Eye-Gaze Tracking Analysis of Driver Behavior While Interacting With Navigation Systems in an Urban Area

Article *in* IEEE Transactions on Human-Machine Systems · December 2015

DOI: 10.1109/THMS.2015.2504083

Rencheng Zheng
Tianjin University

Kimihiko Nakano
The University of Tokyo

Eye-Gaze Tracking Analysis of Driver Behavior While Interacting With Navigation Systems in an Urban Area

Rencheng Zheng, *Member, IEEE*, Kimihiko Nakano, *Member, IEEE*, Hiromitsu Ishiko, Kenji Hagita, Makoto Kihira, and Toshiya Yokozeki

***Abstract*—With the advent of global positioning system technology, smart phones are used as portable navigation systems. Guidelines that ensure driving safety while using conventional on-board navigation systems have already been published but do not extend to portable navigation systems; therefore, this study focused on the analysis of the eye-gaze tracking of drivers interacting with portable navigation systems in an urban area. Combinations of different display sizes and positions of portable navigation systems were adopted by 20 participants in a driving simulator experiment. An expectation maximum algorithm was proposed to classify the measured eye-gaze points; furthermore, three measures of glance frequency, glance time, and total glance time as a percentage were calculated. The results indicated that the convenient display position with a small visual angle can provide a significantly shorter glance time but a significantly higher glance frequency; however, the small-size display will bring on significantly longer glance time that may result in the increasing of visual distraction for drivers. The small-size portable display received significantly lower scores for subjective evaluation of acceptability and fatigue; moreover, the small-size portable display on the conventional built-in position received significantly lower subjective evaluation scores than that of the big-size one on the upper side of the dashboard. In addition, it indicated an increased risk of rear-end collision that the proportion of time that the time-to-collision was less than 1 s was significantly shorter for the portable navigation than that of traditional on-board one.**

***Index Terms*—Driver behavior, eye-gaze tracking, on-board navigation, portable navigation, urban area.**

I. Introduction

IN-VEHICLE navigation systems can provide drivers with traffic information for an unfamiliar region or complicated traffic routes in an urban area [1]. Currently, as an alternative to traditional on-board navigation systems, cellular or smart phones can act as portable navigation systems using global positioning system technology [2]–[4]. Guidelines for the convenient and safe use of on-board navigation systems had been prepared by the Automobile Manufacturers Association, outlining information presentation, operational content, and display arrangements [5], [41]. The main differences between on-board and portable navigation systems are that the latter have smaller displays and their position can be changed. However, there are still few guidelines related to portable navigation systems, and it is necessary to study driver behavior while using these new navigation systems.

Relative to other methods of monitoring drivers such as analyses of head dynamics, EEG, EMG, and perspiration [6]–[8], the assessment of a driver's gaze behavior can quantify whether vision is focused on in-vehicle information sources or the road [9]. As for the secondary task of interacting with in-vehicle navigation systems, gaze and glance behaviors have been used to evaluate the effects of driver distraction, display position and size, and information presentation in driving simulators (DSs) and field experiments [10]–[14]. However, previous studies have mainly used head-mounted devices to track eye movement, which may result in unnatural driving behavior [15]. With technological developments, a real-time and nonintrusive eye-gaze tracking system has been developed and can be implemented for monitoring driver vigilance [16]. Recent studies have shown that this nonintrusive eye-gaze tracking technology provides accurate measurement of eye-gaze movements [17]. Former studies introduced a preliminary experiment in which the nonintrusive eye-gaze measurement was realized when drivers used a portable navigation system in a DS system [18], [19].

The objective of this study was to analyze eye-gaze behavior to provide insight into driving performance when drivers interacted with portable navigation systems in an urban area. Thereby, this paper comprehensively investigated glance frequency and time, time-to-collision (TTC) index, and subjective evaluation, to further understand how the different display sizes and positions of portable navigation systems influence on driver behavior under an existing urban condition.

This paper starts with a description of eye-gaze tracking measurement and analysis; then, an experimental method is explained in detail for the drivers interacting with navigation systems in an urban area. Subsequently, the experimental

Manuscript received May 2, 2014; revised November 4, 2014, December 30, 2014, September 24, 2015, and November 20, 2015; accepted November 23, 2015. The work was supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan, through the project of Next-Generation Energies for Tohoku Recovery. This paper was recommended by Associate Editor J. D. Lee.

R. Zheng and H. Ishiko are with the Institute of Industrial Science, The University of Tokyo, Tokyo 153-8505, Japan (e-mail: topzrc@iis.u-tokyo.ac.jp; h-ishiko@iis.u-tokyo.ac.jp).

K. Nakano is with the Interfaculty Initiative in Information Studies, The University of Tokyo, Tokyo 153-8505, Japan (e-mail: knakano@iis.u-tokyo.ac.jp).

K. Hagita, M. Kihira, and T. Yokozeki are with the Department of Traffic Science, National Research Institute of Police Science, Kashiwashi, Chiba 277-0882, Japan (e-mail: hagita@nrips.go.jp; kihira@nrips.go.jp; yokozeki@nrips.go.jp).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/THMS.2015.2504083

results are presented for eye-gaze tracking analysis, TTC index, and subjective evaluation. Finally, the implications, limitations, and validity of this study are discussed and concluded.

II. Eye-Gaze Tracking Analysis

A. Eye-Gaze Tracking Measurement

A nonintrusive eye-gaze tracking system of Smart Eye Pro 5.9 and a Smart Eye Analysis Suite of Smart Recorder (Smart Eye AB, Gothenburg, Sweden) were used to measure the visual behavior of drivers [20]. By application of the system, three cameras and two infrared flashes were equipped to record gaze direction information. The 3-D world tracking model as a coordination systems was used to define a gaze ray by a gaze origin point plus a gaze direction vector, and the sampling frequency was 60 Hz [21]. The camera calibration ensured an average difference less than 0.5 pixels by projecting a specific chessboard. A personal profile was then created by the collection of 16 snapshots with the marked facial feature points, and the snapshots were equally spread over the 140° rotation range of the head. In the gaze calibration for the three cameras, the targeting accuracy was close to $\pm 1°$ without outliers for all subjects.

The eye tracking data quality was confirmed by the gaze direction quality of the recorded data and can be considered sufficiently high for a mean value of 75.4% and range of 70.1–83.5% of the total distance driven [22]. By adjusting the three cameras in a compact arrangement around the navigation display positions, no eye tracking on the navigation display was missed and a high-quality continuous measurement was made. Missing data mainly resulted from eyelid closure, blinking, and eye tracking out of the measuring range, which were accounted for less than 6% of the totally measuring data.

Considering saccade and fixation problems [23], a threshold method was employed for data processing, using the software setting dialog of the Smart Eye system to change the parameters of the filter. Two parameters were considered to set the parameters for dealing with saccade and fixation problems. The requisite duration is 0.06 s for the 10° horizontal saccade [24], and the fixation duration is typically 0.15–0.4 s [25].

B. Eye-Gaze Tracking Processing

The following analysis is focused on classification of the gaze points from the raw eye-gaze tracking data. In the first step, the gaze points on the plane of the navigation display need to be drawn out. The gaze points are normally distributed as probability density functions around the center of the gaze points, as drivers tend to gaze at one specific target [26]–[28]; therefore, it can be assumed that the distribution of the gaze points belongs to a Gaussian mixture model [29]. Finally, an expectation maximum algorithm was used as an iterative maximum likelihood estimation method to estimate related parameters of the Gaussian mixture model [30], [31], and then, the gaze points can be classified for the different gaze targets. Employing the classified gaze points, the glance frequency and time can be calculated following changes in the visual targets over time.

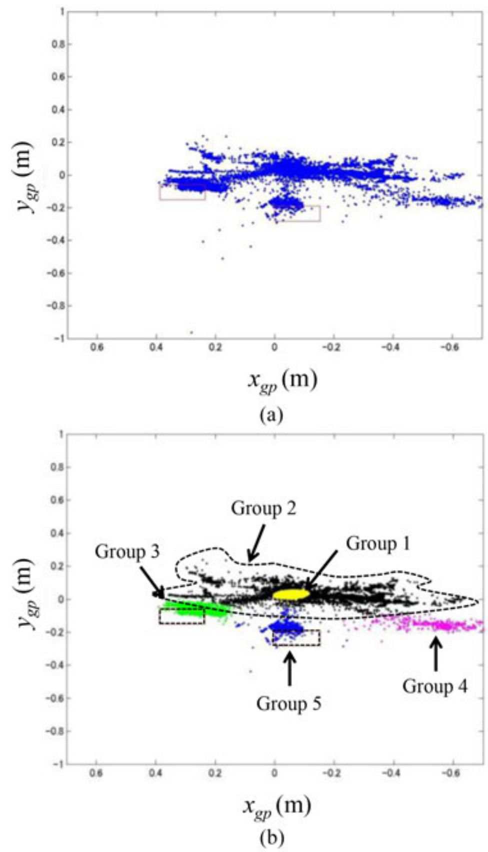


Fig. 1. Measured and classified gaze points (group 1: central part of the foreground, group 2: left and right sides of the foreground, group 3: navigation display, group 4: right-side mirror, and group 5: speedometer). (a) Measured gaze points. (b) Classified gaze points.

At a distance d from the planar plane of the navigation display to the origin point of the coordinates, the spatial coordinates of the mean location of the eyes are denoted (x_p, y_p, z_p), and the mean gaze vector of the eyes is denoted (x_d, y_d, z_d). Thereby, the gaze points on the same plane of the navigation display (x_{gp}, y_{gp}) can be defined as

$$x_{gp} = (d - z_p)\frac{x_d}{z_d} + x_p \quad (1)$$

$$y_{gp} = (d - z_p)\frac{y_d}{z_d} + y_p. \quad (2)$$

As an analytical example, the measured gaze points are plotted on the planar plane of the navigation display in Fig. 1(a). This study prepared the three positions of the navigation display as experimental conditions (see Fig. 5 and Table I); therefore, the distance d depended on the setting positions of the navigation systems.

On the hypothesis of the distribution of the gaze points as a Gaussian mixture model, the $k\text{th}$ Gaussian model for a total of K Gaussian models mixed in the measured data can be expressed as

$$g(y|\pi,\mu,\sigma) = \sum_{k=1}^{K} \frac{\pi_k}{\sqrt{2\pi\sigma^2}} e^{\left(-\frac{(x-\mu_k)^2}{2\sigma^2}\right)}, \quad k = 1, 2, \ldots, K \quad (3)$$

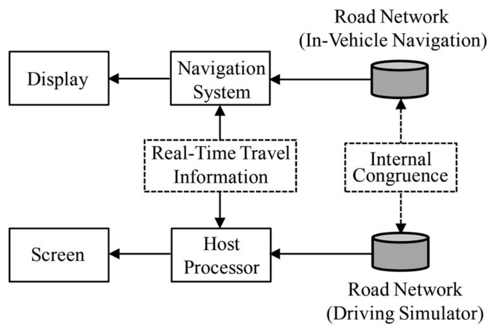


Fig. 2. Schematic of the experimental platform.

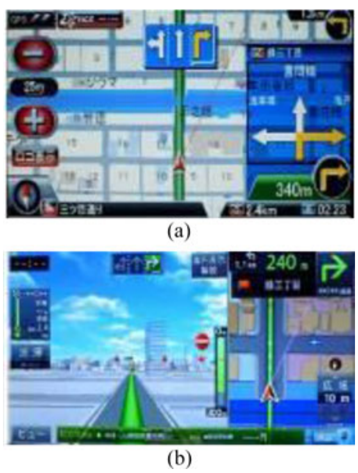


Fig. 3. Map perspectives for right-turn guidance. (a) Map perspective for the portable navigation system. (b) Map perspective for the on-board navigation system.

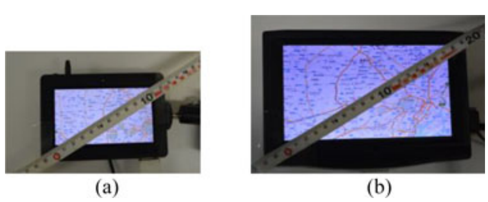


Fig. 4. Physical sizes of the (a) 4.3- and (b) 7-in displays.

TABLE I
EXPERIMENTAL CONDITIONS FOR SCALES, SIZES, AND POSITIONS OF DISPLAYS

Conditions	Types	Scale	Size (inch)	Positions
1	Mapfan Navii	4:25000	4.3	A
2	Mapfan Navii	4:25000	4.3	B
3	Mapfan Navii	4:25000	4.3	C
4	Mapfan Navii	7:50000	7	A
5	Mapfan Navii	7:50000	7	B
6	Mapfan Navii	7:50000	7	C
7	Carrozzeria	7:50000	7	A'

where y is the measured gaze points $(x_{\mathrm{gp}}, y_{\mathrm{gp}})$ as the inputting data. π_k, μ_k, and σ^2 are the probability, mean, and variance of the kth Gaussian model, respectively.

The unknown parameters of π_k, μ_k, and σ^2 can then be estimated in expectation (E) and maximum (M) steps employing an iterative calculation method. By appropriately setting

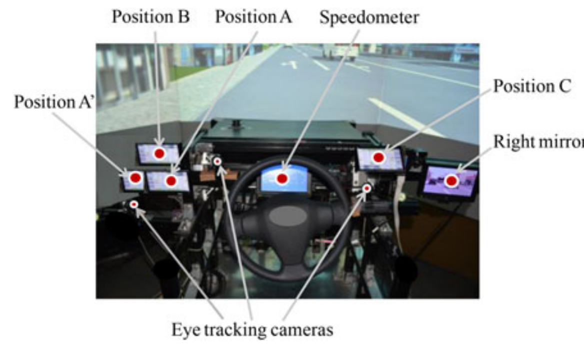


Fig. 5. Diagram of the positions of the navigation displays.

starting values for $\pi^{(0)}$, $\mu^{(0)}$, and $\sigma^{(0)}$, while $p = 0, 1, 2, \ldots$, for the integrated data of $y_1, y_2, \ldots, y_n$, the expectation step can be simply expressed as

$$Q(\pi, \mu, \sigma) = \sum_{i=1}^{N} \sum_{k=1}^{K} \frac{\pi_k^{(p)} \phi(y_i|\mu_k^{(p)}, \sigma^{(p)})}{g(y|\pi^{(p)}, \mu^{(p)}, \sigma^{(p)})} \log(\pi_i|\mu_k, \sigma_k) \quad (4)$$

where ϕ is the density function and $\phi(y|\pi, \sigma) = \frac{\pi_k}{\sqrt{2\pi\sigma^2}} e^{\left(-\frac{(x-\mu_k)^2}{2\sigma^2}\right)}$.

Subsequently, the parameters of π_k, μ_k, and σ^2 can be found when $Q(\pi, \mu, \sigma)$ is maximum as determined by a maximum likelihood estimation:

$$\pi_k^{(p+1)} = \frac{\pi_k^{(p)} \varepsilon_k^{(p)}}{\sum_{j=1}^{K} \pi_j^{(p)} \varepsilon_j^{(p)}} \quad (5)$$

$$\mu_k^{(p+1)} = \frac{1}{\varepsilon_k^{(p)}} \sum_{j=1}^{K} \pi_j^{(p)} \widehat{\phi}_k^{(p)}(y_i) y_i \quad (6)$$

$$(\mu_k^{(p+1)})^2 + (\sigma_k^{(p+1)})^2 = \frac{1}{\varepsilon_k^{(p)}} \sum_{j=1}^{K} \pi_j^{(p)} \widehat{\phi}_k^{(p)}(y_i) y_i^2 \quad (7)$$

where $\widehat{\phi}_k^{(p)}(y) \equiv \frac{\phi(y|\mu_k^{(p)}, \sigma_k^{(p)})}{g(y|\pi^{(p)}, \mu^{(p)}, \sigma^{(p)})}$ and $\varepsilon_k^{(p)} \equiv \sum_{i=1}^{N} {}_k^{(p)}(y_i)$.

In this study, $k = 5$ was chosen for the five eye-gaze tracking targets, including the central part of the foreground, left and right sides of the foreground, navigation display, right-side mirror, and speedometer. The left mirror was out of measuring range for this study. Based on the measured gaze points in Fig. 1(a), the classified gaze points for the different gaze targets are presented in Fig. 1(b). The gaze points were classified to the five gaze targets: the central part of the foreground (Group 1), the left and right sides of the foreground (Group 2), the navigation display (Group 3), the right-side mirror (Group 4), and the speedometer (Group 5). In the figure, the dotted frames on the left side and in the lower central part correspond to the navigation display (Position B, see Fig. 5) and speedometer, respectively.

III. Experimental Method

This study received approval from the Ethical Examination Committee of the Office of Life Science Research Ethics and Safety at The University of Tokyo (No. 13-9).

A. Participants

Twenty healthy participants took part in the driving experiment (16 men and four women, mean age of 35.6 years, range 22–54 years). All participants had a valid Japanese driving license, and participants had been driving for 16.4 years on average (range 3–44 years). The participants reported having driven 8531 km per year on average (range 1000–15 000 km) in the preceding years, and their mean driving frequency was two times per week (range 1–7 times per week).

All participants had eyesight above 0.3 in one eye, and above 0.7 in both eyes, which were measured at the time of the driving experiment. The decimal visual acuity and Landolt ring were applied to measure the visual acuity of the subjects [32]. The participants had an average of 2.7 years of experience (range 0.5–4 years) using traditional 7-in navigation systems, and only seven participants had had experience using smartphone-type 4.3-in navigation systems (range 1–2 years).

B. Apparatus

A moving-based DS was used to produce driving movements of the vehicle with six degrees of freedom. For the interactive connection of the navigation system and the DS, an experimental platform was designed that combined the two systems. As shown in Fig. 2, matching road networks from the in-vehicle navigation and DS system were connected to the navigation system and host processor of the DS, respectively. The travel information was updated in real time between the two systems with a communication frequency of 60 Hz. While drivers operated the DS, they could observe road information on the navigation system display.

In addition, two types of in-vehicle navigation systems were used in the driving experiment: a portable navigation system, MapFan Navii (INCREMENT P Corporation, Kawasaki, Japan), and an on-board navigation system, Carrozzeria (PIONEER, Kawasaki, Japan). The two navigation systems show a 2-D map and travel information under normal conditions, with travel directions always at the top. For turning guidance, the map perspective for the portable navigation system is a 2-D map of the travel information, with extra information in a subwindow in Fig. 3(a). The map perspective for the on-board navigation system is a 3-D map of the travel information, with extra information in a subwindow in Fig. 3(b).

Both systems provided three audio warnings for turning guidance before signalized intersections. For the portable navigation system, the audio warnings were sent 700, 200, and 100 m before the signalized intersections, whereas for the on-board navigation system, the audio warnings were sent 700, 200, and 50 m before the signalized intersections. The display update rates were 0.75 and 1 Hz for the portable and on-board navigation systems, respectively.

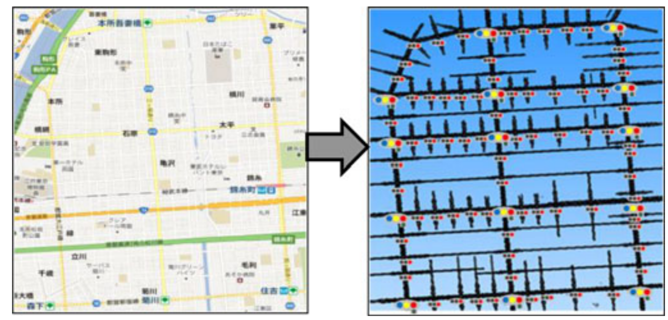


Fig. 6. Driving scenario in an urban area.

The 4.3- and 7-in displays were used for the portable navigation system as shown in Fig. 4(a) and (b), but only 7-in displays were available for the on-board navigation system. The corner–corner dimension is approximately 10.9 cm for the 4.3-in display and 17.8 cm for the 7-in display. The scales for the 4.3- and 7-in displays were 4:25 000 and 7:50 000, respectively.

C. Experimental Design

Three positions of the portable navigation displays were used in the driving experiment, as shown in Fig. 5. Position A was on the right side of the conventional built-in navigation position, position B was on the top of position A and upper side of the dashboard, and position C was on the right and upper side of the dashboard. When the driver's height was 170 cm, the visual angles were approximately 43°, 44°, and 26° for positions A, B, and C, respectively. Even the visual angles are almost similar in the case of positions A and B; however, while drivers watch the portable navigation on position A, they have to draw their gaze into the vehicle and away from the foreground. The on-board navigation system was fixed 17 cm to the left of position A, which is referred to as position A'. All display positions were within the allowed range advised by in-vehicle navigation guidelines [5]. As listed in Table I, a total of seven experimental conditions were prepared for the driving experiment.

As shown in Fig. 6, an actually existing urban road network (Mitsumetoori, Kinshicho, Sumida-ku, Tokyo, Japan) was designed using 3-D modeling software (Multigen Creator; Presagis, Quebec, Canada). The latitude and longitude information of the road network was translated into the coordinates of the model as a driving scenario.

The road traffic signs in the simulation needed to exceed 4.5 m in height and have a character size of 20 cm, and a magnification percentage of 150% with a height of 30 cm for urban roads [33]. Our road traffic signs had a character size of 30 cm and a legible distance of 75.5 m, which was calculated considering the stroke counts of the characters and the legal speed limit of 60 km/h. A visibility evaluation pilot study with six participants having normal vision indicated that a magnification percentage of 200% for road traffic signs would be readable (see Fig. 7). Traffic signals were also set referring to a manual on traffic signal control for situations with and without a specific right-turn lane [34].

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Fig. 7. Road signs reproduced in a DS.

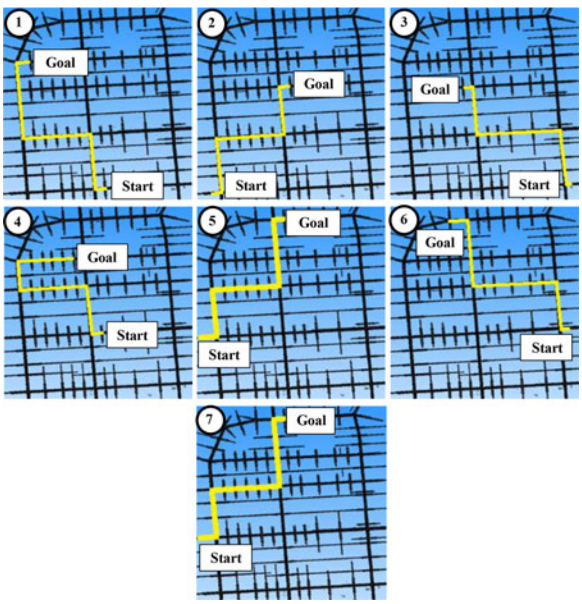


Fig. 8. Seven driving courses with different routes and destinations.

Surrounding vehicles were reproduced to simulate the traffic of an urban area, with a limitation of 80 vehicles at a time. In particular, to observe driver behaviors related to driving safety, the controlling algorithm created preceding vehicles in advance of the driver's perspective. Moreover, seven driving courses with different routes and destinations were prepared with each course having a driving distance of 2300–2700 m, as shown in Fig. 8. There were two left-turn and two right-turn lanes for each driving route. The traffic signals for the different driving courses were set in the same mode for counterbalancing considerations.

D. Procedure

The participants received a detailed explanation about the purpose of the study before engaging in the experiment. At the start of the experiment, the participants practiced operating the DS for about 10 min. The driving experiment was then carried out for the seven experimental conditions with different destinations and routes. Each experimental condition lasted about 10–15 min, with a 5-min rest after each condition was presented.

To avoid a learning influence on task performance, each driver drove each of the seven courses only once; moreover, the seven driving courses were presented in random sequence for each driver. Additionally, participants did not know the routes or destinations in advance. The participants drove to destinations under guidance from the navigation systems; however, directly manual operation of the navigation system was forbidden, and the participants only interacted with the system visually to obtain the correct traffic route, even when the vehicle was stopped. Additionally, participants were asked to obey traffic rules and the 50-km/h speed limit, and to try to follow the traffic flow in the urban area.

E. Dependent Measures

In this experiment, eye-gaze vectors and eye positions were measured for the assessment of the glance frequency, mean glance time, and total glance time as a percentage. Glance frequency was the number of glances at a target on the in-vehicle navigation display during a driving experiment as a predefined task, where each glance was separated by at least one glance at a different target. Glance time was defined as the duration from the moment at which the direction of gaze moved toward the target, namely the in-vehicle navigation display, to the moment the gaze moved away from it. However, total glance time as a percentage is the proportion of the total glance time toward the navigation display to the whole duration of one driving trial. The mean glance time can be deduced from the total glance time divided by the glance frequency.

Operational and driving parameters of the DS were measured to analyze the driving behavior, including the vehicle position, driving velocity, acceleration, and steering angle. The vehicle position, driving velocity, and acceleration of the surrounding vehicles were also measured, and the front vehicle can be distinguished by automatically set identification numbers. These parameters were mainly used to calculated TTC for the evaluation of traffic safety with respect to rear-end collisions. The TTC is defined as

$$\mathrm{TTC} = \frac{L}{v_1 - v_2} \tag{8}$$

where L is the distance of the gap between the following and leading vehicle, and v_1 and v_2 are the driving velocities of the following and leading vehicles, respectively.

F. Questionnaire Investigation

The questionnaire investigations were prepared for the drivers: "How do you rate acceptability, safety, and fatigue when receiving route information from the navigation displays during driving on a five-level scale?" and "How do you evaluate the navigation systems having differently sized displays attached at different positions on a five-level scale?" For the questionnaire results, the five levels of evaluation score were 1 = very low, 2 = low, 3 = average, 4 = high, and 5 = very high.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE II
Statistical P-VALUE OF EYE-GAZE TRACKING ANALYSIS

Condition	Item		Glance Frequency	Glance Time
Whole Period	Main Effect	Size	0.4	0.02
		Position	0.005	< 0.001
	Paired Size	4.3 & 7	none	0.02
	Paired Position	A & B	0.1	1
		A & C	0.07	< 0.001
		B & C	0.006	0.002
Driving Period	Main Effect	Size	0.17	0.01
		Position	0.005	< 0.001
	Paired Size	4.3 & 7	none	0.01
	Paired Position	A & B	1	1
		A & C	0.038	< 0.001
		B & C	0.006	< 0.001

G. Data Analysis

To investigate eye-gaze tracking behavior influenced by the different size displays (4.3 and 7 in) and positions (A, B, and C), six experimental conditions were prepared for the application of the portable navigation system (see Table I). Therefore, a 2 × 3 ANOVA was designed for two within-subject factors of size and position of the navigation displays for 20 sampling subjects. A Bonferroni post-hoc test was used for pairwise comparison analysis, and the *p* value was adjusted by Bonferroni correction.

To understand how different navigation systems in the same position affect, a one-way repeated measures ANOVA was processed for the results of eye-gaze tracking and TTC behaviors in the three experimental conditions: 1) Position A, 4.3-in display, portable navigation (A-4.3-M); (2) Position A, 7-in display, portable navigation (A-7-M); and (3) Position A', 7-in display, on-board navigation (A'-7-C).

Finally, a Friedman one-way nonparametric ANOVA was conducted for the results of the subjective evaluation of participants' feelings of acceptability, safety, and fatigue relating to the 4.3- and 7-in navigation displays, and the results of evaluation of the display positions. The pairwise analyses of the Friedman ANOVA and Wilcoxon signed-rank test were conducted for the corresponding paired results.

IV. RESULTS

A. Eye-Gaze Tracking Analysis

The results of glance frequency, glance time, and total glance time as a percentage for the 20 participants are presented in Fig. 9(a)–(i) for the overall experimental time, the time spent driving, and the time spent stopped. The results are expressed as mean and 95% confidence interval plots. At the 0.05 level of significance, the statistical *p*-value of eye-tracking analysis is shown in Table II.

For the glance frequency of the whole experimental time (see Fig. 9[a]), the glance frequency results were: position A (M = 64.38, SD = 4.37), position B (M = 62.45, SD = 3.42), and position C (M = 81.53, SD = 5.55). The main effect of the position was significant (F[2, 38] = 7.53, p = 0.005, partial $\eta^2 = 0.28$). Bonferroni-corrected post hoc tests showed that the glance frequency of position B was significantly lower than that of position C ($p = 0.006$).

For the glance time of the whole experiment (see Fig. 9(b)], the glance time results were: 4.3-in display (M = 0.77, SD = 0.042), 7-in display (M = 0.68, SD = 0.043), position A (M = 0.78, SD = 0.047), position B (M = 0.79, SD = 0.053), and position C (M = 0.60, SD = 0.032). The main effect of the size was significant (F[1, 19] = 6.45, p = 0.02, partial $\eta^2 = 0.25$), and the main effect of the position was significant (F[2, 38] = 14.06, $p < 0.001$, partial $\eta^2 = 0.43$). Bonferroni-corrected post hoc tests showed that the glance time of 4.3-in display was significantly longer than that of 7-in displays ($p = 0.02$), and the glance times of positions A and B were significantly longer than that of position C ($p < 0.001$ and $p = 0.002$).

For the glance frequency during the time spent driving [see Fig. 9(d)], the glance frequency results were: the position A ($M = 47.05$, $SD = 3.52$), position B ($M = 47.43$, $SD = 2.77$), and position C ($M = 58.38$, $SD = 4.12$). The main effect of the position was significant ($F[2, 38] = 7.49$, $p = 0.005$, partial $\eta^2 = 0.28$). Bonferroni-corrected post hoc tests showed that the glance frequencies of positions A and B were significantly lower than that of position C ($p = 0.038$ and $p = 0.006$).

For the glance time during the time spent driving [see Fig. 9(e)], the glance time results were: 4.3-in display ($M = 0.71$, $SD = 0.039$), 7-in display ($M = 0.64$, $SD = 0.031$), position A ($M = 0.73$, $SD = 0.044$), position B ($M = 0.76$, $SD = 0.038$), and position C ($M = 0.55$, $SD = 0.030$). The main effect of the size was significant ($F[1, 19] = 8.09$, $p = 0.01$, partial $\eta^2 = 0.29$), and the main effect of the position was significant ($F[2, 38] = 25.38$, $p < 0.001$, partial $\eta^2 = 0.56$). Bonferroni-corrected post hoc tests showed that the glance time of 4.3-in display was significantly longer than that of 7-in displays ($p = 0.01$), and the glance times of positions A and B were significantly longer than that of position C ($p < 0.001$ and $p < 0.001$).

B. Time-to-Collision Investigation

The ratio of the period in which the TTC was less than a certain value to the total driving period was calculated, to assess the driving safety of subjects interacting with the navigation systems. The results for the proportions of time that the TTC was less than 2 and 1 s are shown in Fig. 10(a) and (b), respectively. By combining the three positions and two sizes of the navigation display, TTC analysis of six experimental conditions was considered only for the Mapfan Navii navigation system (see Table I). However, there were no significant main effects of the size, position, and size × position interaction, for the proportions of time that the TTC was less than 2 and 1 s.

There was only one rear-end collision with the preceding vehicle at a traffic signal, which occurred for the 20th subject under condition 1 of the 4.3-in navigation display in position A (see Table I and Fig. 5). The crash occurred on the No. 7 driving course, which was the first course driven by the subject. The crash location was immediately before the final intersection, and the crash time point was 5.8 min into the experiment. In

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

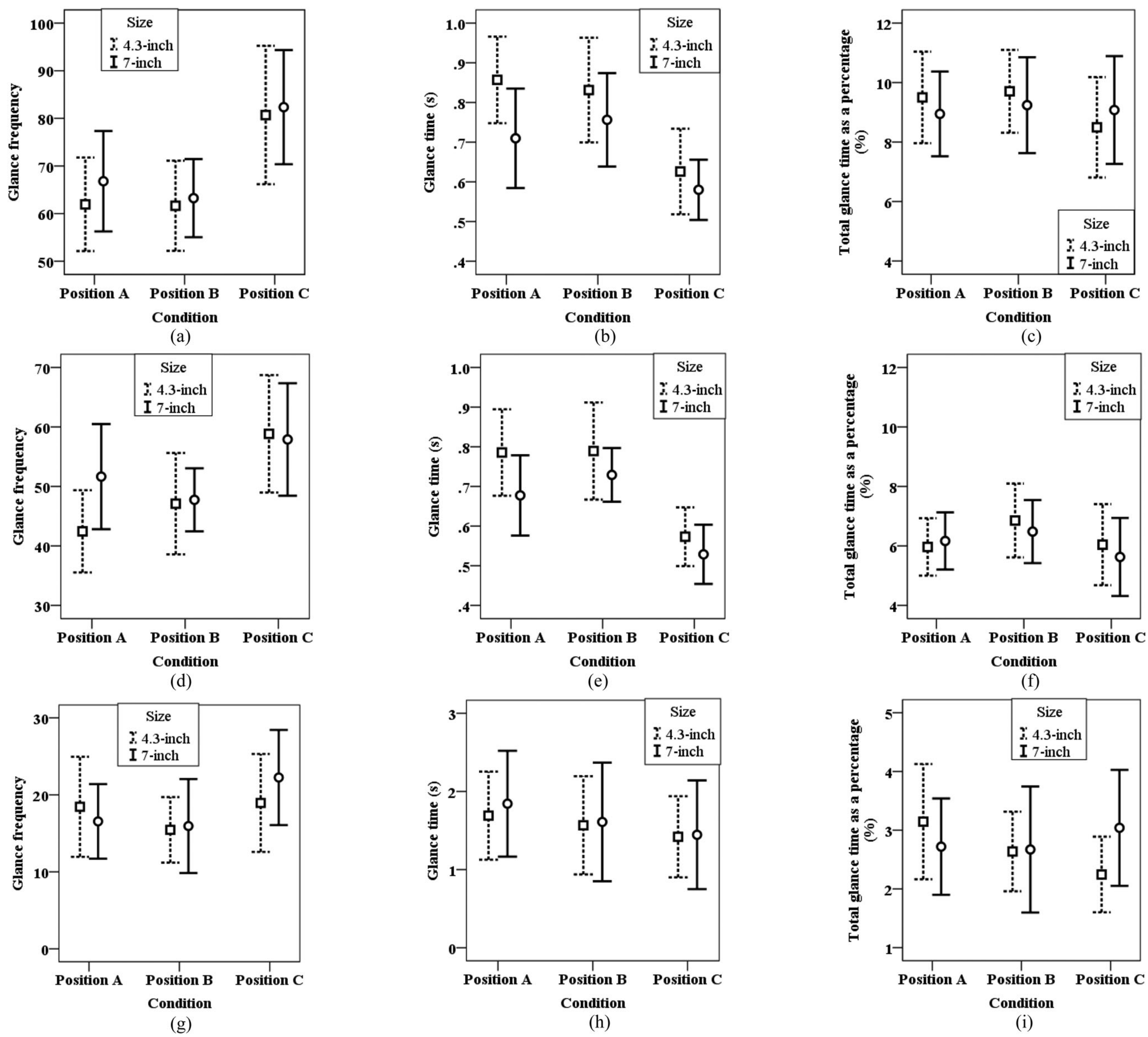


Fig. 9. Results of eye-gaze tracking analysis of the drivers. (a) Glance frequency for the whole experiment. (b) Glance time for the whole experiment. (c) Total glance time as a percentage for the whole experiment. (d) Glance frequency for time spent driving. (e) Glance time for time spent driving. (f) Total glance time as a percentage for time spent driving. (g) Glance frequency for time spent stopped. (h) Glance time for time spent stopped. (i) Total glance time as a percentage for time spent stopped.

the event, the subject prepared to make his final right turn in response to voice guidance received from the navigation system.

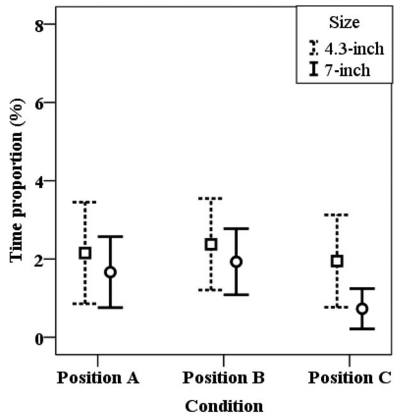
At that time, the preceding vehicle began to decelerate to 20 km/h. Although the subject also decelerated, the gap distance closed to 7 m. Then, while the subject confirmed the road information by gazing at the 4.3-in display of the navigation system, the preceding vehicle decelerated further intending to stop at the red traffic signal, and the rear-end collision followed.

C. Analysis of Different Navigation Systems

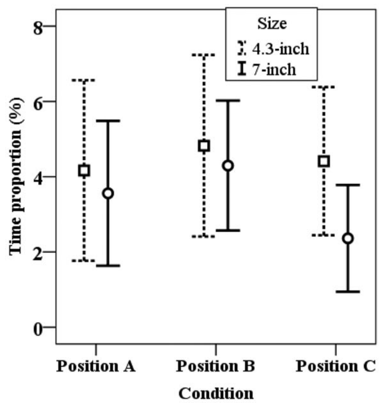
To investigate driver behaviors responding to different navigation systems, eye-gaze tracking and TTC analyses were conducted for three experimental conditions: 1) position A, 4.3-in display, Mapfan Navii navigation (A-4.3-M); 2) position A, 7-in display, Mapfan Navii navigation (A-7-M); and 3) Position A′, 4.3-in display, Carrozzeria navigation (A′-7-C). The related results are presented in Figs. 11 and 12.

For the glance frequency [see Fig. 11(a)], the glance time results were: A-4.3-M ($M = 43.1$, $SD = 4.0$), A-7-M ($M = 56.9$, $SD = 2.4$), and A′-7-C ($M = 40.4$, $SD = 4.0$). The main effect of the condition was significant ($F[2, 18] = 9.29$, $p = 0.002$, partial $\eta^2 = 0.51$). Bonferroni-corrected post hoc tests showed that the glance frequencies of A-4.3-M and A′-7-C were significantly lower than that of A-7-M ($p = 0.017$ and $p = 0.011$).

For the proportion of time that the TTC was less than 1 s [see Fig. 12(b)], the time proportion results were: A-4.3-M ($M = 2.15$, $SD = 0.57$), A-7-M ($M = 1.66$, $SD = 0.40$), and A′-7-C ($M = 0.43$, $SD = 0.13$). The main effect of the condition



(a)



(b)

Fig. 10. Results of time proportions for the TTC analysis. (a) Proportion of time that the TTC was less than 2 s. (b) Proportion of time that the TTC was less than 1 s.

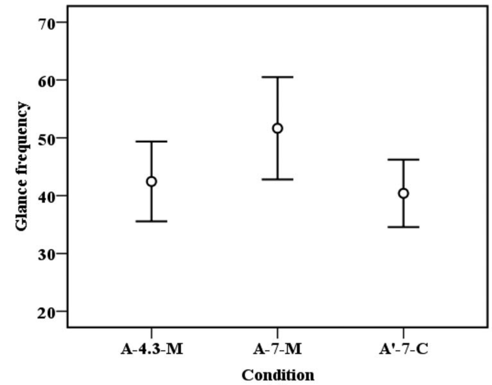
was significant ($F[2, 18] = 5.78, p = 0.023$, partial $\eta^2 = 0.39$). Meanwhile, pairwise analysis showed that the time proportion for A′-7-C was significantly shorter than that for A-4.3-M and A-7-M ($p = 0.04$ and $p = 0.014$).

D. Subjective Evaluation

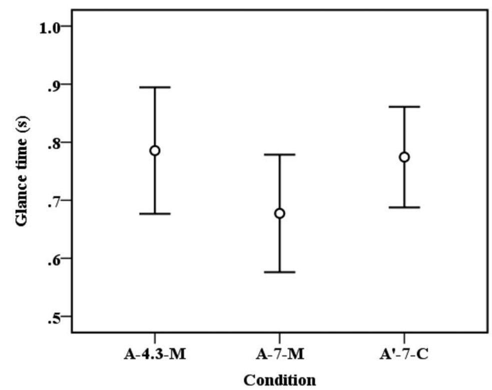
The results of the subjective evaluation of participants' feelings of acceptability, safety, and fatigue were investigated for the 4.3- and 7-in displays, and the mean evaluation score are presented in Fig. 13.

For the 4.3-in display, the evaluation score results were: acceptability ($M = 3.2$, $SD = 1.2$), safety ($M = 2.2$, $SD = 0.8$), and fatigue ($M = 3.3$, $SD = 1.5$). The main effect was significant ($F_r[2, 20] =$ chi-squared $= 10.03$, $p = 0.007$). Pairwise analysis showed that the evaluation score of safety was significantly lower than that of acceptability and that of fatigue ($F_r[1, 20] = 8.07$, $p = 0.005$; $F_r[1, 20] = 6.23$, $p = 0.013$).

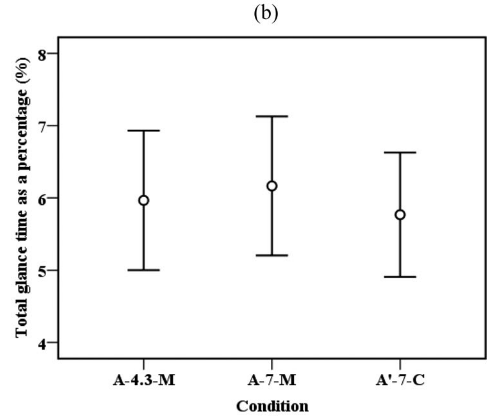
For the 7-in display, the evaluation score results were: acceptability ($M = 4.0$, $SD = 1.1$), safety ($M = 2.7$, $SD = 1.1$), and fatigue ($M = 4.4$, $SD = 0.8$). The main effect was significant ($F_r[2, 20] = \text{chi} - \text{squared} = 23.25, p < 0.001$). Pairwise analysis showed that the evaluation score of safety was also significantly lower than that of acceptability and that of fatigue ($F_r[1, 20] = 17$, $p < 0.001$; $F_r[1, 20] = 12$, $p = 0.001$).



(a)



(b)



(c)

Fig. 11. Results of eye-gaze tracking analysis during the time spent driving under three experimental conditions. (a) Glance frequency. (b) Glance time. (c) Total glance time as a percentage.

By a Wilcoxon signed-rank test for acceptability and fatigue, the evaluation score of the 4.3-in display was significantly lower than that of the 7-in display ($z[20] = -3.22, p = 0.001; z[20] = -2.81, p = 0.005$).

The results of mean evaluation scores for the display positions are presented in Fig. 14. For the 4.3-in display, the evaluation score results were: positions A ($M = 2.9, SD = 1.2$), position B ($M = 3.8, SD = 1.0$), and position C ($M = 3.6, SD = 1.3$). The main effect was significant ($F_r[2, 20] =$ chi-squared $= 8.47$, $p = 0.014$). Pairwise analysis showed that the evaluation score for position A was significantly lower than that for position B ($F_r[1, 20] = 9, p = 0.013$). Moreover, by a Wilcoxon signed-rank test, the evaluation score of the 4.3-in display was

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

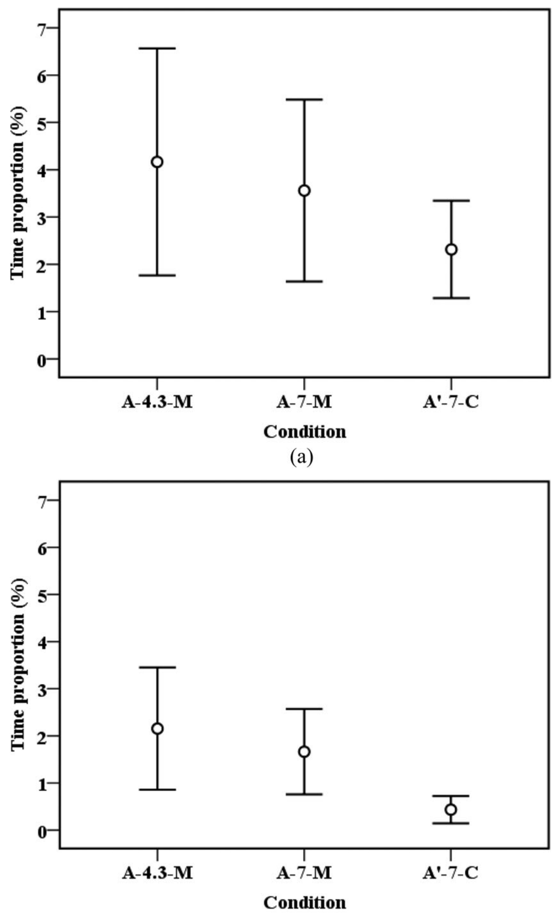


Fig. 12. Results of time proportions for the TTC analysis under three experimental conditions. (a) Proportion of time that the TTC was less than 2 s. (b) Proportion of time that the TTC was less than 1 s.

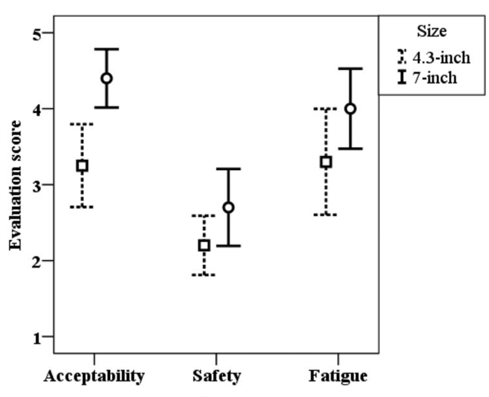


Fig. 13. Subjective evaluation of the display sizes (evaluation scores: 1 = very low, 2 = low, 3 = average, 4 = high, and 5 = very high).

significantly lower than that of the 7-in display at position A ($z[20] = -2.26$, $p = 0.024$).

V. Discussion

For the results of the eye-gaze tracking behavior, there was a significant main effect of the position on the glance frequency in the whole experiment and during the time spent driving. It

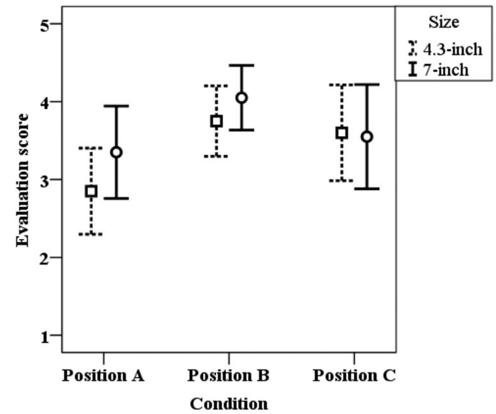


Fig. 14. Subjective evaluation of the display positions (evaluation scores: 1 = very low, 2 = low, 3 = average, 4 = high, and 5 = very high).

is deduced that a smaller visual angle resulted in greater ease of eye movement, and it thus became possible for participants to observe information with a shorter glance time but a higher glance frequency than when the navigation system was placed in the other positions. Significant main effects of the position and size on the glance times were also observed for the whole experiment and during the time spent driving. Therefore, the variations of the position and sizes of the navigation displays, resulting in the different visual angles and visual distances between the navigation display and the forward road scene, should significantly affect the eye-gaze behavior. Thus, even though all display locations considered in this study met the guidelines for in-vehicle display systems [5], the eye-gaze behavior was significantly different for each specific position, especially in the case of the small portable navigation system. The significantly longer glance time may result in the driver taking their eyes off the road and an increased risk of collision.

On the whole, the proportion of the TTC time was less for the 7-in display than for the 4.3-in display, and the TTC time proportion was smallest for the position C with 7-in display. With further analyses, a significant main effect of the proportions of time that the TTC is less than 1 s, indicating that driving behavior for A′-7-C was significantly safer than for A-4.3-M and A-7-M. The evaluation scores of acceptability and safety were higher for the 7-in display than for the 4.3-in display. However, the score for fatigue was also higher for the 7-in display. The reason is that the glance frequency was relatively higher for the 7-in display than for the 4.3-in display. It indicated that participants were concerned about safety with significantly lower evaluation scores, when using a navigation system in the complicatedly urban area, regardless of the size and position of the navigation display. In the case of the small 4.3-in displays, participants found it difficult to process the information presented on the relatively small displays and at large visual angles, especially at position A, as demonstrated by their significantly low subjective evaluation. TTC analysis indicated that the safety of using a navigation system mounted in position C was acceptable [35], yet the participants subjectively evaluated position C to be less safe than position B, which may be a result of the narrow space in which the system is an interference with steering.

The proportion of time that the TTC was less than 1 s was significantly shorter for the on-board navigation than the portable one. It revealed that using the on-board navigation may alleviate the visual burden of drivers in this driving experiment [36]. The main reason for this may be the higher update rate for traffic information and 3-D guidance for turning driving assistance compared with the portable navigation system. Therefore, this analysis shows that the portable navigation system can also improve the effectiveness of driving assistance by using the above methods [37], [38]. Moreover, the timing of the voice guidance, which corresponded to a distance of 50 m from the next signalized intersection, was appropriate for the urban area. However, it is difficult to judge exactly when voice guidance would be useful, when a user drives in an unknown urban area solely depending on navigation information [39].

The scale of the mapping of the navigation systems was not investigated in this study as it was difficult to distinguish the routes and traffic information from the participants' feedback. However, the scale of the small portable navigation system was smaller (coarser) than the normal setting of an on-board system (4:25 000) [40]; this may have had some effect on the results, but is beyond the scope of this work. This study was conducted for the right-hand driving on the left side of the road in Japan. To the best of our knowledge, there is little difference in the eye-gaze tracking behavior when the left-hand driving on the right side of the road; therefore, the results of this study can be referenced for driving on the right side of the road to a certain extent by swapping the positions of A/B with C. However, this remains an interesting topic for further investigation.

VI. Conclusion

Based on the eye-gaze tracking analyses while interacting with navigation systems, this study can provide several guidelines for the use of portable navigation systems. Considering that the TTC index may be lower than 1-s time in an urban area, it becomes important that the glance time should be lower than 1-s time for each gazing behavior on the navigation display. Therefore, the display position for smaller visual angle and visual distance from the forward road scene should be applied with bigger size display of the navigation, like the position B with 7-in display. The contrary situation should be avoided for the example of the position A with 4.3-in display.

A limitation of the study was the relatively strict selection of participants. In future studies, it should be investigated how eye-gaze behavior is affected by variations in age, gender, and driving experiments. Eye-gaze reaction in dangerous situations is also an interesting topic for future study.

Acknowledgment

The authors would like to thank M. Takayanagi and K. Yano of the Kawagoe Plant of Pioneer Corporation for their cooperation.

References

[1] P. J. Feenstra, J. H. Hogema, and T. Vonk, "Traffic safety effects of navigation systems," in *Proc. IEEE Intell. Veh. Symp.*, Eindhoven, Netherlands, 2008, pp. 1203–1208.

[2] W. Lee and B. Cheng, "Effects of using a portable navigation system and paper map in real driving," *Accident Anal. Prev.*, vol. 40, no. 1, pp. 303–308, 2008.

[3] W. Lee, M. Ma, and B. Cheng, "Field comparison of driving performance using a portable navigation system," *J. Navigation*, vol. 63, no. 1, pp. 39–50, 2010.

[4] W. Lee and B. Cheng, "Comparison of portable and onboard navigation system for the effects in real driving," *Safety Sci.*, vol. 48, no. 10, pp. 1421–1426, 2010.

[5] *Guidelines for In-Vehicle Display Systems (Version 3)*, Japan Automobile Manuf. Assoc., Tokyo, Japan, 2004.

[6] M. Clemente, A. Rodríguez, B. Rey, and M. Alcañiz, "Assessment of the influence of navigation control and screen size on the sense of presence in virtual reality using EEG," *Expert Syst. Appl.*, vol. 41, pp. 1584–1592, 2014.

[7] M. Clemente, A. Rodríguez, B. Rey, and M. Alcañiz, "Assessment of the influence of navigation control and screen size on the sense of presence in virtual reality using EEG," *Expert Syst. Appl.*, vol. 41, pp. 1584–1592, 2014.

[8] R. Zheng, K. Nakano, Y. Okamoto, M. Ohori, S. Hori, and Y. Suda, "Evaluation of sternocleidomastoid muscle activity of a passenger in response to a car's lateral acceleration while slalom driving," *IEEE Trans. Human–Mach. Syst.*, vol. 43, no. 4, pp. 405–415, Jul. 2013.

[9] *Road Vehicles: Measurement of Driver Visual Behaviour With Respect to Transport Information and Control System, Part 1: Definitions and Parameters*, 1st ed, ISO 15007-1, 2002.

[10] A. Dingus and M. C. Hulse, "Attentional demand requirements of an automobile moving-map navigation system," *Transp. Res. A, Gen.*, vol. 23, no. 4, pp. 301–315, 1989.

[11] D. D. Salvucci and A. Liu, "The time course of a lane change: Driver control and eye-movement behavior," *Transp. Res. F*, vol. 5, no. 2, pp. 123–132, 2002.

[12] M. Sodhi, B. Reimer, and I. Llamazares, "Glance analysis of driver eye movements to evaluate distraction," *Behav. Res. Meth. Ins. C.*, vol. 34, no. 4, pp. 529–538, 2002.

[13] N. Itoh, A. Yamashita, and M. Kawakami, "Effects of car-navigation display positioning on older drivers' visual search," *Int. Congr. Ser.*, vol. 1280, pp. 184–189, 2005.

[14] M. Wittmann, M. Kiss, P. Gugg, A. Steffen, M. Fink, E. Pöppel, and H. Kamiya, "Effects of display position of a visual in-vehicle task on simulated driving," *Appl. Ergon.*, vol. 37, no. 2, pp. 187–199, 2006.

[15] M. Sodhi, B. Reimer, J. L. Cohen, E. Vastenburg, R. Kaars, and S. Kirschenbaum, "On-road driver eye movement tracking using head-mounted devices," in *Proc. Symp. Eye Tracking Res. Appl.*, New York, NY, USA, 2002, pp. 61–68.

[16] Q. Ji and X. Yang, "Real-time eye, gaze, and face pose tracking for monitoring driver vigilance," *Real-Time Imaging*, vol. 8, no. 5, pp. 357–377, 2002.

[17] O. Lappi, J. Pekkanen, and T. H. Itkonen, "Pursuit eye-movements in curve driving differentiate between future path and tangent point models," *PLOS ONE*, vol. 8, no. 7, e68326, pp. 1–16, 2013.

[18] H. Ishiko, K. Nakano, R. Zheng, K. Hagita, M. Kihira, T. Yokozeki, M. Takayanagi, and K. Yano, "Evaluation of safety of car navigation systems using a driving simulator," presented at the Proc. 20th Intell. Transp. Syst. World Congr., Tokyo, Japan, 2013.

[19] K. Nakano, H. Ishiko, R. Zheng, K. Hagita, M. Kihira, T. Yokozeki, M. Takayanagi, and K. Yano, "Gaze measurement to evaluate safety in using vehicle navigation systems," in *Proc. IEEE Int. Conf. Syst., Man Cybern.*, San Diego, CA, USA, 2014, pp. 3972–3977.

[20] *Smart Eye Analysis Suite—Smart Recorder, Revision 512*, Smart Eye AB, Gothenburg, Sweden, 2012, pp. 1–13.

[21] *Smart Eye Pro 5.9—User Manual, Revision 551*, Smart Eye AB, Gothenburg, Sweden, 2012, p. 80.

[22] C. Ahlstrom, K. Kircher, and A. Kircher, "A gaze-based driver distraction warning system and its effect on visual behavior," *IEEE Trans. Intell. Transp.*, vol. 14, no. 2, pp. 965–973, Jun. 2013.

[23] D. D. Salvucci and J. H. Goldberg, "Identifying fixations and saccades in eye-tracking protocols," in *Proc. Symp. Eye Tracking Res. Appl.*, 2000, pp. 71–78.

[24] R. J. Leigh and D. S. Zee, *The Neurology of Eye Movements*, 3rd ed. London, U.K.: Oxford Univ. Press, 1999.

[25] Advanced Industrial Science and Technology (AIST), *Handbook for Measurement of Human Being*. Tokyo, Japan: Asakura Publishing, 2007.

[26] K. Yamashiro, T. Takahashi, I. Ide, H. Murase, K. Higuchi, and T. Naito, "Automatic calibration of an in-vehicle gaze tracking system using the

driver's gaze behavior," *Inst. Electr. Inf. Commun. Eng.*, vol. J92-D, no. 8, pp. 1308–1316, 2009.

[27] Z. Zhu and Q. Ji, "Eye and gaze tracking for interactive graphic display," *Mach. Vision Appl.*, vol. 15, no. 3, pp. 139–148, 2004.

[28] A. Santella and D. DeCarlo, "Robust clustering of eye movement recordings for quantification of visual interest," in *Proc. Symp. Eye Tracking Res. Appl.*, New York, NY, USA, 2004, pp. 27–34.

[29] B. Muthén and K. Shedden, "Finite mixture modeling with mixture outcomes using EM algorithm," *Biometrics*, vol. 55, pp. 463–469, 1999.

[30] P. K. Mital, T. J. Smith, R. L. Hill, and J. M. Henderson, "Clustering of gaze during dynamic scene viewing is predicted by motion," *Cognitive Comput.*, vol. 3, no. 1, pp. 5–24, 2011.

[31] D. A. Reynolds, T. F. Quatieri, and R. B. Dunn, "Speaker verification using adapted Gaussian mixture models," *Dig. Signal Process.*, vol. 10, nos. 1–3, pp. 19–41, 2000.

[32] W. Grimm, B. Rassow, W. Wesemann, K. Saur, and R. Hilz, "Correlation of optotypes with the Landolt Ring—A fresh look at the comparability of optotypes," *Optometry Vis. Sci.*, vol. 71, no. 1, pp. 6–13, 1994.

[33] Japan Road Association, *Standards for Establishment of Road Traffic Signs and their Interpretation* (in Japanese). Tokyo, Japan: Maruzen Publishing, 1978, pp. 62–69.

[34] Japan Society of Traffic Engineers, *Manual on Traffic Signal Control*, Revised Edition(in Japanese). Tokyo, Japan: Maruzen Publishing, 2008, pp. 40–43.

[35] P. Konstantopoulos, P. Chapman, and D. Crundall, "Driver's visual attention as a function of driving experience and visibility using a driving simulator to explore drivers' eye movements in day, night and rain driving," *Accident Anal. Prev.*, vol. 42, no. 3, pp. 827–834, 2010.

[36] W. Horrey and C. Wickens, "In-vehicle glance duration: Distributions, tails and model of crash risk," *Transp. Res. Record: J. Transp. Res. Board*, vol. 2018, pp. 22–28, 2007.

[37] P. Lin and S. Chen, "The effects of gender differences on the usability of automotive on-board navigation systems—A comparison of 2D and 3D display," *Transp. Res. F, Traffic Psychol. Behaviour*, vol. 19, pp. 40–51, 2013.

[38] C. Lin, H. Wu, and T. Chien, "Effects of e-map format and sub-windows on driving performance and glance behavior when using an in-vehicle navigation system," *Int. J. Ind. Ergonom.*, vol. 40, no. 3, pp. 330–336, 2010.

[39] J. Walker, E. Alicandri, C. Sedney, and K. Roberts, "In-vehicle navigation devices: Effects on the safety of driver performance," in *Proc. Veh. Navigation Inf. Syst. Conf.*, 1991, pp. 499–525.

[40] S. Uang and S. Hwang, "Effects on driving behavior of congestion information and of scale of in-vehicle navigation systems," *Transp. Res. C, Emerging Technol.*, vol. 11, no. 6, pp. 423–438, 2003.

[41] S. Martin, A. Tawari, and M. M. Trivedi, "Monitoring head dynamics for driver assistance systems: A multi-perspective approach," in *Proc. 16th Int. IEEE Annu. Conf. Intell. Transp. Syst.*, The Hague, Netherlands, 2013, pp. 2286–2291.

Rencheng Zheng (M'11) received the Doctor of Engineering degree from the Kochi University of Technology, Kami, Japan, in 2009.

He is currently a Research Associate with the Institute of Industrial Science, The University of Tokyo, Tokyo, Japan. His major research interests include human–machine dynamics and control.

Kimihiko Nakano (M'14) received the Bachelor's and Master's degrees and Doctorate degree in mechanical engineering from the University of Tokyo, Tokyo, Japan, in 1995, 1997, and 2000, respectively.

He is currently an Associate Professor with the University of Tokyo. His major research interests include dynamics and control of vehicles and human factors in driving.

Hiromitsu Ishiko received the Master's of Engineering degree from the University of Tokyo, Tokyo, Japan, 2014.

He is currently a Mechanical Engineer in railway engineering. Now, he is working in a company.

Mr. Ishiko is a Member of the Japan Society of Mechanical Engineering.

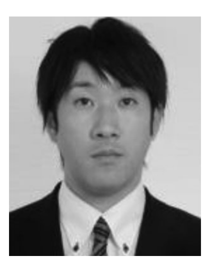
Kenji Hagita received the Bachelor's and Doctorate degrees in civil engineering from Nihon University, Tokyo, Japan, in 1992 and 2005, respectively.

He is currently a Senior Researcher with the National Research Institute of Police Science, Kashiwa-Shi, Japan. His major research interests include the traffic engineering, traffic safety, and traffic control.

Dr. Hagita is a Member of the Japan Society of Traffic Engineers, the Japan Society of Civil Engineers, the Society of Automotive Engineers of Japan, and the Eastern Asia Society of Transportation Studies.

Makoto Kihira received the Bachelor's and Master's degrees from the Tokyo University of Science, Tokyo, Japan, in 1995 and 1997, respectively.

He is currently a Researcher with the National Research Institute of Police Science, Kashiwa-Shi, Japan. His major research interests include human factors in driving.



Toshiya Yokozeki received the Bachelor's and Master's degrees in civil engineering from Nihon University, Tokyo, Japan, in 2002 and 2004, respectively.

He is currently a Researcher with the National Research Institute of Police Science, Kashiwa-Shi, Japan. His major research interests include the traffic engineering, traffic safety, and traffic control.