods (in lieu of illumination) of improving nighttime driving (e.g., improved pavement markings, signing, signaling, reflectors). This application is particularly relevant because of the energy shortage challenging indiscriminate use of lighting.

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