Estimating Visual Demands in Road Traffic Environments

Toshihisa Sato[1], Motoyuki Akamatsu[1], Atsuhi Tanaka[2], Jun Hatada[2], Yukiya Denda[2] and Takaaki Ishii[3]

[1]Human Technology Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Japan

[2]Marketing Strategy Division, Clarion Co., Ltd., Japan

[3]Hitachi, Ltd., Design Division, Japan

Abstract

This study investigates methods of estimating visual demands during driving in road traffic environments. Accurate estimation of visual demands is expected to promote the identification of driving situations in which drivers have sufficient capacity to divide their attention to in-vehicle systems without resulting in distraction or inattention. Two experiments were conducted to identify occlusion methods suitable for assessing the visual demand variations derived from traffic conditions and road structures. First, four occlusion methods were compared to estimate visual demands during driving with and without lead vehicles: (1) depression of a switch allowed the road scene to be viewed for 0.6 seconds, (2) depression of a switch blanked out the driver's vision for 1.5 seconds, (3) the driver was allowed to view the road while depressing a switch, and (4) the driver's vision was blanked out while depressing a switch. The results of the first driving simulator experiment suggested that differences in the proportions of viewing time to driving time were higher in occlusion methods 2 and 4. Second, we estimated the visual demands of road structures (straight sections, curves, etc.) using the two occlusion methods identified in the first experiment. The second simulator experiment suggested that drivers viewed the roadway throughout the curve in occlusion method 2, while some drivers occluded the forward scene for a very short time even during the curve in method 4. The findings suggest that the occlusion method in which the scene is invisible for a specific time at the driver's request may contribute to establishing the conditions in which the driver can safely operate in-vehicle systems.

Introduction

Drivers acquire and process various kinds of information while travelling to a destination. The majority of this information is obtained through the visual channel (Mourant and Rockwell 1970). Appropriate eye movements while driving directly enhance driving safety, and many reports have examined drivers' visual fixations and scanning behaviors (e.g., Land and Lee 1994, Shinar 2008). Driving safety is affected by the appropriateness of eye movements while attention is divided among relevant objects, persons, tasks, and events, within or outside the vehicle. It is important to reduce inappropriate visual behaviors, especially diverting attention away from driving activities toward competing activities that are driving or non-driving related (Regan and Hallett 2011).

Driver assistance systems have been developed to help drivers travel to destinations more safely, conveniently, and comfortably. Some systems, such as adaptive front lighting systems (Jenssen et al. 2007), aim to improve visual conditions surrounding the driver's vehicle. Other assistance systems that present information and warnings via in-vehicle displays are under development and on the market. The first popular in-vehicle product was navigation systems which provide drivers with guidance information, including searches and identification of intersections for turns. In Japan, navigation systems with digital maps have been on the market since 1981 (Ikeda et al. 2011). At present, navigation systems are standard equipment in automobiles, and the display devices will be important means of realizing intelligent transport systems and services. In the near future, vehicle-to-vehicle and vehicle-to-infrastructure communication will be implemented in real traffic situations. In-vehicle systems with such communication tools will provide drivers with various kinds of information, including information not relevant to the driving task (e.g., shopping opportunities along the route), as well as warnings necessary for avoiding traffic collisions.

In order to maintain safe driving conditions, this additional information should not negatively influence driving behaviors. Drivers should interact with the in-vehicle systems when a safety margin exists for them to receive and react to the presented information. Without such a margin, the additional information may become a competing task, leading to a distracted driver condition. It is essential to detect driver's spare capacity, which defines the allowable margin within which the driver can interact safely with the information presented from the in-vehicle displays. Development of a methodology to estimate quantitatively a driver's spare capacity would make it possible to measure the allowable margin and determine whether or not to provide the additional information. Acceptable glance time and operation time of in-vehicle systems, in which the allowable margin is converted to a time-based index, have been published in Japan and the US. JAMA (Japan Automobile Manufacturers Association) guidelines suggest that the total glance time between the start and completion of an operation task should not exceed eight seconds (JAMA 2004). SAE J2364 describes a "15-second total task rule" that specifies the maximum allowable task time when operating an in-vehicle system (SAE 2004). However, these recommended times are fixed criteria and do not adapt to an individual driver's spare capacity, which varies according to driver capability and driving task demands (Fuller 2007).

Driver conditions, which change as driving continues, are one element of driver capability (Fuller 2005). Representative conditions are driver fatigue and driver drowsiness. Physiological indices have been investigated to establish a method for measuring these internal factors (e.g., Lal and Craig 2001). The road traffic environment is one element that determines driving task demand (Fuller 2005). It is difficult to quantify demands deriving from road traffic environments, although demands under specific road traffic conditions have been estimated based on the physical complexity of the restricted environment (Kurahashi et al. 2003). Driving demands change with road structures (e.g., straight roads, curved roads, and intersections). In addition, task demands change with traffic conditions that vary from moment to moment according to movements of other road users, and the demands also change with driving behavior, including velocity (Fuller 2005). Thus, the demands can change with the interactions of various other factors, in addition to physical factors of the road traffic environment. This causes difficulty in developing a method of estimating quantitatively the dynamic task demands while the vehicle is in motion.

In this paper, we focused on visual demands while driving, and we applied an occlusion method to quantitatively estimate the visual demands of road traffic environments. Drivers may require more visual information while driving with higher visual demands in order to complete the driving task successfully. Therefore, we tried to quantify the visual demands using the percentage of time required for viewing the external situation. We targeted only demand, and we assumed driver capability to be almost the same across experimental conditions. Therefore, task difficulty (Fuller 2005), which may be equivalent to the concept of mental workload (De Waard 2002), is beyond the scope of the present investigation. The visual demands estimated from the time percentage of looking ahead by means of the occlusion technique correspond to perceived visual demand, not to objective demand (Fuller 2011).

The objective is to investigate methods of occlusion that are sensitive to changes in visual demand according to different road traffic environments. We assumed that the different road traffic environments have different objective visual demands, and the "sensitivity" of occlusion patterns corresponds to their ability to reflect these differences. (It is necessary to determine the methods of occlusion that correspond to the objective visual demands in order to identify precisely the driving situations in which it is safe to interact with the in-vehicle systems.) The target road traffic environments were two kinds of traffic conditions (car-following and solo-driving) and six kinds of road environments: straight roads, curved roads, merging at junctions, diverging at junctions, and an entrance and an exit of a tunnel. First, we compared four occlusion methods during driving with and without leading vehicles. We selected the occlusion methods most sensitive to the two traffic conditions. We then applied the selected occlusion methods to driving on portions of the Tokyo Metropolitan Expressway that included the different road structures. All experiments were conducted using the AIST driving simulator.

Occlusion method

Occlusion corresponds to the physical obstruction of vision, and the occlusion method is performed by control of the permitted time intervals during which the driver can look at a scene (ISO 2007). The occlusion technique is a method for assessing the visual demands of driving based on the inspection time required to carry out the task successfully. The first demonstration of the occlusion method on a real road was published by Dr. Senders (Senders et al. 1967). Later, driving simulators were used to assess visual demands of several curves with different curve radii and different deflection angles (Tsimhoni and Green 1999). Since the 2000s, the occlusion method has been used to simulate interruption by a secondary task such as a navigation system (Baumann et al. 2004). The occlusion method formed the basis for the JAMA guidelines that present the total viewing time to complete an in-vehicle system operation while the vehicle is in motion.

Occlusion manner (viewing and occlusion method)

In most studies using the occlusion method, the road scene is occluded for most of the session and the scene can be viewed at the driver's request, for example by the driver simply pressing a switch. In the assessment of the visual demands of a driving task, the occluded time corresponds to the time when drivers divert their attention from the road scene, including glancing at an in-vehicle system. The occlusion method in which the driver's vision was opened or closed in the normal state and closed or opened upon request was applied in order to reproduce the driver's visual behavior when interacting with an in-vehicle system while driving. The following four occlusion methods were tested in simulator experiments:

(1) The road scene was normally occluded and the driver's depression of a switch allowed the road scene to be viewed for 0.6 second.

(2) The road scene was normally visible and the driver's depression of a switch blanked out the driver's vision for 1.5 seconds.

(3) The road scene was normally occluded and the driver was allowed to view the road while depressing a switch.

(4) The road scene was normally visible and the driver's vision was blanked out while a switch was depressed.

We hypothesized that occlusion methods 1 and 3 correspond to situations in which drivers are paying attention to in-vehicle tasks (e.g., navigation, air-conditioner control) and turn their eyes to the road scene when gathering information to perform the driving task. Methods 2 and 4 were hypothesized to reflect situations in which drivers are confident of maintaining safety even if they look at and communicate with the in-vehicle systems while driving.

In occlusion method 1, the 0.6 second viewing time was selected based on the 80 percentile value of the distribution of road scene fixation times when drivers drove on city streets and freeways while performing a navigation entry task (Chiang et al. 2004). In method 2, the 1.5 second occlusion time was based on JAMA guidelines describing a 1.5 second shutter open time (corresponding to the occluded time in this paper) (JAMA 2004).

Quantification of visual demands in occlusion methods

Visual demand was defined as the proportion of time when the road was visible during a specific driving interval (Cullinane and Green 2006). Several indices have been proposed to calculate the time proportion. Viewing rate, as calculated by the following expression, was used to estimate visual demand.

$$\text{Viewing rate} = \sum \frac{\text{Viewing time of the road scene at the previous request}}{\text{Time between previous request and current request}} \quad (1)$$

$$= \frac{\text{Sum of the viewing time}}{\text{Driving time}} \quad (2)$$

Experiment 1: Comparison of occlusion methods between traffic conditions

Driving simulator

The four occlusion methods were compared when the driver followed a lead vehicle (car-following condition) and drove without other vehicles (solo-driving condition). The AIST driving simulator used in Experiment 1 consisted of a real vehicle cabin, a visual environment with a 300-degree field of view, a six degree-of-freedom electric motion platform, and a sound system with eight spatially distributed speakers (Akamatsu and

Onuki 2008). The driver operated a steering wheel, an acceleration pedal, and a brake pedal. Drivers felt as if they were driving a real vehicle.

The switch for the driver's request was set on the steering wheel in the vehicle cabin of the driving simulator. Tapping the switch once indicated one request. Gray-painted images were displayed on the screens when the driver tapped the switch.

Driving behavior data were recorded at a sampling rate of 60 Hz. The data included the driver's operation of the steering wheel and pedals, vehicle status, such as speed, position, and distance to the lead vehicle, and the time of the driver's switch press.

Driving route

Participants drove on a rural road with straight and curved segments. Total distance was 5400 m (about 5 minutes and 30 seconds at the driving speed of 60 km/h). The driver remained in the left lane until reaching the destination (all drove in Japanese driving conditions, on the left side of the road). Figure 1 presents an overview of the target course.

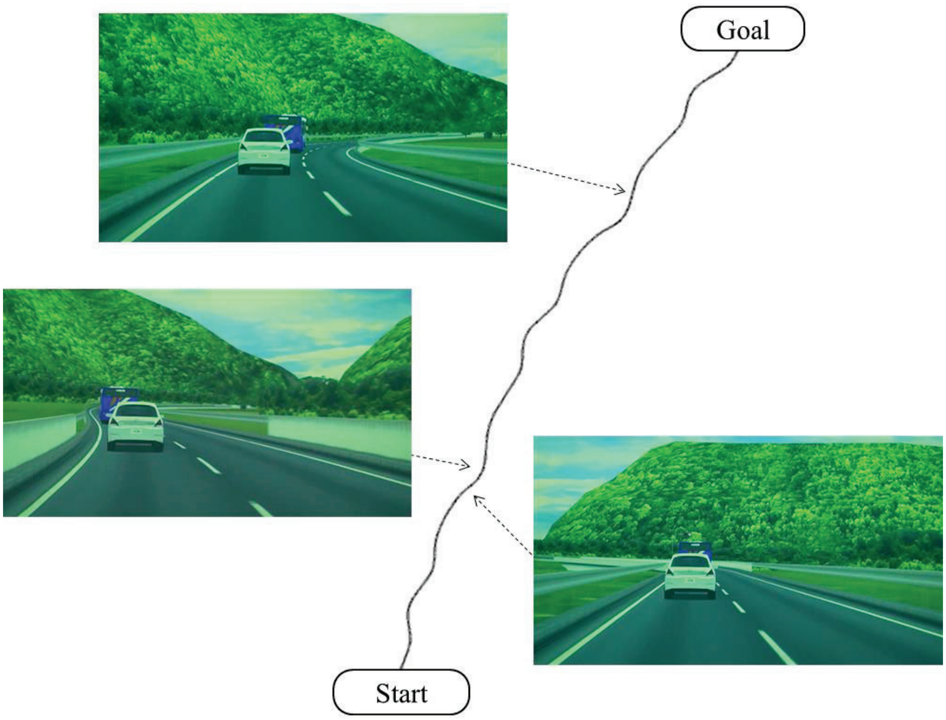

Figure 1 Driving course and photos of the road scene with lead vehicles

Driving conditions

The driving speed was 60 km/h. The traffic conditions were driving with (car-following) and without (solo-driving) lead vehicles (see Figure 1). The driving simulator had a speed limiter to limit the top speed. The limiter held the maximum speed at 63 km/h while the driver depressed the accelerator pedal. The task when driving without the lead vehicle was solo driving at a stable speed, and the task when driving with the lead vehicle was car following within a certain range of headway distance. The setting of the speed limiter was intended to make the solo-driving task easier than the car-following task.

The driver was instructed to keep the headway distance around 25 m in the car-following condition. The headway distance used in the trials was based on naturalistic driving behavior studies. The average time headway of drivers aged 25 to 57 years old is about 1.5 seconds (Sato and Akamatsu 2012). In order to maintain a stable headway distance, an alert with a visual icon and a beep was provided for the driver when the headway distance fell below 22 m or above 28 m. The velocity of the leading vehicles varied between 57 km/h and 62 km/h.

Participants

Eight drivers (four males and four females) participated in this experiment. The average age was 36.3 years (ranging from 27 to 42 years old). Most participants had 10 to 20 years of driving experience. All participants drove a passenger car almost every day, and all had previous experience driving the AIST driving simulator.

Procedures

The participants made practice drives before the recorded trials to familiarize them with the driving route. Additionally, practice drives using each occlusion method were made. In the measurement drives, the four occlusion methods were used in a random order in each traffic condition.

The participants were instructed to maintain driving speed and to maintain headway distance as well as speed when following lead vehicles. They were required to tap the switch on the steering wheel as many times as they could while following the instructions. An explanation of the occlusion method was provided just before each trial. Thus, the participants understood well the occlusion method used on the current trial.

Results

Table 1 presents averages and standard deviations of driving speeds for each occlusion method in the two traffic conditions. Average driving speeds were higher in the solo-driving condition than in the car-following condition, because the speed limiter was set to 63 km/h and the lead vehicle drove around 60 km/h. No significant differences were found between the occlusion methods in each traffic condition.

Table 1 Driving speeds for four occlusion methods

Occlusion manner	Traffic condition	Average velocity (km/h)	Standard deviation of velocity
(1) Viewing on request for 0.6 seconds	Solo-driving	62.26	1.20
(2) Occluded on request for 1.5 seconds	Solo-driving	62.38	0.87
(3) Viewing while depressing switch	Solo-driving	62.26	0.88
(4) Occluded while depressing switch	Solo-driving	62.45	1.00
(1) Viewing on request for 0.6 seconds	Car-following	60.78	0.11
(2) Occluded on request for 1.5 seconds	Car-following	60.80	0.04
(3) Viewing while depressing switch	Car-following	60.82	0.17
(4) Occluded while depressing switch	Car-following	60.76	0.05

Figure 2 presents average viewing rates computed for each occlusion method in each traffic condition. A two-way ANOVA (analysis of variance) was conducted with viewing rate as the dependent variable and traffic condition and occlusion method as independent variables. The analysis revealed a significant main effect of occlusion method ($F(3,55) = 7.563$, $p < 0.001$). The viewing rate was lower for occlusion method 1 than for the other three occlusion methods, for both driving conditions. The viewing rates in the solo-driving condition were almost the same for occlusion methods 2, 3, and 4. The difference in the viewing rate between the two traffic conditions was larger in occlusion methods 2 and 4 than in method 3.

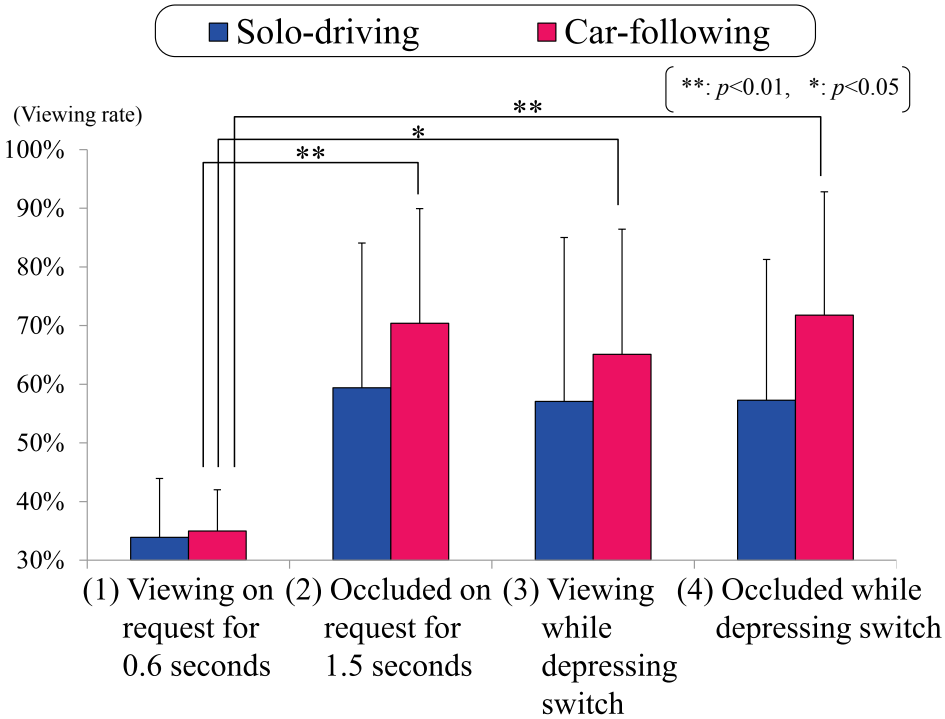

Figure 2 Viewing rates for four occlusion methods

Discussion

The viewing rates for occlusion method 1 were the lowest among the four occlusion methods, and almost no difference was found between the car-following and solo-driving conditions. The driver paid less attention to the road scene with occlusion method 1. Figure 3 presents headway distances when driving with the lead vehicle and the total number of steering wheel reversals in the two traffic conditions, for each occlusion method. The number of steering wheel reversals reflects the number of times the driver corrects the steering while driving (McLean and Hoffman 1975). In this paper, a steering wheel angular change of 3 degrees is used as the steering reversal threshold. The number of reversals was counted along the entire experiment route. We used the calculation method described in the AIDE report (Ostlund et al. 2005). A headway distance closer to 25 m and fewer steering wheel reversals indicate more successful performance of the driving task.

The headway distance appeared to be longer and the number of steering wheel reversals larger with occlusion method 1 than with the other occlusion methods, although no significant differences were found in the ANOVAs. The driving speeds were the same for the four occlusion methods, indicating that the drivers performed only the speed-maintaining task and neglected to maintain headway distances and stable trajectories as instructed with occlusion method 1. They received only the minimum information required for maintaining velocity, leading to almost the same viewing rates in the car-following and solo-driving conditions.

The viewing rate was higher for occlusion method 3 than for method 1. A driver who used occlusion method 3 received more than the minimum information needed to maintain driving speed. The driver maintained not only the instructed driving speed but also the required headway distances and also drove within stable lateral positions, supporting the results shown in Figure 3. (Variations of the headway distances during the route were also smaller for occlusion methods 2, 3, and 4 than for method 1). We hypothesized that the drivers in occlusion methods 1 and 3 paid more attention to the in-vehicle displays and divided their attention to the road ahead when they required information to perform the driving task. When the road scene was occluded automatically and the viewing time of the scene was restricted, the drivers processed the minimum amount of information needed to perform the required minimal driving task. This indicates that the driver perceived the minimum visual demand. When the viewing time of the road ahead was controlled by the drivers themselves, they processed more information that they required to achieve safer and smoother driving in addition to the minimum visual demand.

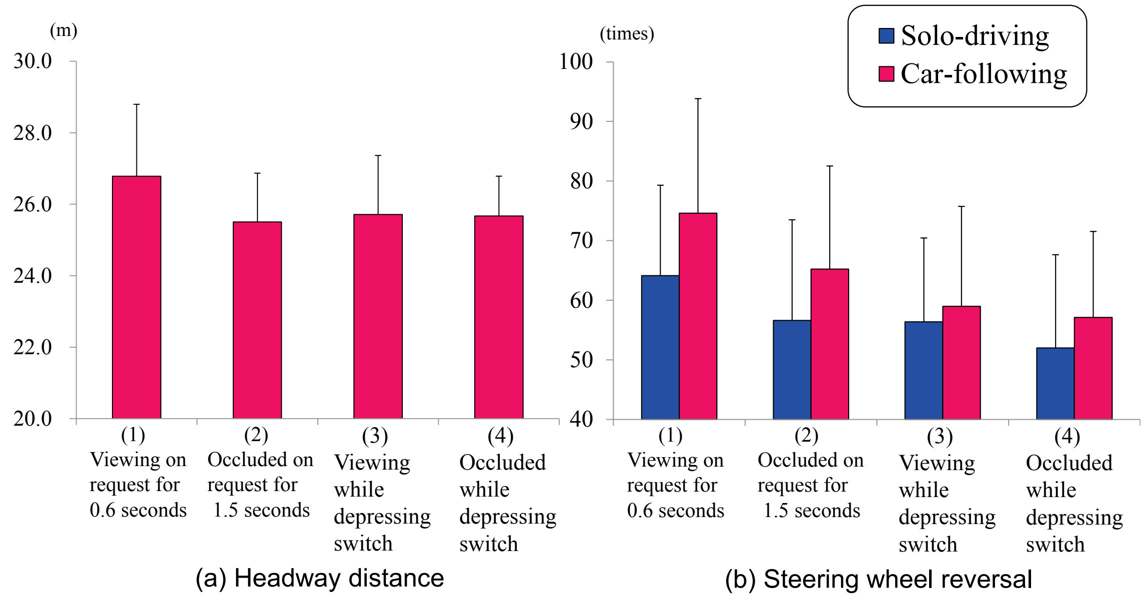

Figure 3 Driving behaviors for four occlusion methods

The viewing rates for occlusion methods 2 and 4 when driving without the lead vehicles were larger than those for occlusion method 1 and were similar to those for occlusion method 3. This indicates that the driver intended to perform the driving task more safely and smoothly with occlusion methods 2 and 4, just as with method 3. This was confirmed by the results for driving speed and steering reversals in the solo-driving condition.

The viewing rates in the car-following situation were higher and the differences in the viewing rates between the traffic conditions were larger for occlusion methods 2 and 4 than for methods 1 and 3. It is possible that the objective visual demand was higher in the car-following condition than in the solo-driving condition. The simulator results suggest that drivers using occlusion methods 2 and 4 were sensitive to the visual demands derived from the traffic conditions. We hypothesized that the primary task with occlusion methods 2 and 4 is driving. In situations where drivers controlled their attention allocation to a secondary task (e.g., glancing at in-vehicle displays), they intended to accomplish the most successful driving possible, including following the lead vehicles with stable headway, and processed more information to better understand the movements of the lead vehicles.

The results of Experiment 1 indicate that the amount of information required to perform the driving task, which corresponds to the perceived visual demand, was different for the occlusion methods, because the driver's intended task level was different. In occlusion method 1, the driver intended to perform a minimal driving task, and the perceived visual demand was least. In occlusion method 3, the driver intended to perform the driving task within the instructed headway distances and with smooth steering, leading to an increase in the perceived visual demand, compared to the minimum demand. In occlusion methods 2 and 4, the driver intended to achieve the instructed driving task more perfectly and smoothly and required more information about the movements of the lead vehicle. Our findings suggest that occlusion methods in which the road scene was normally visible and was occluded at the driver's request were most sensitive to visual demand variations in traffic conditions.

Experiment 2: Comparison of occlusion methods among road environments

Methods

The purpose of this experiment was to compare visual demands among road environments. We focused on two occlusion methods used in Experiment 1. The experiments were conducted using the same driving simulator as in Experiment 1.

In this experiment, an expressway was used, which included straight sections, curves, junctions, and a tunnel. Figure 4 represents the expressway course. This road database was strictly similar to a real expressway (Metropolitan Expressway). The total distance was about 7500 m (about an 8-min trip at 60 km/h). We set one type of traffic condition: driving at 60 km/h and without other vehicles. The speed limiter was active, as in Experiment 1, and the limiter held the maximum speed at 60 km/h. No other road users were present on the target course in order to focus drivers on visual demands that derived only from road structures.

Twenty-one drivers (10 males and 11 females) participated in Experiment 2. The average age was 38.3 years (ranging from 22 to 58 years). Most participants drove a passenger car almost every day. Five drivers had less than 10 years driving experience, 8 drivers had 10-20 years of experience, 7 drivers had 20-30 years of experience, and 1 driver had more than 30 years of experience.

We used occlusion methods 2 and 4: the road scene was normally visible and the driver's depression of the switch blacked out the driver's vision for 1.5 seconds (method 2) or while the switch was depressed (method 4). The experimental order differed among participants: 10 participants (selected randomly) used occlusion method 2 first, and the others used occlusion method 4 first.

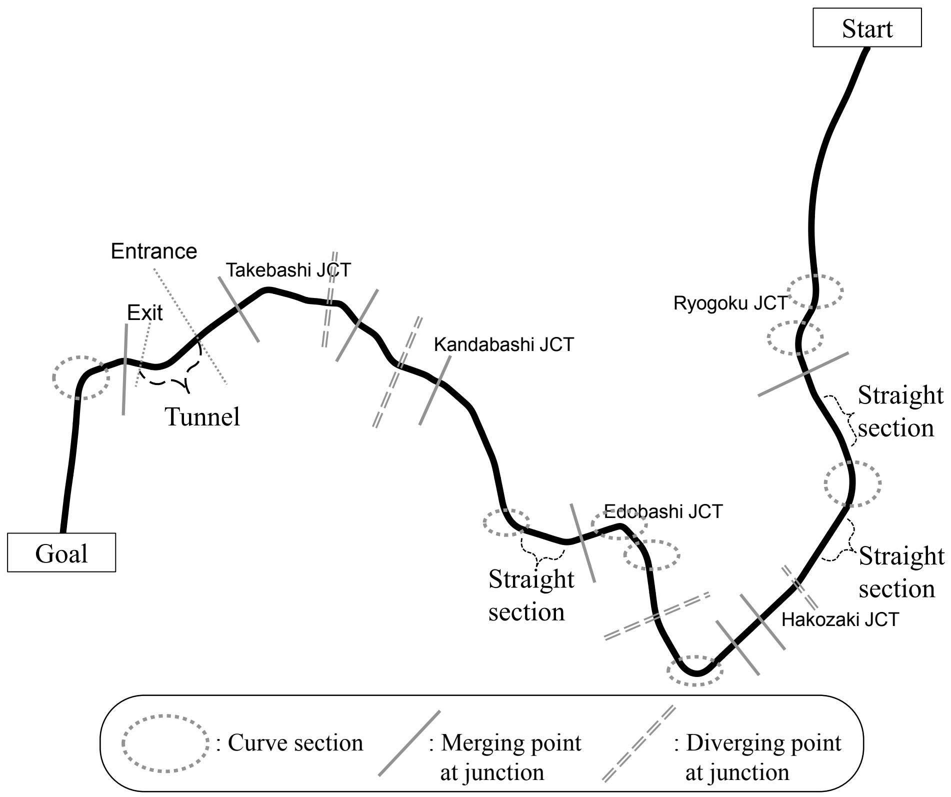

Figure 4 Overview of expressway course used in Experiment 2

The experiment procedures were the same as in Experiment 1. The participants were instructed to drive at 60 km/h with the occlusion methods and to tap the switch as many times as they could while maintaining the required driving speed. They were also instructed to select the route according to the guide signs and travel to the destination without navigation or a map.

Viewing rates were calculated for each road environment. Figure 4 presents the locations of type of each road environment. There were three straight sections, eight curved sections, eight merging points, four diverging points, and one tunnel. The viewing rate at the curved section was calculated from 50 m before the beginning of the transition curve until the end of the curved section. The viewing rates at the merging point and diverging point of a junction and those at the entrance and exit of the tunnel were computed 50 m before and after each site. The viewing rates at the straight sections, curved sections, merging points, and diverging points were averaged among the relevant sites, respectively.

In addition to the viewing rate at each road environment, we analyzed the viewing and occluded patterns at 1 m intervals. The percentage of drivers who were not occluded at every 1 m point of the driving route was calculated.

Results

The average driving speed for occlusion method 2, occluded on request for 1.5 seconds, was 59.54 km/h (SD: 1.05). The speed for occlusion method 4, occluded while depressing the switch, was 59.85 km/h (0.34). No significant difference in driving speed was found between the two occlusion methods, suggesting that the participants maintained the instructed speed in both occlusion methods.

Figure 5 presents average viewing rates for the two occlusion methods at each road environment. A two-way ANOVA was conducted with viewing rate as the dependent variable and road environment and occlusion method as independent variables. The analysis showed a significant main effect of road environment ($F(5, 236)=18.776$, $p<0.001$). The viewing rate at curves was the highest among the target road environments in both occlusion methods 2 and 4. The viewing rates were lower at the straight sections and at the entrance of the tunnel than at the other road sections. The viewing rate was lower at the tunnel entrance than that at the tunnel exit, a difference which was especially notable in occlusion method 2. The difference between the two occlusion methods was smaller at all of the road environments except at the entrance of the tunnel.

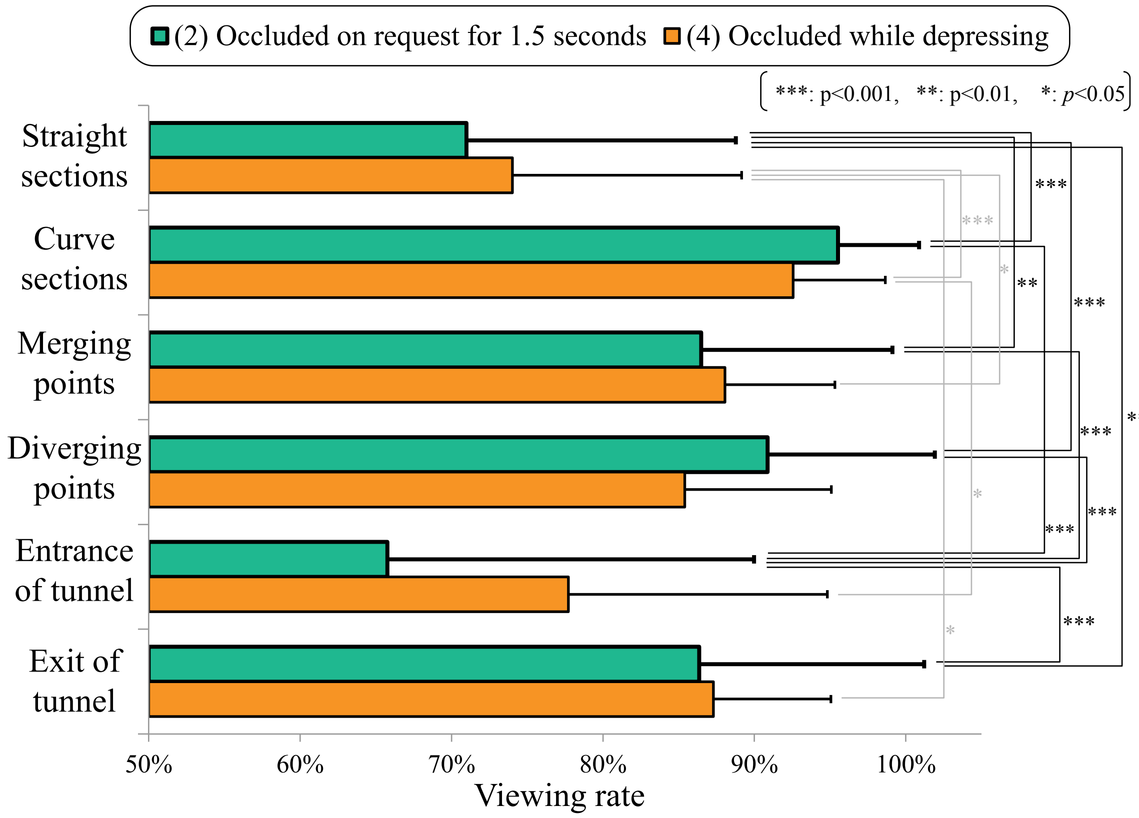

Figure 5 Viewing rates at each road environment

Figure 6 presents the percentages of participants who were not occluded per 1 m, from 800 m to 1400 m on the expressway course, in which left and right curves and a merging point were included. None of the participants depressed the switch during the curved sections in occlusion method 2. Some drivers depressed the switch while driving on the left and right curves in occlusion method 4, and they were occluded for a very short distance (a few meters; about 0.3 seconds). Similar results were found at other locations of curves and merging points.

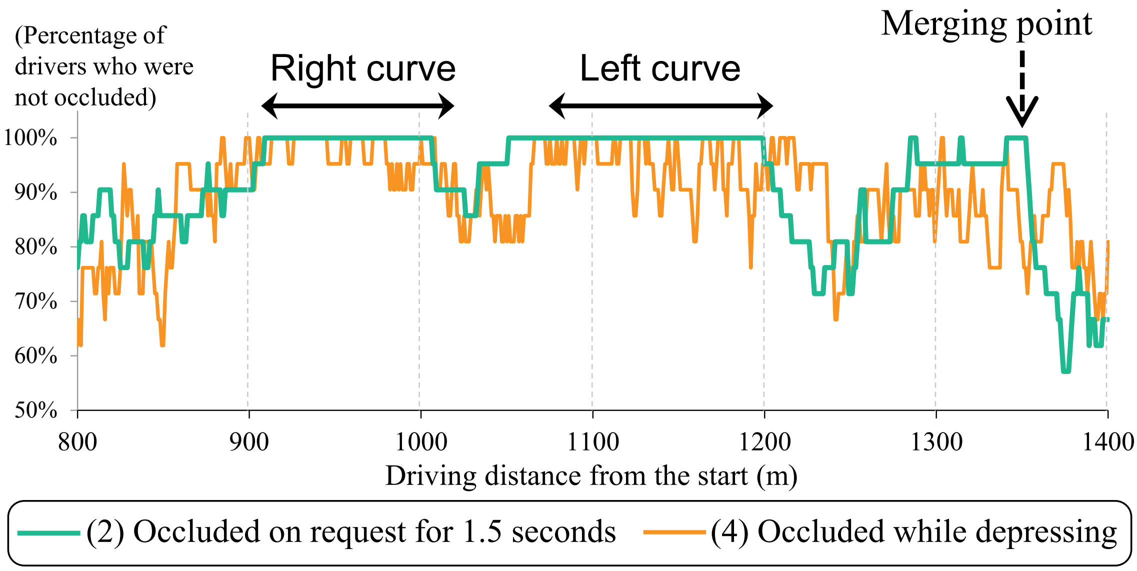

Figure 6 Time series percentages of drivers who were not occluded

Discussion

The viewing rates differed among the target road environments for both occlusion methods 2 and 4. In both methods, drivers were sensitive to the visual demands derived from the road environments. The differences in viewing rate between the two methods were small at all environments except at the entrance of the tunnel. There was a straight road before the entrance of the target tunnel. In occlusion method 2, drivers encountering the target tunnel recognized the visual demand similar to that during driving on the straight road, based on the road alignment. On the other hand, drivers in occlusion method 4 may have paid more attention to the road ahead because of the change of brightness inside versus outside the tunnel, indicating that the drivers intended to perform the driving task more successfully with the self-paced occlusion pattern.

All participants using occlusion method 2 did not depress the switch while driving on left and right curves or just before the merging points. The driver should have maintained attention to the road scene where the road alignment was changing continuously and where the other vehicles could cut in front suddenly. The system-paced occlusion method may have led drivers to refrain from tapping the switch when they confronted such situations. We hypothesized that occlusion method 2 corresponded to situations where drivers were confident they could maintain safety even if they interacted with the in-vehicle systems while driving. The results of the time series data support this hypothesis. Occlusion method 2 could assist in identifying specific points where a driver could operate in-vehicle systems while driving.

Some drivers in occlusion method 4 were occluded at their request even during the curves or before the merging points. Drivers who were confident that very short occlusion would not affect their successful task performance may have depressed the switch and blacked out the view at a very short range. This method may reflect individual drivers' characteristics, for example, whether they are confident they can perform the task successfully under a very short occlusion condition. This confidence may be related to a driver's prediction ability: drivers who are conscious of making preparatory driving behaviors could occlude the front view at a very short range when the road alignment is changing dynamically and continuously.

The results of Experiment 2 imply that occlusion method 2 should be useful in finding locations where a driver could perform in-vehicle tasks. The perceived visual demand estimated by occlusion method 4 may be influenced by driver personality: their confidence in managing the driving task successfully under a brief occluded condition.

Conclusions

We used varying occlusion approaches and investigated occlusion methods to estimate quantitatively the perceived visual demand in road traffic environments. First, four occlusion methods were applied to the estimation of visual demands when drivers followed lead vehicles and when they drove without other vehicles. The visual demands derived from road environments were then estimated using occlusion methods which were sensitive to differences in the visual demands between two traffic conditions.

The comparison of the four occlusion methods implies that the minimum visual demand when performing only the driving task (i.e., maintaining velocity) was estimated by the pattern in which access to the road scene was normally closed but opened for a specific time at the driver's request. The visual demand that was required to achieve a higher performance level was measured by the pattern in which the road scene was normally visible but was occluded during the driver's request. The pattern with a pre-determined occlusion time may be useful in identifying the conditions under which a driver can pay attention to an in-vehicle task. The visual demands estimated by the pattern with a self-paced occlusion time may be influenced by the driver's personal characteristics.

We focused on only one driving speed condition in this study. Further experiments will be conducted in several velocity conditions to evaluate whether the occlusion methods can be applied to the estimation of visual demands at different speeds. Additional examinations will be necessary to validate the findings obtained from this study. We plan to collect driving behavior data for the four occlusion methods with the participation of a larger number of drivers. The occlusion methods should be applied to the estimation of visual demands in a combination of varied traffic conditions and road environments.

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