社団法人　情報処理学会　研究報告
IPSJ SIG Technical Report

2005－CVIM－150（6）
2005／9／5

夜間安全運転支援システム

視行動解析による有効性の定量評価

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あらまし　本論文では，夜間安全運転支援システムの有効性に関する実験に基づく評価結果を述べる．本システムは，ドライバが，歩行者を見えない段階で，警報を伴って歩行者位置をヘッドアップディスプレイに提示する．このようなシステムを定置型のドライビングシミュレータ上に実装した．実験の結果, 歩行者に関するドライバの視覚的注意の頻度の増加と，衝突回数の 1/3 減少が見出された．したがって，歩行者位置を事前に知らせることは，夜間運転の安全性にとって有効であることが示唆された．

キーワード　安全運転支援システム, 衝突警報システム, 車載情報提示, 視行動解析, 運転行動モデル.

Night Driver Support System

A Quantitative Evaluation of Effectiveness Using Driver Eye Gaze Analysis

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Abstract　This paper presents an empirical evaluation of the effectiveness of a night-time driver support system. The system provides advance notice of pedestrian location by displaying a warning-cue on a head-up display. A simulated night-time environment was created in a fixed-base driving simulator. Experiment results indicated the system yielded an increase in the driver's visual attention on salient objects (pedestrians) and a reduction in the number of collisions by a factor of three. These results are indications of the benefit of providing advance notice of pedestrian location to improve night-time driving safety.

Key words　Driver support systems, collision warning systems, in-vehicle information displays, eye movements, driver behavior modeling.

1. Introduction

Night-time driving is known to be an unsafe task mostly due to reduced visibility of poor contrast objects. Statistics on traffic safety collected from the National Police Agency of Japan [9], [10], revealed that in 2004 alone, night-time accidents represented about 29.5% of the total number of casualties. Nonetheless, they accounted for 53.0% of all fatalities, day-time accidents included. This said, the rate of fatal casualties at night, measured by the number of deaths involved per 1000 accidents, was 2.7 times that measured during day-time driving.

Several factors could be associated with a large portion of the overall number of night-time accidents: (1) Atmosphere, which includes monotony, repetition, and tiredness; (2) Toxicology, i.e. alcohol, tobacco, and drugs; (3) Psychology, with euphoria or fear as examples; (4) Vision, highlighted by such characteristics as visual performance, glare sensitivity, or optical illusion. Nevertheless, in most cases, reduced visibility has been found to be the most important factor for night-time accidents.

A few solutions could be suggested to solve this problem. The first would be to use high-beam headlights to enhance objects contrast. This is well acknowledged as an effective way to improve contrast sensitivity. However, high-beam headlights should not be used when there are oncoming vehicles. While using low-beam head-

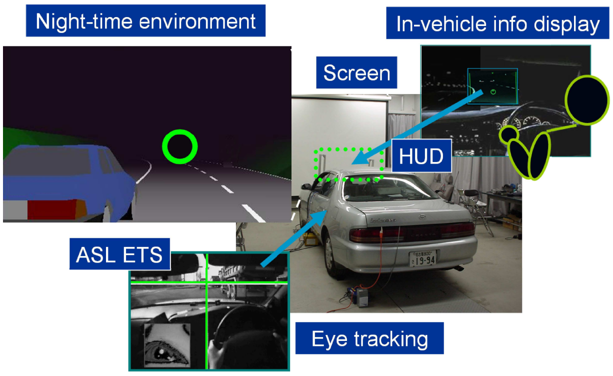

Figure 1 Descriptive illustration of the proposed AdaptIve Driver advicE system (AIDE).

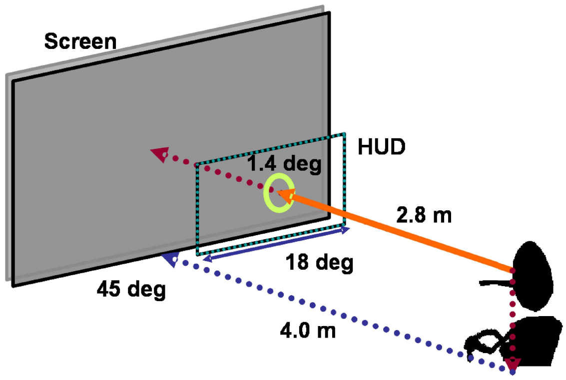

Figure 2 Optical specifications of our driving simulator.

lights, the driver's visibility range in this condition drops to roughly 40 meters.

A second solution consists in adopting an increasingly popular type of in-vehicle information display known as Night Vision Enhancement Systems or NVES in short [1], [2]. They leverage images obtained from sensors such as millimeter-wave radars, UV headlights, or infrared cameras, and provide the driver with enhanced contrast image of the environment, displaying them on a device built inside the vehicle.

A third possibility would be to devise a system that compensates for the driver's reduced visibility at night by providing with advance notice of pedestrians location. The system works by displaying what we termed the *warning-cue*, on a head-up display that covers most the driver's field of view, when he/she is looking forward. This is the approach selected in this paper. Using a fixed-base driving simulator, we have built a system we called AdaptIve Driver advicE system or AIDE in short. There is a fundamental difference between the approach embodied by AIDE and the previously described technique based on NVES which shows on a small device an enhanced but contracted image of the driving scene. In contrast, AIDE does not attempt to show what is unseen to the naked eye but instead to indicate in advance the exact position of a pedestrian ahead, as seen from the driver'seat.

To effectively compensate for the reduction of the driver's visual range at night, the proposed assistance system should: (1) Provide pedestrian information early enough, prompting the driver to take anticipatory actions, such as accelerator release and brake application, necessary to avoid an eventual collision; (2) Induce the reduction of the vehicle speed to a level that would be enough to minimize the fatality of a potential impact with a pedestrian.

Driver eye movement behavior has been the subject of intensive research activity during the last decade. Land and Lee [3] studied the driver's eye movement patterns during curve negotiations. Liu *et al.* [4] performed a thorough investigation of eye fixations during car following. Salvucci *et al.* [5], [6], researched the visual scanning behavior of drivers before, during, and after the execution of a lane change. Sodhi *et al.* [8], analyzed the impact of in-vehicle information system upon vehicle safety, solely relying on eye movement analysis. The objective of this paper is to examine how driver eye movement behavior depends on the modality of the pedestrian information display. This paper has two primary objectives: (1) Examine how driver eye movement behavior depends on the modality of the pedestrian information display; (2) Assess the effectiveness of AIDE in improving driving safety, as measured by the number of collisions in the experiment.

2. Method

2.1 Participants

Eighteen participants, 8 women and 10 men, ranging in age from 23 to 46 years old (33.6 years on average), took part in the experiment. They were required to have a valid driver's license and two years or more of driving experience. None of the participants was familiar with the experiment. Those with glasses were excluded in order to ease the use of the eye tracking system. As a motivation incentive, all were paid for their enrollment.

2.2 Materials

A medium-fidelity driving simulator developed in-house, with a fixed-base platform, was used for the experiment. This driving simulator used a Toyota Cresta, a 2.5 liters in-line six cylinders sedan. The virtual driving scene was projected on a flat screen with a visual field of view of about 45 degrees. The projection screen was located approximately four meters from the driver's eye. Advance notice of pedestrians was achieved by displaying their location on a head-up display (HUD), mounted on the hood, with a field of view of approximately 18 degrees.

Engine and road noise were simulated and rendered through standard PC speakers. Meanwhile, pedestrian notification was not accompanied by any auditory warning; in other words, visual warning was the sole cue used in this experiment. A synoptic illustration of AIDE is portrayed in Fig. 1.

Driver vehicle control data was collected from the driving simulator computer, and this included steering wheel angle, accelerator, and brake-pedal positions. In addition, information related

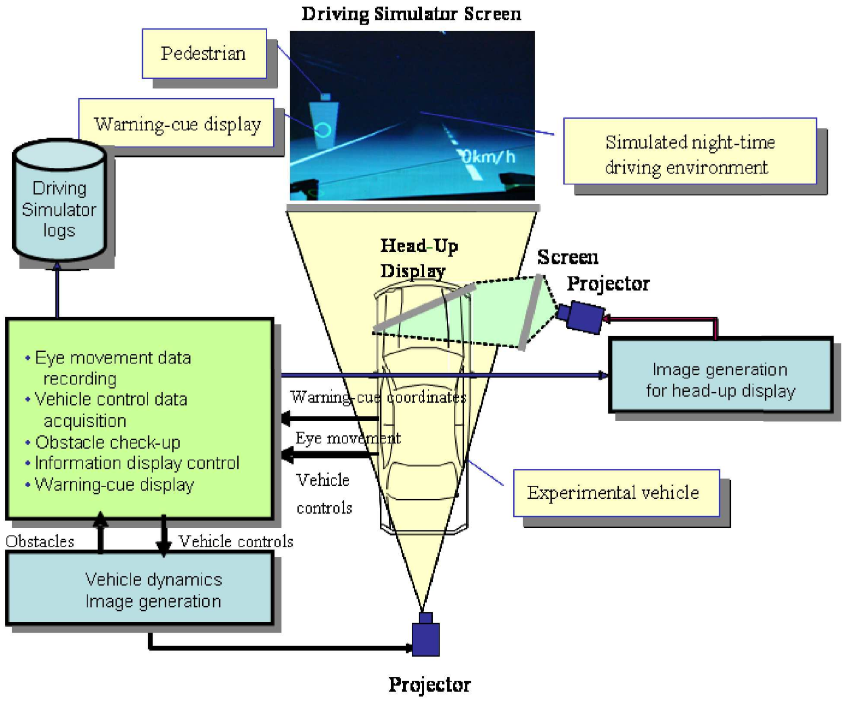

Figure 3 Experimental setup. Assistance is provided to the driver, through the head-up display mounted on the hood, by drawing a warning-cue at the center of a bounding rectangle containing the pedestrian.

to warning-cues was also recorded and included the local time in micro-seconds, the vehicle's current speed, and a flag indicating the state of the information display. States were represented in binary format, with "0" meaning no warning-cue was being displayed, and "1" corresponding to a state when pedestrian warning information was being displayed. Eye movement data was collected using an Eye Tracking System (ETS) from Applied Science Laboratories (ASL), integrated into our driving simulator. Following a short calibration, the ETS estimates the point-of-regard by mapping the pupil center and the reflection points of a small infrared light. The optical specifications of the driving simulator are shown in Fig. 2, and the entire experimental set-up is depicted in Fig. 3.

Other types of data recorded include the position, heading, and speed of each object in the scene, including the participant's own vehicle.

2.3 Experimental Design and Independent Variables

The system was set to detect sidewalk or road-crossing pedestrians from about 100 meters ahead. The driver would then be notified by a colored circle, the *warning-cue*, on the HUD, at the exact location of the pedestrian, as viewed from the driver' seat. Pedestrian location information was only provided when the latter was out of the visibility range of the driver. The onset distance from which pedestrian information was provided depended on the vehicle speed but always lasted 3 seconds.

A within-subjects design was used throughout the experiment, featuring information display conditions and driving scene types. The investigation consisted of comparing the effects of different information display conditions on driver behavior: (1) Baseline condition or No Display, where no pedestrian information was provided to the driver. (2) Fixed Display, where the warning-cue was displayed using a bright green color. The color of this warning-cue remained unchanged even after awareness, until the pedestrian reached the visibility range of 40 meters. (3) Adaptive Display, where the warning-cue was first displayed using a bright green color for duration 150 msec duration. Afterwards, this color was changed to dark blue as soon as the driver gazed at the warning-cue. There were no false alarms or missed alarms in the experiment. The settings of all parameters related to information displays is shown in Fig. 4.

Three scene types, respectively denoted A, B, and C, were presented to the driver, as shown in Fig. 5. These scenes were characterized by the presence of absence of two parameters: (1) The possibility of a collision; (2) The complexity of the driving task at hand. Scene A featured the possibility of a collision, as the pedestrian stood in the middle of the left lane, the slower lane in Japan. There was no complexity involved in the underlying driving task. In scene B, the driver passed a vehicle parked along the left shoulder while the warning-cue was indicating the location of the pedestrian. There was a possibility of colliding with the parked vehicle. The complexity of the driving task required a simultaneous monitoring of the parked vehicle, the warning-cue, and full control of the driver's own vehicle. Scene C involved a pedestrian standing on the right-hand side of the road. Here, the possibility of a collision with the pedestrian was highly unlikely. However, the underlying driv-

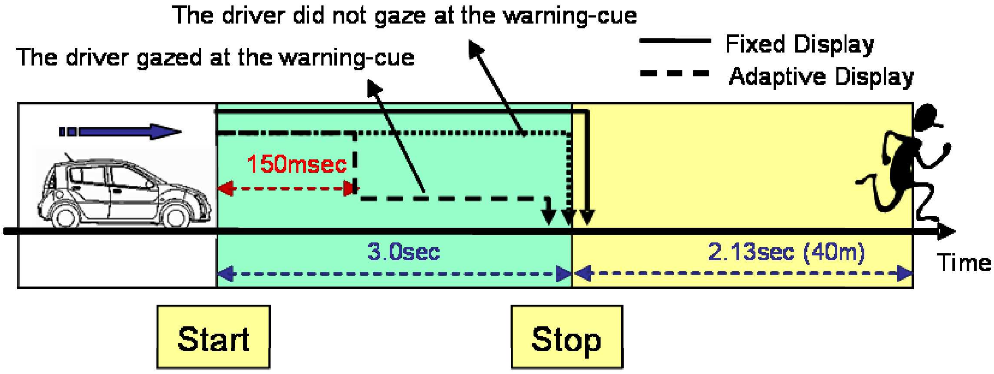

Figure 4 Information display parameters. Assistance is thought to last at least 3 seconds if no deceleration takes place. With Adaptive Display, the color of the warning-cue would change only after a minimal persistence duration of 150 msec. No change of color takes place with Fixed Display. After reaching the point of normal visibility, the driver would reach the pedestrian location in 2.13 seconds if driving at constant speed of 60 km/h.

ing task was considered complex because of the presence of a turn the driver encountered while the warning-cue was displayed on the HUD.

Participants drove in a 15 km long simulated countryside driving environment made of two lanes. The road was a series of straight segments alternating with curves. Meanwhile, the virtual driving scene simulated night-time conditions. Under these conditions, the distance from which a pedestrian could be visible to the driver's naked eye was set to 40 meters, simulating the kind of illumination that could be obtained from low-beam headlights. Along each 15 km drive, 8 events were encountered, but of these, only 3 were used for analysis.

There was no lead vehicle in the experiment. To prevent drivers from steering as a response to imminent collision with a pedestrian ahead, oncoming vehicles were used to make steering around pedestrians problematic. The traffic of these oncoming vehicles was made dense enough to mitigate the association of an oncoming vehicle with the presence of a pedestrian. In other words, braking was the only appropriate response in avoiding pedestrian collisions. This constraint was used to simplify the evaluation of the proposed information display.

2.4 Dependent Variables

A set of dependent measures were used to characterize the effects of the information display conditions on driver behavior: (1) The total duration of all gazes during a given time interval; (2) Gaze dwell ratio, i.e. the ratio of time spent looking at different selected regions of interest during the allocated time window; (3) Gaze dwell distribution, which is the ratio of time spent gazing at different objects of interest; (4) Collision ratio, i.e, the ratio of the total number of collision by the total number of events in the experiment; (5) Task completion duration: this is the amount of time the driver spent to complete each phase of the driving task.

These variables were decomposed into two response measures: (1) During driver assistance, recorded 3 seconds before the pedestrian became visible to the driver's naked eye; (2) After driver assistance, measured when the distance to the pedestrian ahead was less than 40 meters.

Responses to questionnaires were also used as dependent measures. The questionnaires were made up of questions related to: (1) participants' general driving behavior using a Driving Style Questionnaire (DSQ); (2) the usefulness of the system in safety driving; (3)the appropriateness of the display onset timing; (4) and the display annoyance and trust.

2.5 Experimental Procedure

Prior to the experiment, participants completed an informed consent form, were given a general introduction, briefed on how to operate the driving simulator and finally instructed about the required task. These instructions included driving as safely as one could in the simulated environment as one would in the real world. However, they were not supposed to drive faster than 70 km/h.

The experiment itself was made of a practice session followed by a calibration phase and a primary session made of four experimental sessions. The practice session used a five kilometers long, two-lane, countryside road and involved two display conditions: one without driver assistance, for the participants to become accustomed to the driving simulator; and another one in which a pedestrian warning information display was provided for participants to learn about the visual display operation. Both practice sessions lasted about five minutes. This was followed by a calibration procedure for the ASL ETS. The experimental sessions were carried out, each using a 15 km long driving course, during which data was recorded for analysis.

Each experimental session lasted 25 minutes and was followed by a subjective evaluation of the system using a questionnaire. Driver behavior was measured under three display conditions, (1) No Display; (2) Fixed Display; (3) and Adaptive Display; and each of the

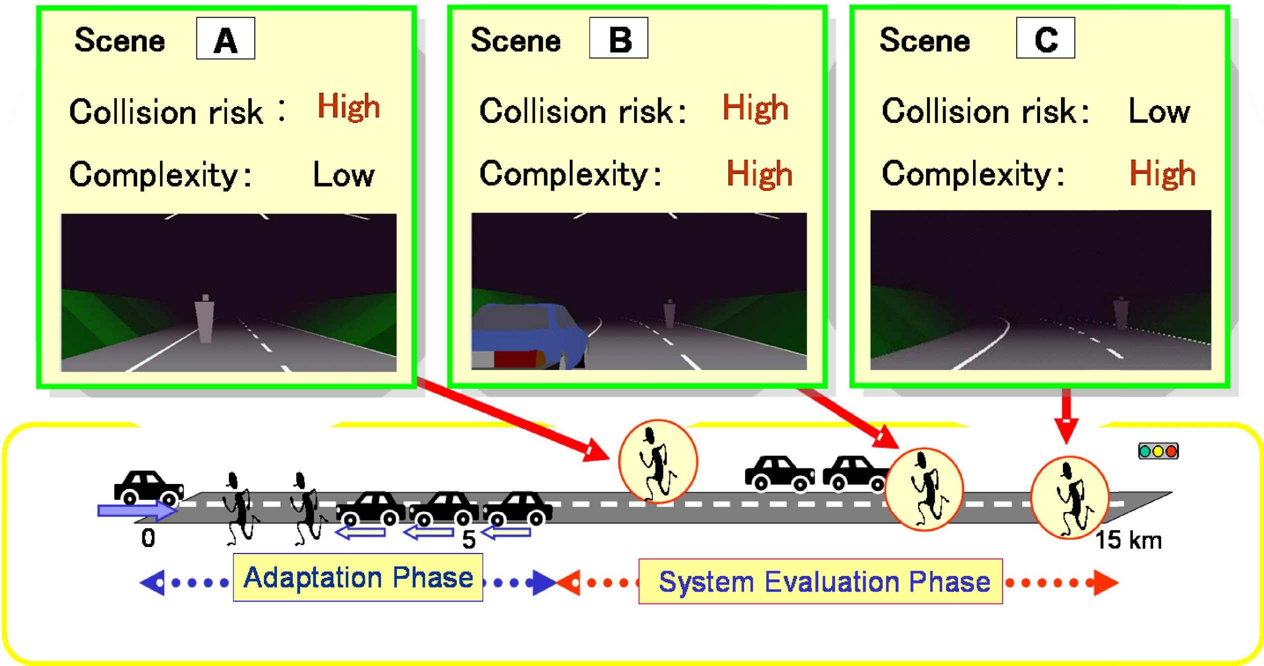

Figure 5 Scene types used in the experiment. Scene A involves a pedestrian located on the middle of the slower lane. In scene B, a car appeared parked along the road when assistance was being provided. The pedestrian in scene C was on the right-hand side of the road, a position where the probability of a collision was fairly low.

driving scene types A, B, C, in randomized order, to counterbalance the effect of learning. At the end of the whole experiment, participants were asked to fi ll a general questionnaire about their driving habits. It took about two hours per participant to complete the entire experiment.

3. Experimental Results

Investigation of the drivers' eye movement behavior was carried out by analyzing their eye gaze during, and after assistance from AIDE. A repeated measures analysis of variance (ANOVA) was performed using gaze measurements as dependent variables. Information display conditions (Adaptive, Fixed, or No Display), and scene types (Scenes A, B, or C) were used as independent variables.

3.1 Eye gaze processing

Analysis of the drivers' eye movement behavior was achieved by giving a high-level interpretation to raw eye movement data recorded by the ETS eye tracker. The fi rst stage of this process involved fi xation identifi cation. For this purpose, a modifi cation of the velocity threshold algorithm was used [7].

The velocity threshold of saccadic movements was set to 20 degrees/second. Meanwhile, the duration threshold was set to a value of 80 msec. Consecutive fi xation points were then aggregated into gazes. These gazes were mapped to salient objects in the virtualized environment. During assistance, the warning-cue was used as a salient object; Some driving scenarios involved a vehicle parked along the road during this phase. After assistance, the pedestrian was the most important salient object. Each gaze point was mapped to the bounding rectangle of the underlying salient objects. These were classifi ed as *seen* or *not seen* by the driver based on their distance to the gaze point.

3.2 Total gaze duration

We focused our attention on the average total duration of gazes during a given time interval. The results are depicted in Fig. 6, where the asterisk indicates a statistically signifi cant difference as described hereafter.

The ANOVA was applied to the total gaze duration measure, with the warning-cue conditions as within-subjects variables. The effect of the information display on the driver total gaze duration during assistance was found to be statistically signifi cant, $F(2, 14) = 23.19$, $p < .01$. The No Display condition was found to exhibit the shortest gaze duration. The scene type had a statistically signifi cant effect on total gaze duration, especially when comparing scene A with scene C, $F(2, 14) = 5.199$, $p < .05$. Meanwhile, no interaction was found between information display conditions and scene types.

The driver spent roughly $1.5 \sim 2$ sec looking at the warning-cue when using either Adaptive Display or Fixed Display; with gaze durations getting shorter while driving with scene C. When No Display condition was used, as expected, the driver looked less at the location of the pedestrian. The total gaze duration fell to approximately 1 sec for any warning-cue condition. With scene B, a vehicle parked along the road was encountered while the warning-cue

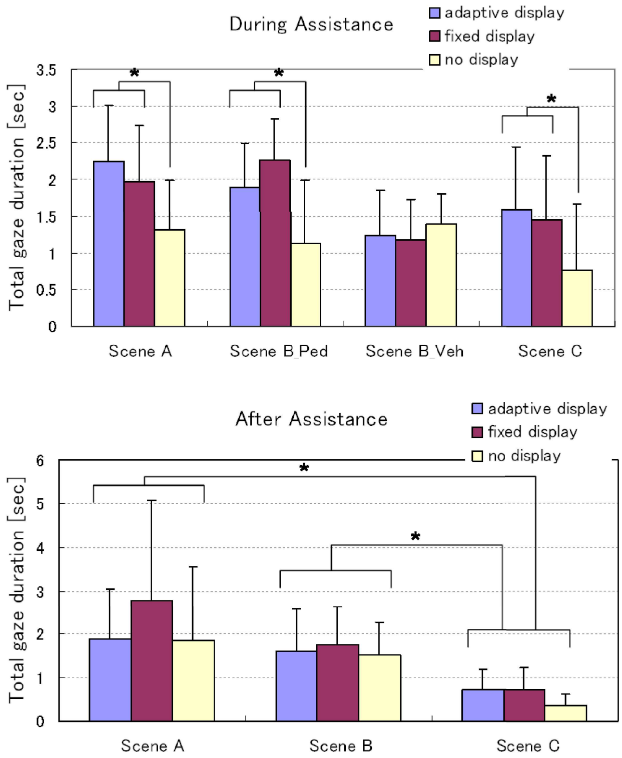

Figure 6 Error bars (mean and standard deviation) of total duration of gazes on salient regions of each scene. During assistance, the regions of interest were the warning-cue, for all scenes, and the vehicle parked along the road for scene B (Scene B_Veh). After assistance, analysis was carried out for the pedestrian.

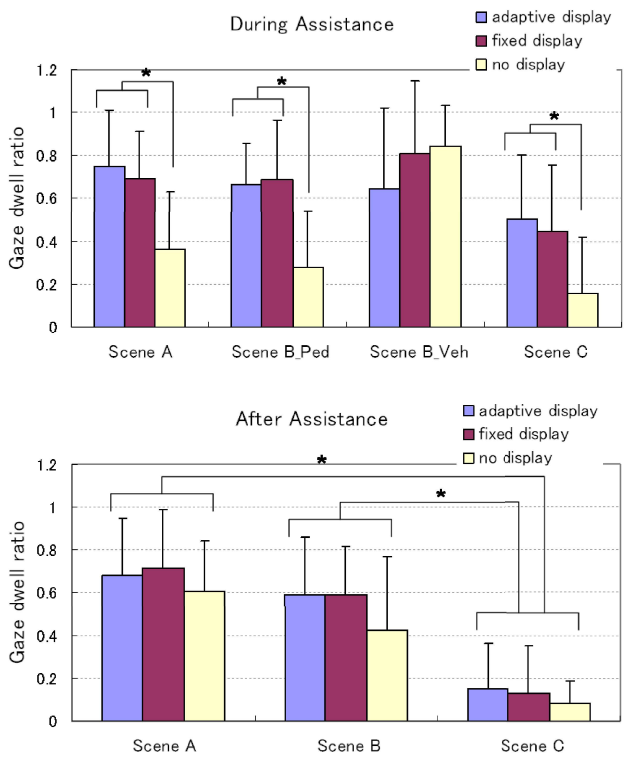

Figure 7 Error bars (mean and standard deviation) of gaze dwell ratio. During assistance the gaze dwell ratio was estimated for the warning-cue with Scene A, Scene B_Veh (the vehicle parked along the raod), and Scene C. After assistance, the only salient region considered was the pedestrian.

was being displayed. The amount of time the driver spent gazing at that vehicle was found independent of warning-cue conditions and lasted about 1 sec.

After assistance, the ANOVA revealed significant differences in total gaze duration from warning-cue conditions, $F(2, 12) = 4.203$, $p < .05$; the No Display condition yielding the shortest gaze duration. The scene type had a reliable effect on gaze duration, $F(2, 12) = 10.022$, $p < .01$, with scene C exhibiting the shortest gaze duration. No interaction was found between AIDE warning conditions and scene types.

The driver looked at the pedestrian for roughly 3 sec with Fixed Display as compared to approximately 2 sec with both Adaptive Display and No Display. In contrast, scene B yielded a similar amount of total gaze duration on the pedestrian for all warning-cue conditions. With scene C, this same measure dropped below 1 sec, it was approximately the same for Adaptive Display and Fixed Display at 800 msec, and about 300 msec for No Display condition.

In summary, the difference between Adaptive Display and Fixed Display was not significant. However, these two displays were found much better at attracting the driver's attention than No Display.

3.3 Gaze dwell ratio

The gaze dwell ratio is the ratio of time spent looking at different selected regions of interest during the allocated time window. During assistance, the regions of interest included: (1)the warning-cue with Adaptive Display or Fixed Display conditions; (2) the pedestrian location when No Display condition was used; (3) the vehicle parked along the road for scene B. After assistance, the region of interest of the pedestrian. Fig. 7 shows the gaze dwell ratio for all three scene types.

An ANOVA was applied to gaze dwell ratio data during assistance, with information display condtions as within-subjects variables. It revealed a significant effect of warning-cue conditions, $F(2, 14) = 16.288$, $p < .01$; the No Display condition exhibited the shortest gaze dwell ratio. The effect of scene type was also found to be statistically significant, $F(2, 14) = 4.374$, $p < .05$. Scene C yielded a smaller gaze dwell ratio under any warning-cue condition. There was no interaction between AIDE display modalities and scene types.

The ANOVA was also applied to gaze dwell ratio data collected after assistance. The effect of warning-cue conditions was not found statistically significant. Meanwhile, the scene type induced a significant difference in the underlying dwell ratio, $F(2, 12) = 35.871$, $p < .01$. A significant difference was found between No Display and the two others. No significant difference was found between the effects of Adaptive Display and Fixed Display conditions. Moreover, there was no interaction between AIDE display conditions and scene types.

After the pedestrian reached the visibility distance, the effect of of Adaptive Display and Fixed Display on the gaze dwell ratio was similar. The inherent complexity of scene C, with the pedestrian located in a safe region while the driver is undertaking a sharp turn yielded an overall drop in the gaze dwell ratio with any display condition.

In summary, assisting the driver with pedestrian location using either Adaptive Display or Fixed Display had the positive effect of attracting the driver's attention toward the region of interest. This effect persisted even in situations where the pedestrian was located well out of the normal driving visual field, (scene C).

3.4 Gaze Dwell Distribution

We investigated the angular dwell deviation. This parameter measures the Euclidean distance from the gaze point to either the warning-cue indicating pedestrian location during driver assistance, or the pedestrian bounding box center, after driver assistance. Of particular interest was the distribution of the dwell deviation during driver assistance, for all three display conditions. Our consideration was limited to angular deviation range of 10 degrees, which corresponds to a distance of roughly 2.5 meters on the projection screen of the simulator. Results are shown in Fig. 8.

An analysis of scene A revealed that with both Adaptive Display and Fixed Display conditions, approximately 95% of all gazes occurred within a horizontal angular range of 3 degrees of the warning-cue. Objects within that range from the point-of-regard were found to be noticeable by the driver. When the No Display condition was used, only 70% of gazes were on the region where the pedestrian was located but unseen.

With scene B, about 65% of gazes were directed on the warning-cue, while only 30% were oriented there with the Fixed Display condition. This effect was attribute to the presence of a vehicle parked on the left-hand side of the road, readily visible while assistance was being provided. With No Display condition, only 15% of gazes where on the region where the pedestrian was located

The absence of a distractive object on the road during assistance in scene C should had yielded an increase of the attention level on the warning-cue, but the presence of a turn constrained the driver to pay careful attention to the driving task. Consequently, the distributions of gazes on the warning-cue were respectively 60% with Adaptive Display, 50% with Fixed Display, and 30% with No Display.

3.5 Safety assessment of the system

The awareness delay is defined as the amount of time elapsed before the driver becomes aware of a salient region (the pedestrian) that is already visible in the allocated time window. Considering the visible pedestrian, no delay was recorded with Adaptive and Fixed Displays, while a 438 msec delay (SD 740 msec) was observed with No Display, while driving with scene A.

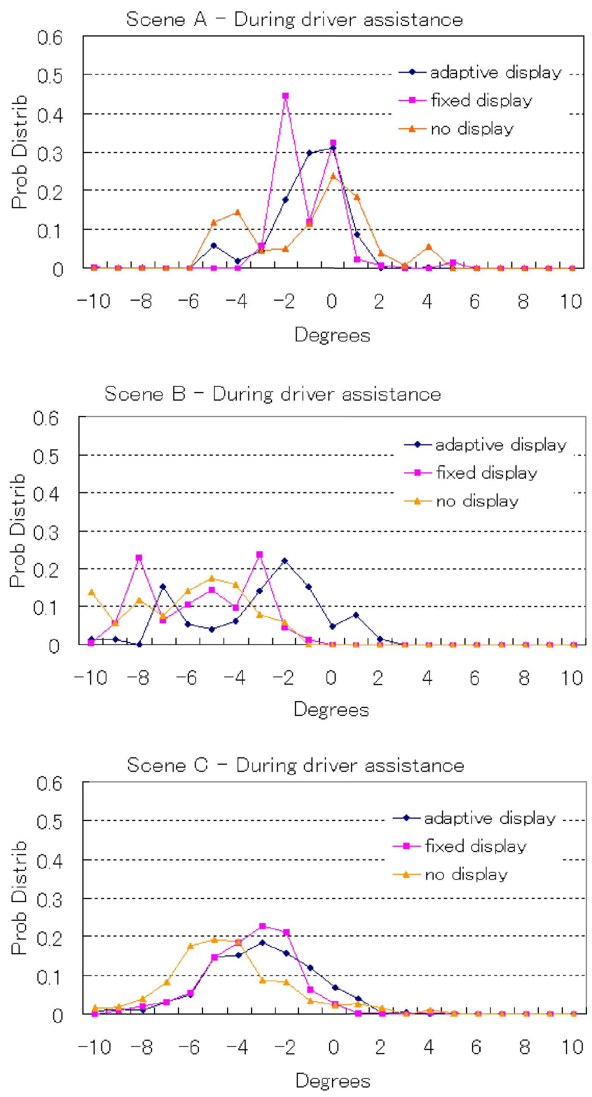

Figure 8 Estimates of the probability distribution of the angular dwell deviation during assistance, for all three information display conditions and scene types.

The advance notice provided by the assistance mark seemed to allow the driver to predict the region of the scene where a pedestrian was going to reach the visibility range. Tracking the movement of the assistance mark had the effect of reducing the awareness delay.

An important issue was the relationship between the awareness delay and the collision ratio of the driver's vehicle with the pedestrian. The collision ratio is defined as the ratio of the number of collisions by the total number of eventsIt was found that the number of collisions for each information display condition was respectively 3 for Adaptive Display, 2 for Fixed Displays, and 7 for No Display. Amongst all subjects, only one collided with the pedestrian, while using all three display modes. These results again confirmed the benefit provided by the advance notice of the pedestrian location. A small awareness delay seemed to be associated with a high situational awareness, as shown by the collision ratios depicted in Table 1.

Table 1 Collision ratios for the system under all display conditions with different scene types.

Collision Ratios			
Information Display	Scene A	Scene B	Scene C
Adaptive Display	0.11	0.06	0
Fixed Display	0.11	0	0
No Display	0.33	0.06	0

Another implication of the awareness delay lies in the verification of the 150 msec during which the warning-cue is highlighted using a bright color even when the driver has gazed at it. Experiment results showed that the driver looked at the assistance mark after it appeared with a delay of roughly 100 msec. Under scene B, this same delay was in the neighborhood of $300 \sim 400$ msec, and approximately $200 \sim 400$ msec with scene C, for both Adaptive and Fixed Displays.

In summary, the driver discovered the warning-cue with a delay that strongly depended on the complexity of the driving task, i.e. the scene, the persistence highlighting minimal duration of 150 msec was found adequate. Instant notice of the warning-cue was only recored with scene A, as it was displayed straight in the line of sight

3.6 Task completion duration

We were interested in the amount of time the driver spent to complete each phase of the driving task. Results are depicted in Fig. 9. Assistance was supposed to last exactly 3 seconds if the driver did not slow down. This was found in our data except within scene B while driving with Fixed Display. Here it took about 3.4 sec going through assistance. Nevertheless, application of the ANOVA revealed that this effect was not statistically significant.

After assistance, the ANOVA revealed a significant effect of the scene type on task duration, $F(2, 12) = 28.165$, $p < .05$. There was no interaction between AIDE display conditions and scene types. The general tendency for participants was to slow down their vehicles with scene A, while they drove slightly faster under scene B, but did not practically slow down under scene C.

4. Conclusion

An evaluation of the effectiveness of a night-time driver support system providing information about pedestrian location was presented. Emphasis was on the driver's eye movement behavior under different scenes and warning display conditions. No significant difference was found between Adaptive Display and Fixed Display conditions. However, they were both shown to better attract the driver's attention than the No Display condition. The system also yielded a three-fold reduction in the number of pedestrian collisions. Providing advance notice of pedestrian location appears to be an effective way of improving night-time driving safety. In our future investigations, these findings will be incorporated into driver prediction models.

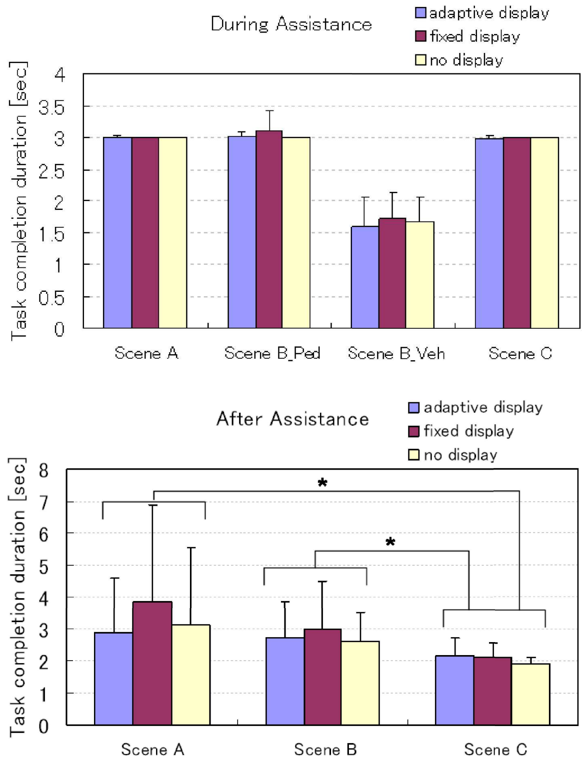

Figure 9 Error bars (mean and standard deviation) of the duration necessary to complete all driving tasks with Adaptive/Fixed/No Displays. During assistance, the salient regions were the assistance mark and the vehicle parked along the road (Scene B_Veh). After assistance, task duration was provided relative to the pedestrian.

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