Displaying System Situation Awareness Increases Driver Trust in Automated Driving

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***Abstract*—Self-driving systems are expected to become increasingly popular in the foreseeable future. However, a driver who is out of the control loop might reduce overall situation awareness by overly trusting automated driving systems. Alternatively, the introduction of automated driving systems could lead to misuse or disuse. For these reasons, an automated driving system should encourage appropriate driver reliance to achieve social acceptance. Imperfect information of the system sensing range might adversely affect trust. This study used a vibrotactile display with an automated driving system to provide situation awareness. The display contributes to driver trust by enabling a driver to predict or perceive actions selected by the system. The display provides spatial information related to traffic objects by haptic stimulus. The driving scenario of passing a motorbike with vehicles approaching from behind was considered. The results of this driving simulator study demonstrated that the spatial information and the behavior of the system affected trust.**

***Index Terms*—Autonomous vehicles, driver behavior, human–computer interaction.**

I. Introduction

HIGHLY automated driving (HAD), which corresponds to the automated driving levels of 3–5 [1], might degrade driver situation awareness (SA) if a driver is engaged in nondriving tasks [2]. Situation awareness is defined as “knowing what’s going on so you can figure out what to do” [3]. The proportion of time a driver’s gaze is fixed on the center of the road is lower during HAD than during manual driving when instructed to perform a nondriving task such as video-watching, handheld telephoning, eating, or reading [4]. Drivers are more likely to use a DVD player, read a magazine, or eat during HAD than during manual driving [5]. An earlier study [6] demonstrated that none of five participants could keep a car on the road after an HAD system failed 2 s before entering a curve, although an acoustic warning was provided at the moment of failure.

“Trust” affects the use of automated systems [7]. Many reports from pilots that mention monitoring failures have described overreliance on automated systems such as autopilots [8], [9]. With over-trust, a driver’s trust exceeds the HAD system capabilities, leading to misuse and driver-degraded SA. Moreover, disuse of automation has been studied to design for appropriate trust [10].

Appropriate driver SA is expected to depend on how much trust a driver has in automated driving. When overly trusting HAD, the driver will not devote attention to the road even if a situation requires monitoring. HAD drivers might be less likely to direct their gaze to the road center [4] or be inclined to engage in nondriving tasks [5]. Overreliance in HAD conditions will lower a driver’s SA. By contrast, distrust or low trust might impose a higher monitoring workload on drivers. Drivers using HAD systems are sensitive to speed, lateral distance, and steering timing when passing other traffic objects [11]. Consequently, “trustable” automation [7], which is designed to be comprehensible, understandable, or well anthropomorphized for drivers, is expected to give the driver appropriate SA.

Questions arise related to trust. What affects a driver’s trust in automated driving? System SA, or how the system comprehends the surrounding traffic environment, is a factor that is strongly expected to affect driver reliance. In a driving situation, an HAD system observes the traffic environment, plans an action such as depressing an accelerator or brake pedal or turning the wheel, and then executes the plan. Human drivers cannot easily know an HAD system plan in advance. The drivers know the HAD driving plan only after it is completed. Consequently, they judge trust in the HAD system only after its performance. One study [11] revealed that a driver feels appropriate steering timing if the HAD has earlier steering timing than manual driving when passing other traffic objects. A driver might need to ascertain how the system plans by watching the wheel movements before the appropriate steering timing. HAD system planning is invariably a black box for drivers that is expected to increase the difficulty in appropriately trusting automation [7].

Considering the matter differently, what would happen if a driver could know that the system comprehends other traffic objects before lane changing? Knowledge about the system comprehension of a traffic situation is expected to affect trust in automation. How to use an automation system changes trust in automation dynamically [12]–[14]. This study constructed a vibrotactile display that provided spatial information of close traffic objects by a haptic stimulus, which equals the SA of an HAD system. The display showed the system recognition of the driving context to a driver. The driver could anticipate the action selection of HAD; such expectation might contribute to trust in

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Fig. 1. Driving simulator and course.

automated systems. The driving scenario of passing a motorbike with vehicles approaching from behind was considered. The driving automation level was defined as 4 or 5, in which the driver might look around at the traffic situation even when engaged in nondriving tasks.

II. METHODS

This study investigated the possible effects and influences of a vibrotactile display on driver trust in an automated driving system. The display used for the driving assistance method was tested in driving simulator experiments.

Visual or audio representation may also be an effective way of displaying SA. For example, an icon may appear if a front vehicle is detected, or the vehicle may illustrate detected surrounding vehicles by providing an animation of the road scene. However, in this study, we considered the situation in which the driver was not carefully monitoring during automated driving at level 4 or 5, in which tactile information is expected to be more suitable. This study aims to explore the possibility of haptic devices for presenting spatial awareness indirectly without preventing driver activity on nondriving tasks.

A. Experimental Setup and Participants

The experiment was conducted with a stationary driving simulator that has three LCD displays in the front and sides (see Fig. 1). Drivers could see the rear traffic situation through simulated side mirrors with computer graphics. A 250-W brushless DC motor (Maxon Precision Motors Inc.) was attached to a steering shaft to generate torque around the axis for assisting manual driving or emulating automated driving. A torque sensor (Kyowa Electronic Instruments Co., Ltd.) was installed on the steering wheel to measure torque exerted on the shaft. Computer graphics were generated using software (Unity 3D; Unity Technologies). Vehicle motion behavior was calculated using CarSim (Mechanical Simulation Corp.).

A vibrotactile display was constructed with a flat coreless vibration motor (FM34F; Tokyo Parts Industrial Co., Ltd.) controlled by a microcomputer (PIC, PIC16F1938 I/SP; Microchip Technology Inc.). Participants wore bands around each wrist with a motor attached (see Fig. 2).

The group of participants consisted of 10 men, aged between 21 and 23 years. Each participant had a valid driver's license. They received a written explanation of the experiment and signed an informed consent sheet.

Fig. 2. Vibrotactile device on driver wrists.

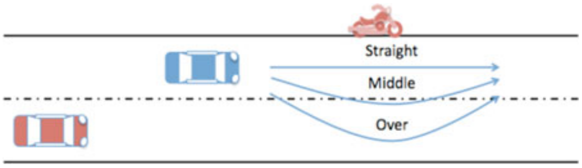

Fig. 3. Driving methods for passing other traffic objects.

B. Driving Scenario

The driving course was a two-lane straight urban street with no signal-regulated intersections. Drivers, or the automated driving system, maintained a speed of at 70 km/h (44 mph) in the left lane of the two-lane road, with lane width of 4.0 m, in urban areas on the assumption that traffic keeps to the left in Japan. The study was focused on the situation of passing other objects. The two-lane urban street, speed limit, and lack of intersections were expected to have no effect. A similar scenario was used in a previous study [11].

We set up scenes in which drivers encountered a motorbike on the left side with a vehicle approaching from behind on the right side after two leading vehicles passed (see Fig. 3). Three driving methods (straight, middle, over) were constructed based on how to avoid the motorbike while paying attention to the following vehicle. The details are described in Section C of the experimental design. The motorbike appeared 100 m ahead when the drivers ran 200 m and drove on the left white line at 15 km/h (9.3 mph). Three passenger vehicles ran on the right lane at 100 km/h (62 mph). Specifically, two were 30 m and 38 m behind while the driver ran at 40 m. The other vehicle and the motorbike appeared 90 m behind when the driver reached a point 200 m from the start point.

C. Experimental Design

A situation was considered in which the automated vehicle passed a motorbike when the other vehicle was approaching from behind after two leading vehicles passed (see Fig. 3). The experiment was a 3 × 3 within-subjects design.

The automated vehicle had three methods of passing the bike: *straight*, *middle*, and *over*. The *straight method* did not avoid the bike when passing but had no contact with the bike. The *middle method* avoided the bike while running slightly over the right white line when passing and then returned to the left lane. The *over method* avoided fully crossing into the right lane of the two-lane road during the apex of its maneuver, and the following vehicle approached very closely when returning to the left lane. Each method differed in lateral distance from the bike but was conducted with the same steering timing if avoiding a bike. Each of the three automated driving methods was generated using each of three recorded datasets of the experimenter's manual driving. The participants experienced each driving scenario (straight, middle, and over) three times with different information representations. The widths of the load and vehicle were 4 m and 1.8 m, respectively. The lateral distances of avoiding the bike for each method were 1.1 m (straight), 3.1 m (middle), and 5.1 m (over).

The vibrotactile display provided information related to close traffic objects in three ways: *directed*, *nondirected*, and *no*. The information was based on whether other objects were close to the automated vehicle within the distance of time to collision (TTC) = 7 s. The display indicated only the presence of some vehicles; i.e., it did not distinguish two vehicles. It was designed to provide a binary indication of traffic in the left vs. right lane and did not indicate the volume or density of this traffic. *Directed* information presented the traffic situation of each side through each vibration motor. The pulses on each side of the driver's vehicle were toggled at different times based on event dynamics. *Nondirected* information presents both sides through both motors, where the information did not distinguish each side of the vehicle. Multiple pulses, which were constantly provided when other vehicles were present, were used consistently for nondirected vs. directed. The intensity of the pulse was constant notwithstanding the value of TTC ($0 \text{ s} < \text{TTC} < 7 \text{ s}$). *No* information presents nothing.

Each driver experienced each of the three methods (*straight*, *middle*, *over*) of automated driving when passing the motorbike once with each of the three types (*directed*, *nondirected*, *no*) of information. The order was grouped with the driving method, and the information type was mixed in the group. Each driver had no repeated exposure. For example, a driver experienced the middle method group first (directed, no, nondirected alert), over method second (no, directed, nondirected alert), and straight last (nondirected, no, directed alert). Thus, each driver tested a total of 9 automated driving rides with counterbalance.

D. Dependent Variables

The effects of varying automated driving methods were investigated with spatial information related to driver trust in automation. Ten variables were used to record a driver's subjective ratings of the automated vehicle. Low "usability (comfort)" might decrease trust. "Avoidance," which is one of the automated driving methods regarding motorbike, relates to the driver judgment of "system situation awareness." After completing a test ride for each driving condition, the drivers wrote judgments in response to the following questions; i.e., each driver answered 90 questions. An eleven-point rating scale was used.

Usability:

1) *Driver perception*: Subjective estimation of driver perception of other vehicles. 0 indicates "not at all," and 10 represents "very easy." The question was the following: ***How easily did you perceive approaching vehicles?***
2) *Driver comfort*: Subjective estimation of comfort with haptic assist. 0 indicates "too uncomfortable," and 10 represents "very comfortable." The question was the following: ***How was the haptic assist comfort?***

Avoidance:

1) *Avoidance radius*: Subjective estimation of avoidance radius for motorbike. 0 indicates "too small," and 10 represents "too large." The question was the following: ***How large did you feel the avoidance of the motorbike was?***
1) *Avoidance timing*: Subjective estimation of avoidance timing for motorbike. 0 indicates "too late," and 10 represents "too fast." The question was the following: ***How fast did you feel the avoidance of the motorbike was?***
2) *Return timing*: Subjective estimation of return timing after the avoidance of the motorbike. 0 indicates "too late," and 10 represents "too fast." The question was the following: ***How fast did you feel the return after avoidance of the motorbike was?***

Awareness:

1) *Motorbike awareness*: Subjective estimation of system SA about the motorbike. 0 indicates "not at all," and 10 represents "completely." The question was the following: ***How did you feel about the system situation awareness of the motorbike?***
2) *Rear vehicle awareness*: Subjective estimation of system SA about rear vehicle. 0 indicates "not at all," and 10 represents "completely." The question was the following: ***How did you feel about the system situation awareness of the rear vehicle?***

Trust:

1) *Performance trust*: Subjective estimation of trust in system performance. 0 indicates "not at all," and 10 represents "completely." The question was the following: ***How much do you trust the automated system performance?***
2) *Awareness trust*: Subjective estimation of trust in system SA. 0 indicates "not at all," and 10 represents "completely." The question was the following: ***How much did you trust the situation awareness of the automated driving system?***
3) *Overall system trust*: Subjective estimation of trust in overall automated driving system. 0 indicates "not at all," and 10 represents "completely." The question was the following: ***How much did you trust the automated system overall?***

E. Procedure

All drivers were required to provide informed consent after being briefed on the driving scenario and the task requirements of practice runs. Each driver was then given four practice drive patterns: The driver drove freely in the first two trials and was instructed to avoid the bike in the last two. Manual driving was used only as practice and not for analysis. Finally, after donning the vibrotactile displays, the experimental trials were started. All driving maneuvers were controlled automatically on driving conditions. Drivers placed their hands on their legs and looked around to observe the traffic situation during automated driving. The set of 10 questions was administered after each run.

III. RESULTS

Subjective ratings related to driving behavior and SA of the automated driving system were analyzed. It is noteworthy that

TABLE I
TWO-WAY ANOVA OF SUBJECTIVE ESTIMATIONS

	Method		Information		Interaction	
	F value	p value	F value	p value	F value	p value
Perception	F(2, 18) = 6.789	.006**	F(2, 18) = 50.005	.000**	F(4, 36) = 2.149	n.s.
Comfort	F(2, 18) = 8.581	.012*	F(2, 18) = 4.567	.025*	F(4, 36) = .865	n.s.
Avoidance radius	F(2, 18) = 74.679	.000**	F(2, 18) = 6.056	.010*	F(4, 36) = .602	n.s.
Avoidance timing	F(2, 18) = 5.796	.027*	F(2, 18) = 3.447	n.s.	F(4, 36) = .281	n.s.
Return timing	F(1, 9) = 4.187	n.s.	F(2, 18) = 2.707	n.s.	F(2, 18) = 1.731	n.s.
Motorbike awareness	F(2, 18) = 11.217	.001**	F(2, 18) = 19.745	.001**	F(4, 36) = 4.915	.020*
Rear vehicle awareness	F(2, 18) = 5.847	.011*	F(2, 18) = 24.621	.000**	F(4, 36) = 3.088	.028*
Performance trust	F(2, 18) = 22.158	.000**	F(2, 18) = 6.336	.008**	F(4, 36) = 1.149	n.s.
Awareness trust	F{2, 18) = 4.587	.025*	F(2, 18) = 33.165	.000**	F(4, 36) = 7.230	.000**
System trust	F(2, 18) = 20.365	.000**	F(2, 18) = 32.807	.000**	F(4, 36) = 4.185	.007**

**, $p < 0.01$; *, $p < 0.05$; n.s., not significant

the terms "driving method" and "spatial information" were not used in dependent variables, but "driving performance" and "situation awareness" were used to guide participants not to examine individual functions of the automated driving system specifically, such as method or information. *System trust* was then assumed to be composed of other variables, and each variable was first analyzed separately using ANOVA. The system trust was then analyzed with the other variables using multiple regression analysis.

Two-way ANOVA was used for each variable (see Table I), in which subjective ratings could be treated as interval scales [15]. Post hoc tests were conducted using the Bonferroni method. Multiple regression analysis was conducted to predict system trust based on the other variables. Ten data points were used for each condition of method and information, i.e., the set of 10 questions was administered after each run. An eleven-point rating scale, 0 indicating low and 10 high, in which each question item was attached to 0 and 10 and not the others, was used.

A. Usability

1) Driver Perception of Other Vehicles: Fig. 4(a) portrays the effects of differences in the subjective ratings for driver perception of other vehicles. The two-way ANOVA of the subjective rating according to the method and information conditions and their interaction showed that the main effects were significant in the method and information conditions but not significant in their interaction (see Table I). Post hoc tests using the Bonferroni method showed greater significance in the *middle* method than *straight* ($p = 0.013$; Table II) and significant differences among the types of information.

2) Driver Comfort With Haptic Assist: Fig. 4(b) depicts the effects of differences in the subjective rating of driver comfort related to haptic assist. The two-way ANOVA of the subjective rating according to the method and information conditions and their interaction showed that the main effects were significant in the method and information conditions but not significant in their interaction (see Table I). Post hoc testing using the Bonferroni method showed greater significance for the *middle* method than *over* ($p = 0.042$) and for *directional* information than *no* ($p = 0.048$; Table III).

B. Avoidance

1) Avoidance Radius for Motorbike: Fig. 4(c) depicts the effects of differences in the subjective rating of the avoidance radius for the motorbike. Two-way ANOVA of the subjective rating according to the method and information conditions and their interaction showed that the main effects were significant in the method and information conditions but not significant in their interaction (see Table I). Post hoc testing using the Bonferroni method showed significant differences among the methods but no difference among the types of information (see Table IV).

2) Avoidance Timing for Motorbike: Fig. 4(d) depicts effects of differences in the subjective rating of avoidance timing for the motorbike. The two-way ANOVA of the subjective rating according to the method and information conditions and their interaction showed that the main effects were significant in the method and information conditions but not significant in their interaction (see Table I). Post hoc tests using the Bonferroni method showed greater significance for the *middle* method than *straight* ($p = 0.018$) but no significant difference among the types of information (see Table V).

3) Return timing After Avoiding the Motorbike: Fig. 4(e) portrays the effects of differences in subjective ratings of return timing after avoidance of the motorbike. The two-way ANOVA of the subjective rating according to the method and information conditions and their interaction showed that the main effects were not significant in the method and information conditions or in their interaction (see Table I).

C. Awareness

1) System Situation Awareness of Motorbikes: Fig. 4(f) presents the effects of differences in the subjective rating of system SA for motorbikes. The two-way ANOVA of subjective rating according to the method and information conditions and their interaction showed that the main effects were significant in the method and information conditions and their interaction

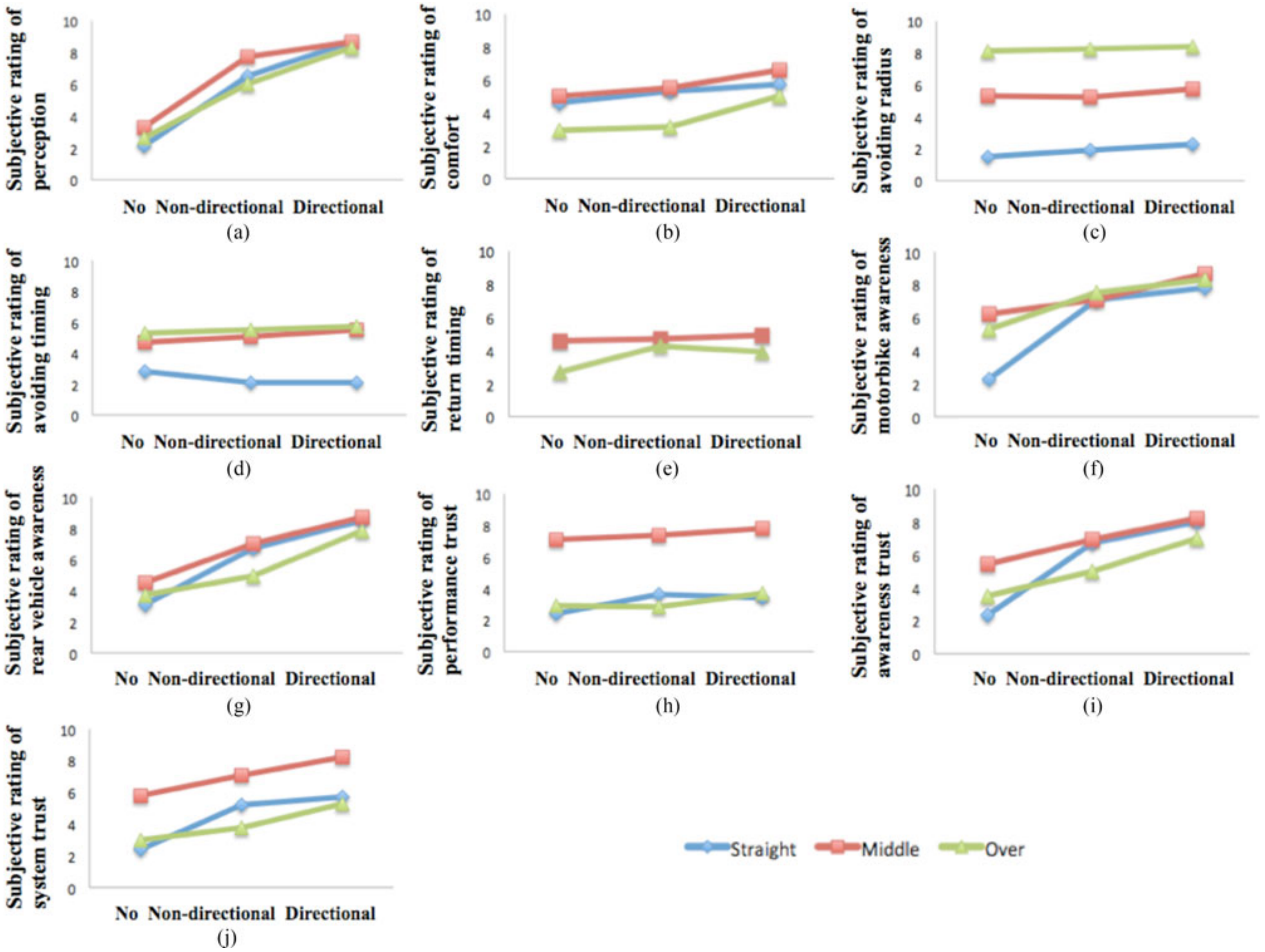

Fig. 4. Subjective estimations: (a) Perception of other vehicles—0 denotes "not at all," and 10 represents "completely"; (b) Comfort about haptic assist—0 denotes "too uncomfortable," and 10 represents "very comfortable"; (c) Avoidance radius for motorbike—0 denotes "too small," and 10 represents "too large"; (d) Avoidance timing for motorbike—0 denotes "too late," and 10 represents "too fast"; (e) Return timing after the avoidance of motorbike—0 denotes "too late," and 10 represents "too fast"; (f) System situation awareness of motorbike—0 denotes "not at all," and 10 represents "completely"; (g) System situation awareness about rear vehicle—0 denotes "not at all," and 10 represents "completely"; (h) Trust in system performance—0 denotes "not at all," and 10 represents "completely"; (i) Trust in system situation awareness—0 denotes "not at all," and 10 represents "completely"; (j) Trust in overall system—0 denotes "not at all," and 10 represents "completely."

TABLE II
POST HOC TEST OF PERCEPTION

	St	Mi	Ov
St	-	-	-
Mi	.013*	-	-
Ov	n.s.	n.s.	-

	No	Nd	Di
No	-	-	-
Nd	.001**	-	-
Di	.000**	.002**	-

St, straight method; Mi, middle; Ov, over
No, no information; Nd, nondirectional; Di, directional
**, $p < 0.01$; *, $p < 0.05$; n.s., not significant; –, not applicable

TABLE III
POST HOC TEST OF COMFORT

	St	Mi	Ov
St	-	-	-
Mi	n.s.	-	-
Ov	n.s.	.042*	-

	No	Nd	Di
No	-	-	-
Nd	n.s.	-	-
Di	.048*	n.s.	-

St, straight method; Mi, middle; Ov, over
No, no information; Nd, nondirectional; Di, directional
**, $p <$ 0.01; *, $p <$ 0.05; n.s., not significant; -, not applicable

TABLE IV
POST HOC TEST OF AVOIDANCE RADIUS

	St	Mi	Ov
St	-	-	-
Mi	.000**	-	-
Ov	.000**	.000**	-

	No	Nd	Di
No	-	-	-
Nd	n.s.	-	-
Di	n.s.	n.s.	-

St, straight method; Mi, middle; Ov, over
No, no information; Nd, nondirectional; Di, directional
**, $p < 0.01$; *, $p < 0.05$; n.s., not significant; -, not applicable

(see Table I). For the *straight* method, post hoc testing by the Bonferroni method showed that the effects were significantly less in *no* information than in *directional* $(p = 0.001)$ or *nondirectional* $(p = 0.001$; Table VI). In *no* information, the test showed that the effects were significantly less in the *straight* method than *middle* $(p = 0.005)$ or *over* $(p = 0.010$; Table VI).

2) System Situation Awareness of Rear Vehicles: Fig. 4(g) presents the effects of differences in subjective ratings of

TABLE V
POST HOC TEST OF AVOIDANCE TIMING

	St	Mi	Ov
St	–	–	–
Mi	.018*	–	–
Ov	n.s.	n.s.	–

St, straight method; Mi, middle; Ov, over
**, $p < 0.01$; *, $p < 0.05$; n.s., not significant; -, not applicable

TABLE VI
POST HOC TEST OF MOTORBIKE AWARENESS

		No	Nd	Di
St	No	-	-	-
	Nd	.001**	-	-
	Di	.001**	n.s.	-
Mi	No	-	-	-
	Nd	n.s.	-	-
	Di	.021*	n.s.	-
Ov	No	-	-	-
	Nd	n.s.	-	-
	Di	.042*	n.s.	-

		St	Mi	Ov
No	St	-	-	-
	Mi	.005**	-	-
	Ov	.010*	n.s.	-
Nd	St	-	-	-
	Mi	n.s.	-	-
	Ov	n.s.	n.s.	-
Di	St	-	-	-
	Mi	n.s.	-	-
	Ov	n.s.	n.s.	-

St, straight method; Mi, middle; Ov, over
No, no information; Nd, nondirectional; Di, directional
**, $p < 0.01$; *, $p < 0.05$; n.s., not significant; -, not applicable

TABLE VII
POST HOC TEST OF REAR VEHICLE AWARENESS

		No	Nd	Di
St	No	-	-	-
	Nd	.015*	-	-
	Di	.001**	.042*	-
Mi	No	-	-	-
	Nd	.005**	-	-
	Di	.000**	.009**	-
Ov	No	-	-	-
	Nd	n.s.	-	-
	Di	.002**	.021*	-

		St	Mi	Ov
No	St	-	-	-
	Mi	n.s.	-	-
	Ov	n.s.	n.s.	-
Nd	St	-	-	-
	Mi	n.s.	-	-
	Ov	n.s.	n.s.	-
Di	St	-	-	-
	Mi	n.s.	-	-
	Ov	n.s.	n.s.	-

St, straight method; Mi, middle; Ov, over
No, no information; Nd, nondirectional; Di, directional
**, $p < 0.01$; *, $p < 0.05$; n.s., not significant; -, not applicable

system SA related to the rear vehicle. The two-way ANOVA of subjective ratings according to the method and information conditions and their interaction showed that the main effects were significant in the method and information conditions and their interaction (see Table I). In the *over* method, post hoc testing using the Bonferroni method showed that the effects were significantly larger in *directional* information than *no* ($p = 0.002$) or *nondirectional* ($p = 0.021$; Table VII). In respective information conditions, the test showed that the effects were not significantly different among the methods (see Table VII).

TABLE VIII
POST HOC TEST OF PERFORMANCE TRUST

	St	Mi	Ov
St	-	-	-
Mi	.002**	-	-
Ov	n.s.	.001**	-

	No	Nd	Di
No	-	-	-
Nd	n.s.	-	-
Di	.035*	n.s.	-

St, straight method; Mi, middle; Ov, over
No, no information; Nd, nondirectional; Di, directional
**, $p < 0.01$; *, $p < 0.05$; n.s., not significant; -, not applicable

TABLE IX
POST HOC TEST OF AWARENESS TRUST

		No	Nd	Di
St	No	-	-	-
	Nd	.002**	-	-
	Di	.000**	n.s.	-
Mi	No	-	-	-
	Nd	n.s.	-	-
	Di	.005**	n.s.	-
Ov	No	-	-	-
	Nd	.020*	-	-
	Di	.001**	.011*	-

		St	Mi	Ov
No	St	-	-	-
	Mi	.002**	-	-
	Ov	n.s.	n.s.	-
Nd	St	-	-	-
	Mi	n.s.	-	-
	Ov	n.s.	n.s.	-
Di	St	-	-	-
	Mi	n.s.	-	-
	Ov	n.s.	n.s.	-

St, straight method; Mi, middle; Ov, over
No, no information; Nd, nondirectional; Di, directional
**, $p < 0.01$; *, $p < 0.05$; n.s., not significant; -, not applicable

D. Trust

1) Performance Trust: Fig. 4(h) portrays the effects of differences in subjective ratings of trust in system performance. The two-way ANOVA of subjective rating according to the method and information conditions as well as their interaction showed that the main effects were significant in the method and information condition and not significant in their interaction (see Table I). Post hoc testing using the Bonferroni method showed that the effects were not significantly different between *straight* and *over* methods and also not different between *no* and *nondirectional* information and larger in *no* information than in *directional* ($p = 0.035$; Table VIII).

2) Situational Awareness Trust: Fig. 4(i) presents the effects of differences in the subjective rating of trust in system SA. The two-way ANOVA of the subjective rating according to the method and information conditions and their interaction showed that the main effects were significant in the method and information conditions and their interaction (see Table I). For the *straight* method, post hoc testing using the Bonferroni method showed that the effects were significantly smaller in *no* information than *nondirectional* ($p = 0.002$) and *directional* ($p = 0.000$; Table IX). In the *no* information condition, the test showed that the effects were significantly larger in the *middle* method than in *straight* ($p = 0.002$) and not significantly different between the *middle* and *over* methods (see Table IX).

3) Entire System Trust: Fig. 4(j) portrays the effects of differences in the subjective ratings of trust in the overall system. The two-way ANOVA of the subjective rating according to the method and information conditions and their interaction showed the main effects that were significant in the method and information conditions and their interaction (see Table I). In the *straight* method, post hoc tests using the Bonferroni method showed that the effects were significantly smaller in *no* information than in *nondirectional* ($p = 0.001$) and *directional* ($p = 0.000$; Table X). In *nondirectional* information, the test showed that the

TABLE X
POST HOC TEST OF SYSTEM TRUST

		No	Nd	Di
St	No	-	-	-
	Nd	.001**	-	-
	Di	.000**	n.s.	-
Mi	No	-	-	-
	Nd	n.s.	-	-
	Di	.004**	.035*	-
Ov	No	-	-	-
	Nd	n.s.	-	-
	Di	.003**	n.s.	-

		St	Mi	Ov
No	St	-	-	-
	Mi	.000**	-	-
	Ov	n.s.	.006**	-
Nd	St	-	-	-
	Mi	n.s.	-	-
	Ov	n.s.	.001**	-
Di	St	-	-	-
	Mi	.006**	-	-
	Ov	n.s.	.016*	-

St, straight method; Mi, middle; Ov, over
No, no information; Nd, nondirectional; Di, directional
$^{**}, p < 0.01; ^{*}, p < 0.05$; n.s., not significant; -, not applicable

TABLE XI
SUMMARY OF MULTIPLE REGRESSION ANALYSIS FOR VARIABLES PREDICTING SYSTEM TRUST

Variable	Coefficient (β)	SE	*t* value	p value
Constant	.063	.218	.290	–
Awareness trust	.427	.055	7.142	.000**
Performance trust	.549	.036	12.890	.000**
Driver perception	.146	.043	2.787	.007**
	IP-. 894	F(3,83)—243.735		.000**

$^{**}, p < 0.01; ^{*}, p < 0.05$; n.s., not significant; -, not applicable

effects were significantly larger in the *middle* method than *over* $(p = 0.001)$ and not significantly different between the *middle* and *straight* methods (see Table X).

E. Regression Analysis

A multiple linear regression was performed to predict the overall system trust based on awareness trust, performance trust, and driver perception (see Table XI). A significant regression equation was found $(F\,(3, 83) = 243.735, p = 0.000)$, with R^2 of 0.894. The predicted overall system trust is equal to

$$0.063 + 0.427\mathrm{X}_1 + 0.549\mathrm{X}_2 + 0.146\mathrm{X}_3, \qquad (1)$$

where X_1 stands for awareness trust, X_2 signifies performance trust, and X_3 denotes driver perception. Awareness trust, performance trust, and driver perception were significant predictors of overall system trust $(p = 0.000, p = 0.000, p = 0.007$: Table XI).

The full set of remaining nine questions was included as part of the regression analysis to predict overall system trust (question 10). However, the stepwise methods of regression analysis remained only "awareness trust," "performance trust," and "driver perception," and the other questions were deleted. The effects of the categorical variables of the vibrotactile display (no, nondirected, directed) and automated drive maneuver method (straight, middle, over) were already analyzed by ANOVA and not included in the regression model. This analysis focused on the level of question.

IV. DISCUSSION

This study assessed driver trust in automated driving when passing other objects in a heavy traffic situation with spatial information of approaching vehicles using a vibrotactile display. Spatial information was expected to increase driver trust because a driver can perceive some part of the decision process of an automated driving system through the information. This effect is expected to increase when the system performs lane changes in which a driver might feel the risk of collision with other objects.

The driving method is a necessary factor for driver trust in automated driving. When an automated vehicle passes another object such as a bicycle or motorbike, the driver is sensitive to the steering timing of lane changes and the lateral distance from the object [11]. With earlier steering timing or longer lateral distance, the subjective rating of system trust was high [11]. Especially, each driver felt that it was inappropriate when the auto driving used exactly the same distance or timing as the driver's own performance. Designing a trustable system requires driving with earlier timing or more distance than that of each driver when passing other objects, which is expected to affect automation usage [16]–[18]. In the present study, the *middle* driving method of automated driving showed a higher subjective rating for trust than either the *straight* or *over* method [see Fig. 4(i)]. The *straight* method did not avoid the left side motorbike, which might affect performance trust. The *over* method returned late to the left lane. The rear vehicle passed very close to the driver's vehicle. The subjective rating of return timing was not significantly different in the *over* and *middle* methods [see Fig. 4(e)]. The close passage of a rear vehicle might affect the performance trust of the *over* method, which was smaller than that of *middle* [see Fig. 4(h)].

Spatial information is highly effective to increase trust in automation [see Figs. 4(i) and (j)]. The information also made it easy for drivers to perceive other vehicles [see Fig. 4(a)]. Consequently, *directed* information contributed more to driver trust than *nondirected* information [see Fig. 4(j)]. From the information related to whether or from which direction other vehicles approach, a driver can anticipate the driving performance of an automated driving system, especially for avoiding collisions. The predictability or SA of an automated driving system cultivates much trust in a driver [see Fig. 4(i)]. Therefore, displaying information of other vehicles can increase driver trust [see Fig. 4(j)].

Such a display can be effective even if the driving method is exactly the same with the exception of spatial information: the *straight* method did not avoid the motorbike, and the *over* method allowed the close approach of the rear vehicle. Without behavioral outcomes, the system can obtain driver trust, showing the system SA of the traffic environment.

System trust consists of awareness trust, performance trust, and driver perception (1). System trust increased with the display of spatial information [see Fig. 4(j)]. The trust also increased depending on the driving method: the *middle* method showed the highest subjective rating in all information conditions. However, performance (driving method) and awareness trust might not be independent factors. Awareness trust presented a higher rating with the *middle* method than with *straight* or *over* in the *no* information condition [see Fig. 4(i)]. Consequently, the performance of an automated driving system might affect awareness trust. The driver might judge whether the system can perceive the surrounding traffic situation by its driving performance, which is expected to reduce the potential risk of collision. The results show that displaying system SA by showing performance will be highly effective to increase driver trust in automation.

Displaying system SA is expected to be useful when designing an automated driving system [19]. If a driver can know the system SA, the driver would perceive the sensor range of the system. When system sensors do not detect traffic objects, the driver can ascertain the system error. Therefore, the knowledge is expected to facilitate driver readiness to back up the system during a system emergency [20], [21]. The facilitation will be valuable for the takeover process [22]–[24]. Furthermore, spatial information can make a driving method more acceptable to drivers [see Fig. 4(j)]. When some drivers prefer longer lateral distance from other objects when passing, the spatial information can reduce driver dissatisfaction without changing the driving method.

This study showed that displaying the system SA increased driver trust in the automated vehicle. Over-trust effects were not investigated in this study. However, the proposed assist method is expected to reduce over-trust because spatial information gives the driver system comprehension for the ongoing traffic situation that would prevent misunderstanding of the system ability. This hypothesis must be investigated in future work.

This study was based on previous work presented in conference proceedings [25]. The previous work presented partial evidence for the effects of the proposed method. The present study, however, revealed how factors contribute to increased driver trust in automated driving. Further analysis and deeper discussions were provided.

V. CONCLUSION

A vibrotactile display for system SA was used to investigate driver trust in automated driving. Three driving methods were considered with the scenes of passing traffic vehicles. Although the sample is narrow and small, the results supported the following conclusions:

1) Spatial vibrotactile information contributes to driver trust in automated vehicles. *Directional* information for approaching vehicles increases driver trust more than *nondirectional* information.
2) The driving method used for passing other traffic objects affects driver trust in automated driving systems. Appropriate lateral distance is best for trust. However, the SA display can compensate for inadequate driving methods.

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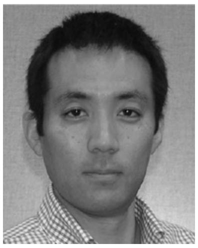

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