

RESEARCH ARTICLE

Effectiveness of Tactile Warning and Voice Command for Enhancing Safety of Drivers

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ABSTRACT Safety is impaired when drivers are required to perform main driving task (tracking of own car, distance maintenance between own car and a leading car, and response to target objects) and secondary task simultaneously, for example, responding to target cars on the road while operating in-vehicle equipment. A two-factor (presence or absence of tactile warning by input modality (no secondary task, voice command for a secondary task, and manual input for a secondary task)) within-subject design of ten licensed males was used to investigate how to compensate for safety impairments (decreased performance of a main and a secondary task such as increased tracking error during driving or increased reaction time to target cars on the road). We investigated whether the use of tactile warnings transmitted via left and right thighs for detecting road objects and voice command to operate in-vehicle equipment could compensate for safety impairments such as the increased reaction time to target cars on the road, the increase of detection error of target cars, or increased tracking error in driving. The accuracy and speed of responses to target cars encountered during driving were reduced when a driver was asked to perform the main and the secondary task simultaneously compared to situations performing only the main driving task (tracking, distance maintenance, and response to target cars). The availability of a tactile warning system for road objects compensated for these diminished performance measures, including slower response times and the increased detection error of target cars. Likewise, voice command contributed to enhanced performance of the main driving task such as decrease of tracking error.

INDEX TERMS Automotive safety, interference of multiple tasks, tactile warning, voice command.

I. INTRODUCTION

The need to perform multiple tasks while driving increases a driver's visual and cognitive workload and substantially complicates the driver-vehicle interaction. Safety will be impaired due to inattentive driving during multi-task performance [1], [2], [3], [4], [5], [6], [7], [8]. The need to perform multiple tasks simultaneously while driving can result in delayed responses to hazardous situations and increased potentials for crashes.

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Visual and auditory perceptions are encountered more frequently while driving than are tactile perceptions. Tactile warnings can alert drivers [9], [10], [11], [12] and prompt rapid reactions to road hazards [13], [14], [15], [16], [17], [18], [19]. Murata *et al.* [13] demonstrated the advantage of tactile versus auditory warnings for drivers operating vehicles in noisy environmental conditions. Therefore, one might anticipate that, in the absence of interfering visual or auditory information, tactile warnings may lead to more rapid responses to road hazards and contribute to driving safety. Viewed from the stimulus input modality, visual warning interferes with a visual hazard and auditory warning interferes

with noise in traffic environment. Tactile warning, on the other hand, does not interfere with a visual hazard or noise in traffic environment. Therefore, the advantage of tactile warning over visual or auditory warning in traffic environment is apparent.

Voice command is another promising technology that can enhance cognitive processing and promote rapid responses than can be achieved with manual responses, most notably when multiple tasks are involved [20], [21], [22], [23], [24], [25]. One's capacity to perform two tasks simultaneously is improved when one task can be addressed with a manual response (i.e., pressing a key or button) and another can be addressed with voice command [24], [25], [26]. Murata [26] investigated the benefit of voice command in a dual-task situation and concluded that the outcomes associated with voice command were superior to those requiring key responses, most notably when the workload of the secondary task was increased. According to multiple resource theory [22], [23], [25], the performance of a secondary task will be improved if the response mode does not interfere with that necessary to accomplish the main task. Therefore, one might anticipate the improved performance of both main and secondary tasks when the latter can be addressed with voice command that does not interfere with the manual responses required by the former (main task).

The following studies demonstrated the effectiveness of voice command. Owens *et al.* [27] evaluated on-road driver performance when performing a secondary task (controlling in-car technology) manually or with voice command, and demonstrated the effectiveness of voice command when conducting a secondary task. Miller *et al.* [28] showed that hybrid display tasks (auditory response and visual display (input)) were completed more quickly than equivalent audio only tasks (auditory response and auditory display (input)). Alvarez *et al.* [29] found that amongst all modalities, voice interfaces were more effective for consulting information while driving.

Ranney *et al.* [30], on the other hand, found that the benefits of the voice-based interface were not large enough to appreciably reduce the distraction potential associated with performing the secondary tasks in a car-following scenario. Although Lee *et al.* [5] did not show the advantage of voice command (voice command was slower than manual input), the overall performance was not impaired when using voice command. These studies never show ineffectiveness of voice command in driving situations. Rather, the studies on the effectiveness of voice command generally seem to show the promising property of voice command under a dual-task driving situation if voice command is used appropriately. Based on the literature review on voice command above, we assumed that voice command was more effective for a secondary task to improve the performance decrement of a main driving task as compared to manual input for a secondary input.

Jung *et al.* [31] proposed a voice interface with touch pad interactions as a superior method for accomplishing

secondary tasks during driving. Although the findings of Jung *et al.* [31] demonstrated the advantages of a secondary task interface that utilized both voice and tactile senses, they investigated only the effect of voice command and tactile display on the secondary task performance and did not explore how these modifications affected driving itself or hazard detection while driving. In other words, they did not examine the effect of tactile warning on both driving task and secondary task.

Based on the discussion above, we attempt to explore the effectiveness of tactile warning and voice command within the framework of S-C-R compatibility [22], [23]. The rationale of using voice command and tactile warning is summarized as Hypotheses 1-5 below (see Figure 1). The cognitive information required to process a target object includes its perception and recognition followed by the appropriate motor responses. According to the S-C-R compatibility principle, performance will be enhanced by avoiding interference between stimulus input modalities, between cognitive (central) processing modalities, and between response (output) modalities.

This study focused on ways to improve driving efficiency (safety) by using tactile warning and voice command when a secondary task (e.g., operating in-vehicle equipment) interfered with the main driving task (tracking, distance maintenance, and response to target cars). Specifically, while verifying Hypotheses 1-5 below, we investigated how the simultaneous use of tactile warnings to detect target cars and voice command to execute a secondary task contributed to compensate for the impaired performance that resulted from performing the two tasks simultaneously to provide some implications for enhancing safety by means of tactile warning and voice command.

II. RESEARCH HYPOTHESES

As mentioned above, tactile warning was superior to visual or auditory warning in response speed and accuracy because of lack of interference of the stimulus input modalities like stimulus (input) modality interference of visual warning with a visual target or that of auditory warning with noise in traffic environment [14], [15], [17]. In Hypothesis 1, therefore, we assume that tactile warning would promote rapid responses to target cars on the road because of the absence of the interference between stimulus modalities associated with a visual object (visual target car and visual warning to this target).

Avoidance of stimulus modality competition between visual warning and visual attention to a target car by tactile warning does not mitigate other activities such as tracking (visual stimulus modality) and maintenance of distance between own car and leading car (visual stimulus modality) necessary for the main driving task, because resource competition for central processing among the three spatial activities (tracking, distance maintenance, and responses to target cars) during the main driving task cannot be mitigated by avoidance of stimulus modality competition by tactile warning. Therefore, it is expected that tactile warning does

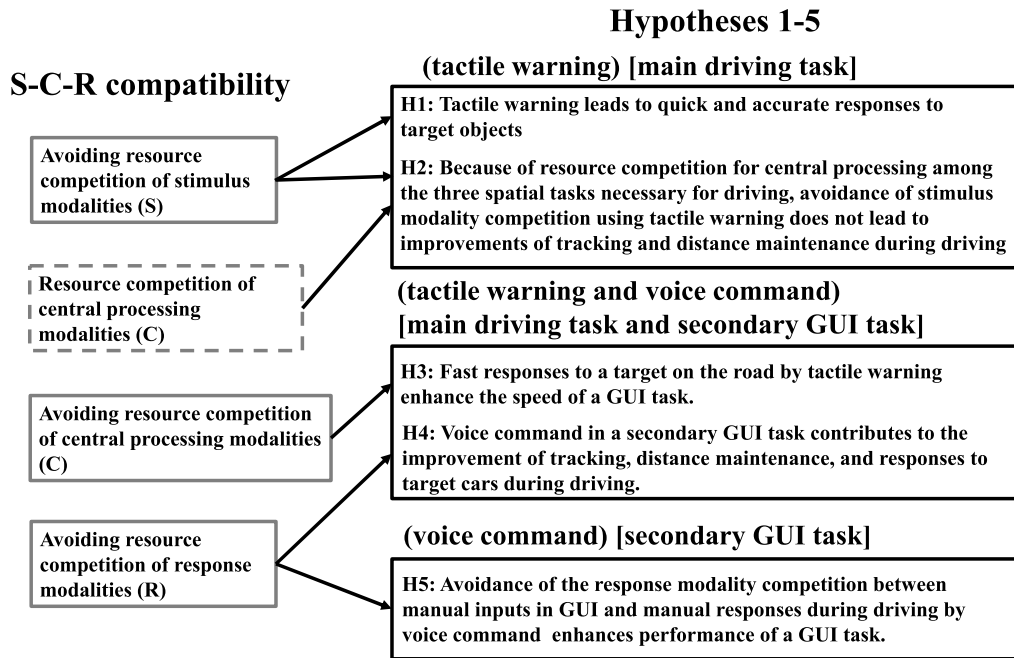


FIGURE 1. Hypotheses 1-5 based on the framework of stimulus-central processing-response (S-C-R) compatibility.

not improve the performance of tracking task and maintenance of appropriate distance between own and the leading cars (Hypothesis 2). It must be noted that Hypotheses 1-2 are related to the main driving task (tracking, distance maintenance, and response to a target car) and tactile warning.

There is no resource competition for central processing between a secondary graphical user interface (GUI) task (verbal processing) and a reaction task to target cars on the road (spatial processing), because the former is verbal and the latter corresponds to a spatial task. Therefore, it is expected that fast spatial response to target cars on the road by tactile warning will enhance the performance of a GUI task irrespective of whether a GUI task is performed either manually or with voice command (Hypothesis 3).

The S-C-R compatibility principle also assumes that simultaneous performance of the main driving task and the secondary task with manual responses represents a case of interfering response modalities and such an interference will lead to impaired performance (safety), including an increase in the tracking errors and a decrease in the fraction of time spent at the appropriate distance from the leading car. Therefore, it is expected that the use of voice command for a secondary task would eliminate the interference between the two manual response modalities (manual driving and manual response to a GUI task) and thus might compensate for performance (safety) impairments associated with the main driving task in a multi-task situation. When voice commands are used to perform a secondary task, this interference does not occur. Therefore, we anticipate that voice command results in improvements in efficiency of the main driving task in a multi-task situation. This hypothesis is also supported by past findings [24], [26], [27], [28], [29], [30] that voice commands

were effective under a multi-task situation. Therefore, it is expected that avoidance of response modality competition between manual input to a GUI task and manual tracking, manual distance maintenance and manual response to target cars enhances performances of tracking, distance maintenance, and response to target cars on the road and contributes to the improvement of the three tasks related to driving (Hypothesis 4).

It is also expected that avoidance of the response modality competition above by voice command enhances performance of a GUI task itself (Hypothesis 5). This hypothesis is concerned with only the secondary GUI task and voice command.

III. METHODS

A. PARTICIPANTS

Ten healthy 21–23-year-old males (graduate or undergraduate students) were recruited from Dept. of Intelligent Systems, Okayama University and participated in the experiment. All participants were licensed drivers for 1–5 years. All participants provided written informed consent after receiving a brief explanation of the aim and content of the experiment. The experiment was approved by the Ethical Committee, Department of Intelligent Mechanical Systems, Okayama University, Japan (Approval No.2019-sys-04). Although only male participants took part in the experiment, we judged that gender difference would not affect the results and the research hypotheses 1-5.

B. APPARATUS

A steering controller (Logicool, LPRC-14000) was connected to a personal computer (PC) (CPU, Intel Core2 Quad

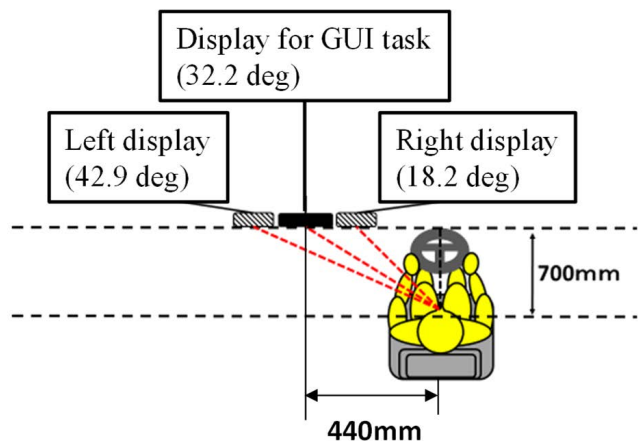


FIGURE 2. Approximate layouts of in-vehicle displays and display of GUI task.

Q9400 2.66GHz; GPU, NVIDIA GeForce GTX650, 4GB) which permitted the participants to direct the car on the simulated driving display. We used the PC, a graphic box for multiple-monitor outputs (Matrox, TripleHead2Go digital edition), and a projector (EPSON, EB-S04) to display a simulated main driving task. Participants were required to maintain velocity within the speed limit of 80 km/h and to maintain a specific distance between their cars and the leading cars using the accelerator and the brake pedal of the steering controller. We developed the driving simulator using Hot Soup Processor 3.4. Four tactors with a diameter of 45 mm (Acouve Laboratory Inc., Vp216) were used for tactile warning. According to Murata *et al.* [13], the vibration frequency of tactor was set to 64 Hz with an amplitude of 10 Vp-p. The tactors were installed on the surface of the driver’s seat according to Murata *et al.* [13] so that the vibration could be transmitted via left and right thighs. The SOA (Stimulus Onset Asynchrony) and the duration of tactile stimulation were set to 1 s and 1 s, respectively, according to Murata *et al.* [13]. The SOA of 1 s meant that a warning was presented to the participant 1 s before a target car appeared.

The approximate layouts of the in-vehicle displays and the GUI task are shown in Figure 2. As Japanese driver’s seats are located on the right, the driver seat was located on the right as shown in Figure 2. Two 7-inch liquid crystal display (LCDs) (ADOTECHNO, LDC7620) were used to replace both the left and the right side mirror; these were used to carry out detection tasks of target cars. The horizontal distance between an individual participant’s eye and the 7-inch in-vehicle display was about 700 mm. The experimental task for detection of target cars developed using Hot Soup Processor 3.4 facilitated the recording of performance data that included task completion time and driver errors. A 10-inch touch panel (Century, LCD-10000HT) was placed as shown in Figure 2 and used to carry out the GUI task (i.e., secondary task). We developed the GUI task using Hot Soup Processor 3.4 to record task completion time and driver error.

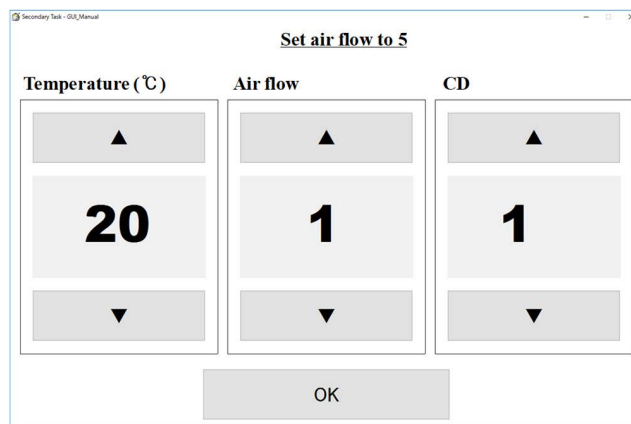


FIGURE 3. Example of the display used for a GUI task.

C. TASKS

Participants were required to perform a simulated main driving task (including tracking, distance maintenance, and response to target cars) with or without a secondary task (GUI task) (see Figure 3) as accurately and rapidly as possible.

Our study involved two tasks, including the main driving task (tracking, distance maintenance, and response to target cars) and the secondary task (GUI task). There were three lanes on the display of driving simulator. In the main driving task, participants were required to drive a middle lane, follow a leading car and suppress the deviation of own car from the center of the 2nd (center) lane as much as possible. Speed was to be maintained at a constant 80 km/h based on readouts provided by a display. Participants were instructed to maintain a distance of 60–100 m between their cars and the leading car. Each participant was informed that he was maintaining an appropriate distance by the display of a green rectangular frame around the image of the leading car. If the distance between the cars fell below 60 m or exceeded 100 m, the participant was informed of this change in status by a change in the color of the rectangular frame.

For the detection task of target cars, each participant was instructed to identify a specified car that was displayed on the in-vehicle monitor located near the display for the GUI task (secondary task) by pressing a button located on the right side of the steering wheel (see Figure 2). The decision to place the in-vehicle monitors at the side mirrors near the display of the GUI task was based on previous studies [32], [33]. Potentially dangerous situation occurs also in front of the vehicle. The reaction to a front or rear object is shown to be based on nearly the same protocol [34]. Moreover, we judged that the attentive level in front of own car could be assessed by the percentage of time spent at the appropriate distance. Therefore, this study dealt with only the rear target. The detection task of target cars behind own car proceeded as follows: While driving in the second (middle) lane, participants encountered a white, a black, or a red sedan that appeared randomly from the rear of the participant’s car in either the first (left) or the third (right) lane and that eventually passed the participant’s car. The approaching cars caught up with the participant’s car

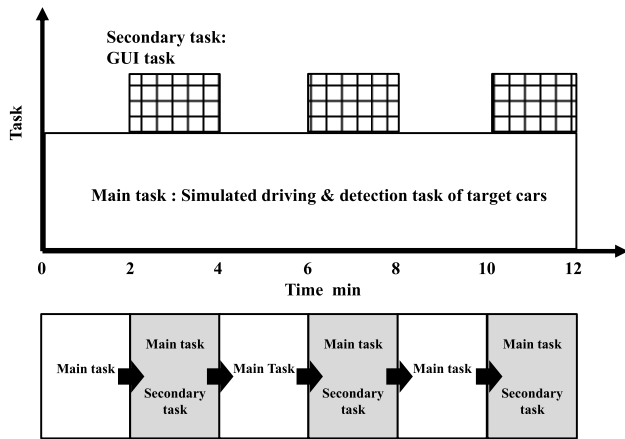


FIGURE 4. Explanation of the overlaps used to examine the impact of interference on the main task (driving task and detection task of target cars) and the GUI task (secondary task).

6 seconds after their appearance. These target cars appeared randomly six times for 6 seconds each in either the left or the right lane, which resulted in encounters with 36 cars (3 types \times 12 cars per type) during a single experimental session. The duration of one experimental session was 12 minutes for all four conditions noted above. Participants were asked to report the detection of the red sedan (the target car) as soon as it appeared in either the left or the right lanes by pressing a button located on the right side of the steering wheel. It must be noted that tactile warning activated not for all cars but only for the target vehicle. Although this detection task based on the color of the following (approaching) car may not be representative of and reflect actual hazards detected during driving, this experimental design that facilitated rapid and accurate detection of a target car was appropriate for the assessment of attentional level during a main driving task.

An example of secondary task (GUI task) is shown in Figure 3. Participants were instructed to perform one of the following three GUI tasks for the overlapping condition in Figure 4, including adjusting the automobile temperature or airflow or selecting music on the in-vehicle compact disc (CD) player. In one set of experiments, the participants used a manual response mode to perform one of the three aforementioned functions. Specifically, they needed to touch the upward- or the downward-pointing arrows on the display to increase or decrease the temperature or airflow or to change the CD track. Participants must then press the “OK” button when the GUI task was completed. When using the voice command, the participant’s voices were registered in the voice dictionary with recognized terms including “temperature,” “flow,” “CD,” “up,” “down,” and “OK.” Participants were then asked to perform a secondary task using the registered voice. This task was repeated for 2 min as shown in Figure 4.

The main and the secondary task do not always overlap with one another in real-world driving situations, and overlap can occur unexpectedly. Secondary tasks are usually discrete events and can result in unexpected interference with the main

driving task (tracking, distance maintenance, and response to target cars). Significant overlap of these two tasks might impair driving safety. Previous studies (for example, [21], [26], [35]), however, did not control for the potential overlap of two tasks. Wickens *et al.* [21] and Murata [26] used a continuous task as a main task and a discrete task as a secondary task, and investigated the effects of voice command or manual input to a secondary task on the dual task performance. The dual-task condition of these studied included both temporal overlap of the main (continuous) and the secondary (discrete) task (both tasks were simultaneously conducted) and temporal non-overlap of both tasks (only a main task was conducted), and regarded both temporal overlap and non-overlap as a dual task condition. It is desirable that only the temporal overlap is analyzed as a dual-task condition. Therefore, our study used an experimental design that controlled the temporal overlap of the main and the secondary task as shown in Figure 4.

The experiments were carried out for the following four conditions that consisted of the presence or absence of tactile warning and input modality of secondary task (voice command or manual input). In other words, experiments included (I) a simultaneous dual-task situation with tactile warning for the detection of target cars and voice command for the secondary task, (II) a simultaneous dual-task situation with tactile warning for the detection of target cars and manual input for the secondary task, (III) a simultaneous dual-task situation without tactile warning for the detection of target cars and with voice command for the secondary task, and (IV) a simultaneous dual-task situation without tactile warning for the detection of target cars and with manual input for the secondary task. To characterize the safety impairments resulting from the overlap of the main and the secondary task, we controlled the overlap and non-overlap of two tasks as shown in Figure 4. It must be noted that each experiment included both the overlap and the non-overlap condition of the main and the secondary task as shown in Figure 4.

Although the above four experiments were conducted, there were actually the following six conditions (presence or absence of tactile warning (two levels) by input modality (three levels: no secondary task (non-overlap), voice command for the secondary task, and manual input for the secondary task): (i) non-overlap with tactile warnings for detecting target cars, (ii) non-overlap without tactile warnings for detecting target cars, (iii) overlap with tactile warnings for detecting target cars and voice command for the secondary task, (iv) overlap with tactile warnings for detecting target cars and manual input for the secondary task, (v) overlap without tactile warnings for detecting target cars but with voice command for the secondary task, and (vi) overlap without tactile warnings but with manual input for the secondary task.

D. DESIGN AND PROCEDURE

The experimental design included two independent within-subject factors. The first factor (independent variable) was the

presence or absence of tactile warnings for detection of target cars. The second factor (independent variable) was the input modality (no secondary task, voice command for the secondary task, and manual input for the secondary task). The dependent variables were the tracking error, the percentage of time during which appropriate distances from the leading car were maintained, the reaction time to target cars on the road, the detection error of target cars, and the subjective ratings of concentration and situational awareness (For more detail, see E. Evaluation measures).

The participants were permitted to adjust the seat so that they could perform the experimental tasks comfortably. After receiving a brief explanation of the main driving task and the secondary task as described above, the participant was provided with time to practice performing the two tasks separately and simultaneously. No limits were imposed on practice time. Participants were permitted to continue practicing with the experimental set-up until they reported that they completely understood and were capable of performing the two tasks as requested. They practiced a single main driving task, a single secondary task, and simultaneously both a main driving and a secondary task. The duration of the practice sessions differed among participants, ranging from 25–35 minutes in length. An investigator recorded the performance data from the practice session and confirmed that there was no association between the duration of the practice session and participant performance during the experiment. The practice data were excluded from the further analysis. The experimental trial began after the investigator confirmed that the participant reported a full understanding of the tasks involved. The learning process was evaluated and the experiment was initiated while suppressing the learning effect to a minimum.

As shown in Figure 4, the presence or absence of the overlap alternated every 2 min during each experimental session. Participants were informed in advance of the alternating overlapping and non-overlapping experimental conditions. Twelve minutes were required to complete each of four experiments (I)-(IV) mentioned in C.Tasks. Each subject participated in four experiments (I)-(IV) (i.e., presence or absence of tactile warnings (two levels)) combined with input modality of secondary task (two levels: manual input for a secondary task, and voice command for a secondary task). Under the dual-task condition, the participants were required to pay attention to both the display of driving simulator and that of GUI task. As soon as the experiment started, the secondary task to be performed such as shown in Figure 3 was presented to the participant via the display shown in Figure 2. Immediately after one trial was over, the next task was presented to the participant until the end of one session. The order in which each of the four experiments was introduced was randomized across the participants. Participants were asked to perform the main driving task alone (i)-(ii) mentioned in C.Tasks) or the main driving task simultaneously with secondary task ((iii)-(vi) mentioned in C.Tasks) as rapidly and accurately as possible during the 12 minutes allotted for each of the four

experiments. The participants were provided with a 5 min break between experiments.

E. EVALUATION MEASURES

Tracking error, which represents the absolute deviation of the participant's car from the center of the driving lane (middle lane out of the three lanes), was used to evaluate performance. Tracking error was recorded every 100 ms. Tracking error corresponded to the aggregated absolute deviation from the center of the middle lane across all of the relevant epochs.

The participant was also required to maintain an appropriate 60–100 m distance between own car and the leading car. This distance was also recorded every 100 ms. The percentage of time in which an appropriate distance between the two cars was maintained was calculated as the duration during which appropriate car distance was maintained divided by the total duration of the experiment (12 min).

From the perspective of road safety, conditions that facilitate more rapid and accurate responses to any given road hazard are desirable outcomes. Overlooking a hazard while driving suggests an inattentive state and thus represents an undesirable event. The time that elapsed from the appearance of a target car on either the left or the right of the participant's car until the response button was pressed was measured as the reaction time.

A total of 72 cars emerged either to the left (36 cars) or to the right (36 cars) of the participant's car during one experimental session. Among these 72 cars, the target car (red sedan) appeared randomly 12 times to the left and 12 times to the right of the participant's car. The participant was required to detect the target car while it was on the left or right display. When the participant could not detect the target car until the participant's car was overtaken by the target car, this was regarded as a detection error. The percentage detection error by each participant was calculated for either left or right side of own car as the ratio of the number of target cars not detected to the total number of target cars ($n = 12$).

The task completion time and the error trials were used as performance measures in the GUI task. At the end of each experiment, the participant was asked to provide a subjective rating on his state of concentration while driving. The scores were recorded on a five-point scale from (1) unable to concentrate on driving at all under these conditions to (5) able to concentrate sufficiently on driving under these conditions. They were also asked to score their ease of situational awareness during a task under these conditions, with scores from (1) indicating that it was very difficult to maintain situational awareness to (5) indicating that it was very easy to maintain situational awareness. It must be noted that the participants were asked to report subjective ratings of concentration and situational awareness not only for the four experimental conditions (iii)-(vi) (overlap) but for the two experimental conditions (i)-(ii) (non-overlap (without secondary task) with and without tactile warning) above mentioned (see Figure 3).

TABLE 1. Results of two-way ANOVAs conducted on the tracking error.

	<i>F</i>	Power of the test
Tactile warning	$F(1,9)=0.124$	0.061
Input modality of secondary task	$F(2,18)=49.608^{**}$	1.000
Tactile warning x GUI task	$F(2,18)=0.338$	0.095

**: $p<0.01$

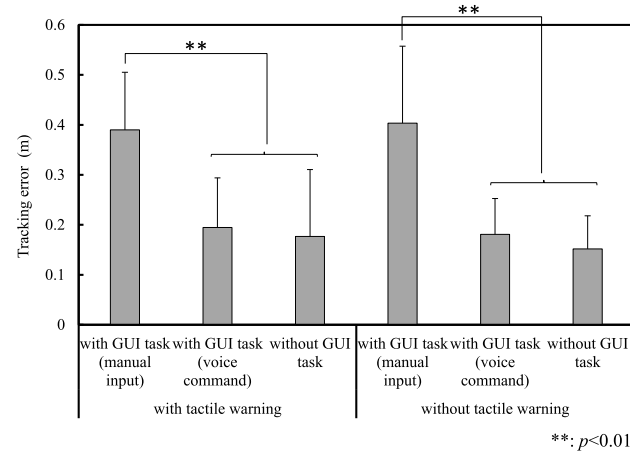


FIGURE 5. Tracking error recorded in the presence or absence of tactile warnings and input modality (no secondary task, secondary task with manual input, secondary task with voice command).

IV. RESULTS

A. TRACKING ERROR

A two-way (the presence or absence of tactile warnings by input modality (three levels: no secondary task, manual input to a secondary task, and voice command to a secondary task)) analysis of variance (ANOVA) was carried out on the tracking errors. The results of the ANOVA are summarized in Table 1. The ANOVA for the tracking error revealed only a significant main effect of input modality, and no significant interaction was detected.

In Figure 5, the tracking error is plotted as a function of the presence or absence of tactile warnings to target cars on the road and the input modality. Tracking error was significantly impaired when the secondary task performed with manual responses interfered with the performance of main driving task (tracking, distance maintenance, and response to target cars). Tracking error was reduced when the secondary task was executed with voice command. As shown in Figure 5 and Table 1, tactile warnings that indicated target cars on the road had no impact on improving the tracking errors.

B. PERCENTAGE OF TIME SPENT AT THE APPROPRIATE DISTANCE FROM THE LEADING CAR

A two-way ANOVA (the presence or absence of tactile warnings by input modality (three levels: no secondary task, manual input to a secondary task, and voice command to a secondary task)) was conducted on the percentage of time spent at the appropriate distance (60–100 m) from the leading car. The results of the ANOVA are summarized in Table 2.

TABLE 2. Results of two-way anovas conducted on the percentage appropriate car distance.

	<i>F</i>	Power of the test
Tactile warning	$F(1,9)=0.207$	0.069
Input modality of secondary task	$F(2,18)=6.812^{**}$	0.877
Tactile warning x GUI task	$F(2,18)=1.309$	0.239

**: $p<0.01$

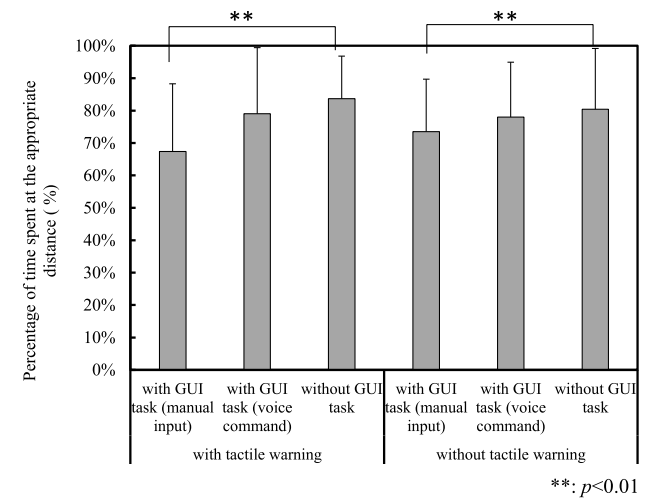


FIGURE 6. Percentage of time during which appropriate distance from the leading car was maintained in the presence or absence of a tactile warning and input modality (no secondary task, secondary task with manual input, secondary task with voice command).

The ANOVA for this evaluation measure revealed only a significant main effect of input modality, and no significant interaction was detected.

Figure 6 shows the percentage of time spent at the appropriate distance from the leading car as a function of the presence or absence of tactile warning and the input modality. When the performance of secondary task interfered with that of the main driving task (tracking, distance maintenance, and response to target cars), this specific safety measure was impaired. Similar to our findings on tracking error, the percentage of time spent at the appropriate distance from the leading car improved when secondary task was performed using voice command. The tactile warnings for the detection of target cars in the main driving task also had no impact on this evaluation measure (Table 2).

C. REACTION TIMES TO TARGET CARS

A two-way (the presence or absence of tactile warnings by input modality (three levels: no secondary task, manual input to a secondary task, and voice command to a secondary task)) ANOVA was conducted on the reaction times to target cars presented to both the right and left sides of the participant’s car. The results are summarized in Table 3. The ANOVA for this evaluation measure revealed significant main effects of presence or absence of tactile warning and input modality, and no significant interaction was detected.

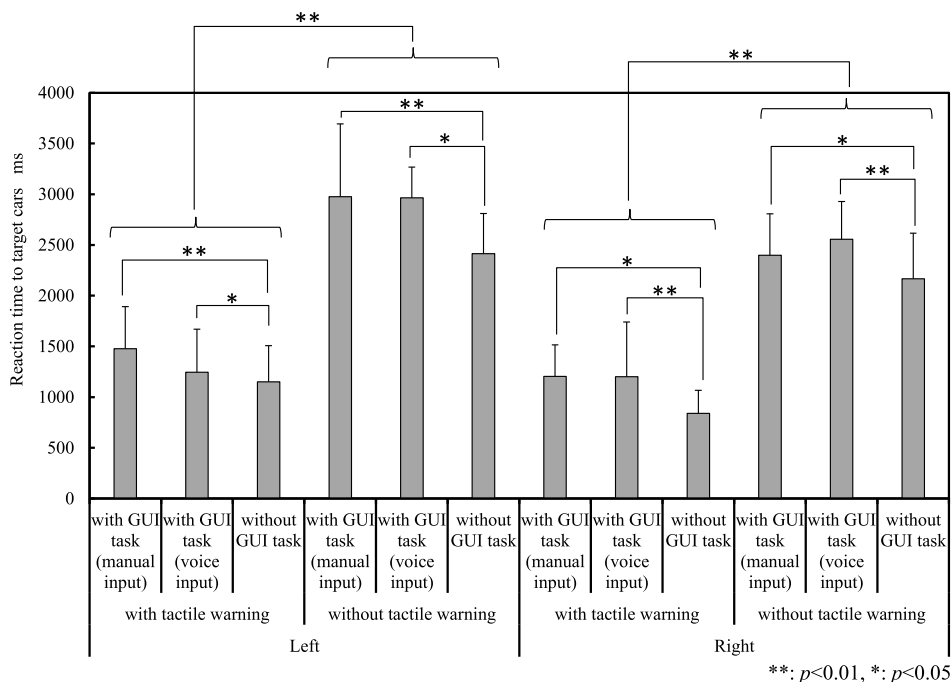


FIGURE 7. Reaction times (ms) in the presence or absence of tactile warnings and input modality (no secondary task, secondary task with manual input, secondary task with voice command).

TABLE 3. Results of two-way anovas conducted on the reaction time.

Reaction time (Left)		
	F	Power of the test
Tactile warning	$F(1,9)=101.887^{**}$	1.000
Input modality of secondary task	$F(2,18)=7.153^{**}$	0.894
Tactile warning x GUI task	$F(2,18)=2.075$	0.360
**.: $p < 0.01$		
Reaction time (Right)		
	F	Power of the test
Tactile warning	$F(1,9)=213.871^{**}$	1.000
Input modality of secondary task	$F(2,18)=8.584^{**}$	0.945
Tactile warning x GUI task	$F(2,18)=0.207$	0.077
**.: $p < 0.01$		

In Figure 7, reaction times are plotted as a function of the presence or absence of tactile warnings and the input modality. The reaction time increased on both the left and the right side when secondary task interfered with the main driving task (tracking, distance maintenance, and response to target cars). Mitigation of safety impairments by tactile warning was more profound when the performance of secondary task interfered with the performance of the main driving task (tracking, distance maintenance, and response to target cars) than in the absence of secondary task.

D. DETECTION ERROR OF TARGET CARS

A two-way ANOVA (the presence or absence of tactile warnings by input modality (three levels: no secondary task, manual input to a secondary task, and voice command to a secondary task)) was conducted on the detection error of target cars on the left or right side. The results are summarized

TABLE 4. Results of two-way anovas conducted on the percentage of target cars that were overlooked.

Percentage hazards overlooked (Left)		
	F	Power of the test
Tactile warning	$F(1,9)=21.931^{**}$	0.990
Input modality of secondary task	$F(2,18)=7.019^{**}$	0.887
Tactile warning x GUI task	$F(2,18)=4.631^*$	0.708
**.: $p < 0.01$, *: $p < 0.05$		
Percentage hazards overlooked (Right)		
	F	Power of the test
Tactile warning	$F(1,9)=8.486^*$	0.743
Input modality of secondary task	$F(2,18)=1.877$	0.329
Tactile warning x GUI task	$F(2,18)=1.943$	0.339
**.: $p < 0.01$, *: $p < 0.05$		

in Table 4. The ANOVA for this evaluation measure revealed significant main effects of presence or absence of tactile warning and input modality and a significant interaction.

In Figure 8, the detection error of target cars is plotted as a function of presence or absence of tactile warning and the input modality. The use of tactile warnings resulted in major improvements of detection error for both conditions with and without a secondary task. A significant interaction between the presence or absence of tactile warnings and the input modality can be interpreted as follows. While the input modality (no secondary task, voice command, and manual input) of a secondary GUI task did not affect the detection error of target cars when the tactile warning was present for the detection of target cars, the improvements in detection error of target cars associated with the absence of tactile warning were significantly larger (in order) in cases in which

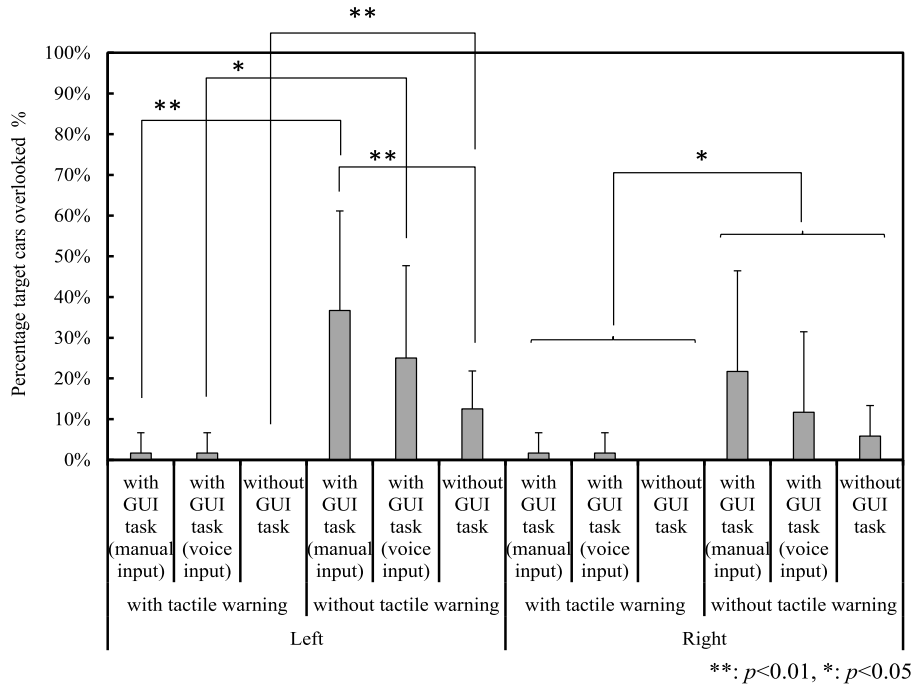


FIGURE 8. Detection error of target cars in the presence or absence of tactile warning and input modality (no secondary task, secondary task with manual input, secondary task with voice command).

the secondary task was conducted with manual input, cases in which the secondary task was conducted with voice command, and when the secondary task was not conducted.

E. TASK COMPLETION TIME AND PERCENTAGE CORRECT RESPONSES IN THE GUI TASK

A two-way ANOVA (presence or absence of tactile warning by input modality of secondary task (manual input or voice command)) was carried out on the task completion time of secondary task. Only the main effect of the presence or absence of tactile warning ($F(1, 9) = 18.278, p < 0.01$, power of the test: 0.986) was detected. The task completion time is shown as a function of presence or absence of tactile warning and the input modality (voice command or manual input) in the secondary GUI task in Figure 9. Throughout the two-way ANOVAs for A to E, the powers of the presence or absence of tactile warning and the input modality of secondary task were high enough to verify the validity of the results.

When the secondary task was conducted using voice command, the mean percentage correct answers with and without tactile warning were 93.81% (SD: 3.97%) and 94.62% (SD: 1.36%), respectively. As for the secondary task conducted using manual input, the mean percentage correct answers with and without tactile warning were 95.71% (SD: 2.54%) and 95.94% (SD: 3.14%), respectively. A similar ANOVA conducted on the mean percentage correct answers revealed no significant main effects and interaction. These results indicate that while tactile warning contributed to more rapid responses when performing the GUI tasks, the voice command did not accelerate the pace of the GUI task.

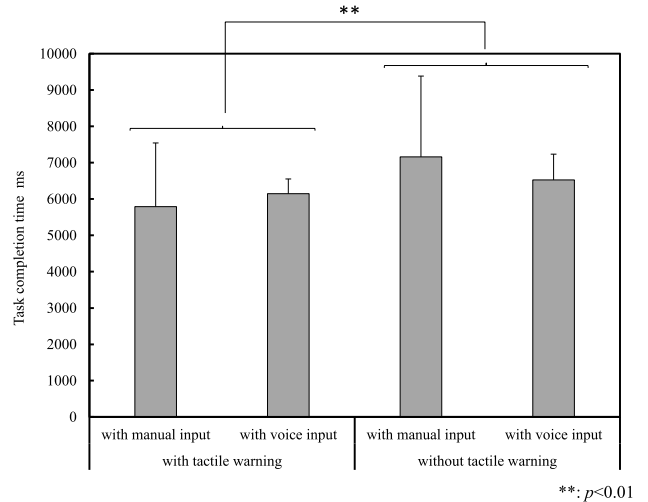


FIGURE 9. Task completion time in the GUI task as a function of the presence or absence of tactile warning and input modality (manual input or voice command).

F. SUBJECTIVE RATINGS ON DRIVER CONCENTRATION AND SITUATIONAL AWARENESS

We evaluated the subjective ratings provided by the participants on conditions for secondary task that included tactile warnings with voice command, tactile warnings without voice command (with manual input), no tactile warnings but with voice command, and no tactile warnings without voice command (with manual input) using a Scheffe’s multiple comparison (see Table 5(1)). The subjective ratings

TABLE 5. Results of non-parametric tests conducted on the subjective ratings on concentration during driving.

(1) Scheffe's multiple comparison (with GUI task)				
	(a)	(b)	(c)	(d)
with tactile warning	(a) with voice command			
	(b) without voice command	n.s.		
without tactile warning	(c) with voice command	*	n.s.	
	(d) without voice command	**	n.s.	n.s.

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

(2) Wilcoxon signed-rank test (without GUI task)		
	<i>z</i>	<i>p</i>
with tactile warning vs without tactile warning	1.955	0.051

(3) Scheffe's multiple comparison				
	(a)	(b)	(c)	(d)
with tactile warning	(a) with GUI task			
	(b) without GUI task	*		
without tactile warning	(c) with GUI task	*	**	
	(d) without GUI task	n.s.	n.s.	**

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

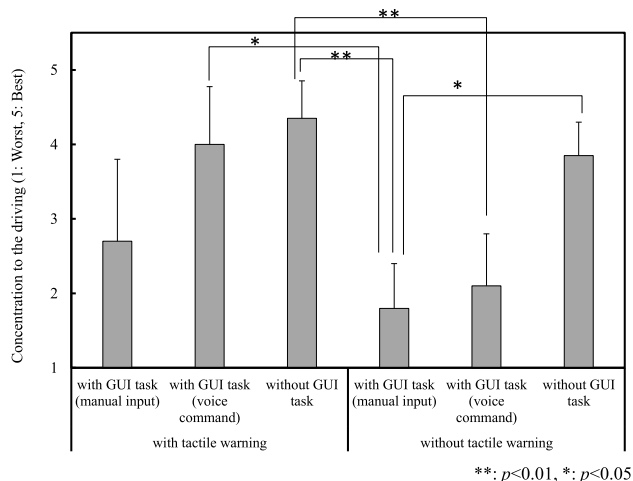


FIGURE 10. Subjective ratings of participant's concentration while driving as a function of presence or absence of tactile warning and input modality (no secondary task, secondary task with manual input, secondary task with voice command).

for driver concentration were evaluated with a focus on the presence and absence of tactile warning using a Wilcoxon non-parametric test when no secondary task was executed (see Table 5(2)). The subjective ratings on driver concentration were compared to one another for conditions that included tactile warnings with secondary task, tactile warnings without secondary task, no tactile warnings with secondary task, and no tactile warnings without secondary task using a Scheffe's multiple comparison (see Table 5(3)).

The results of the analyses for the concentration ratings are summarized in Table 5. Figure 10 corresponds to the subjective concentration ratings plotted as a function of the presence or absence of tactile warning and the input modality (no secondary task, manual input to a secondary task, and voice command to a secondary task). Similar results of

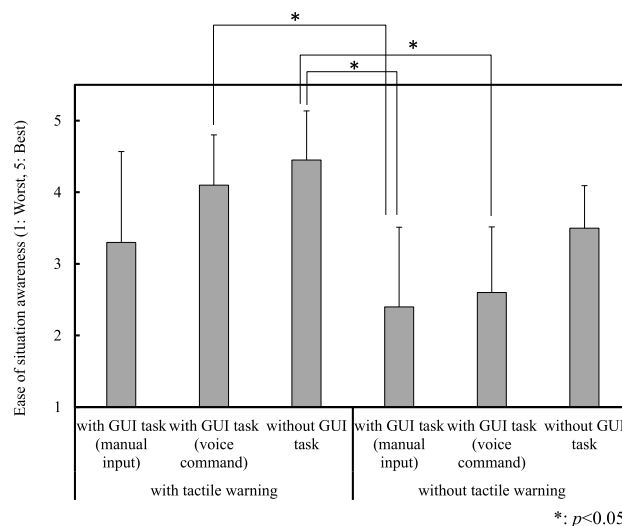


FIGURE 11. Subjective ratings of participant effort required to maintain situational awareness during driving as a function of presence or absence of tactile warnings and input modality (no secondary task, secondary task with manual input, secondary task with voice command).

TABLE 6. Results of non-parametric tests conducted on the subjective ratings of participant effort required to maintain situational awareness during driving.

(1) Scheffe's multiple comparison (with GUI task)				
	(a)	(b)	(c)	(d)
with tactile warning	(a) with voice command			
	(b) without voice command	n.s.		
without tactile warning	(c) with voice command	*	n.s.	
	(d) without voice command	**	n.s.	n.s.

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

(2) Wilcoxon signed-rank test (without GUI task)	
	<i>z</i>
with tactile warning vs without tactile warning	2.366**

**: $p < 0.01$

(3) Scheffe's multiple comparison				
	(a)	(b)	(c)	(d)
with tactile warning	(a) with GUI task			
	(b) without GUI task	n.s.		
without tactile warning	(c) with GUI task	*	**	
	(d) without GUI task	n.s.	*	*

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

statistical tests performed to evaluate the subjective ratings of situational awareness are shown in Table 6. In Figure 11, these subjective ratings were plotted as a function of the presence or absence of tactile warning and the input modality (no secondary task, manual input to a secondary task, and voice command to a secondary task).

For both sets of subjective ratings (i.e., driver concentration (Figure 10) and situational awareness (Figure 11)), several important tendencies were observed. When secondary task interfered with the performance of the main driving task (tracking, distance maintenance, and response to target cars), both driver concentration and situational awareness were impaired. In such a situation, tactile warnings improved both concentration and situational awareness. Moreover, concentration and situational awareness increased when tactile warnings were combined with voice command in the secondary task.

V. DISCUSSION

Hypotheses 1 (see Figure 1) were related to tactile warning and the main driving task. Hypothesis 1 refers to avoidance of stimulus modality competition by tactile warning and predicts that quick and accurate responses to target cars on the road are promoted by tactile warning. As suggested by past studies [10], [11], [12], Hypothesis 1 was verified as shown in Figures 7 and 8. Although the responses to target cars cannot be necessarily regarded as responses to road hazards, quick responses to target cars are expected to lead to quick and accurate responses even to road hazards.

Hypothesis 2, that is also related to tactile warning and the main driving task, predicts that fast responses to target cars do not improve the efficiency of other driving activity such as tracking and distance maintenance, although rapid responses to target cars was promoted by tactile warning as verified above. As shown in Figures 5 and 6, tactile warning did not contribute to the mitigation of spatial processing competition among tracking, distance maintenance, and responses to target cars during driving, which verified Hypothesis 2.

Hypothesis 3 includes the concept of resource competition for central processing and is concerned with both tactile warning and voice command. There is no resource competition for central processing between a secondary GUI task (verbal processing) and a reaction task to target cars on the road (spatial processing). As shown in Figure 9, fast responses to target cars by tactile warning led to fast responses in the GUI task, which was in support of Hypothesis 3.

Hypothesis 4 is related to voice command and tactile warning and avoidance of response modality competition between manual input to a GUI task and manual responses during driving such as manual tracking or distance maintenance, and predicts that avoidance of response modality competition by voice command in a secondary GUI task will contribute to the improvement of the main driving task. Voice command contributed to the decrease of tracking error and the increase of percentage of time at the appropriate distance, which verified Hypothesis 4 (see Figures 5 and 6). This result corresponds well with Owens *et al.* [27], Miller *et al.* [28], and Alvarez *et al.* [29] that verified the effectiveness of voice command under a dual-task condition. On the other hand, voice command did not further contribute to quick and accurate responses to target cars on the road (see Figure 7 and 8) except for the data that the reaction time on the left side was higher when the GUI task was performed with voice command than when it was performed manually. This result must indicate that voice command for a secondary GUI task does not improve the speed and accuracy of target detection in the main driving task. Since the speed and accuracy of target detection was improved to a larger extent by tactile warning, there must be no room for improving the target detection efficiency by voice command.

Hypothesis 5 is concerned with voice command and the GUI task, and predicts that avoidance of the response modality competition between manual inputs in GUI tasks and

manual responses during driving will enhance performance of a GUI task itself. Voice command did not lead to more quick and accurate response in a GUI task than manual input, which did not support Hypothesis 5 (see IV.RESULTS, E and Figure 9). The GUI task must have been too simple to demonstrate an advantage of voice command over manual input. However, it must be noted that the advantage of voice command over manual input appeared not in the secondary GUI task (Figure 8) and the response to a target car (Figures 6 and 7) but in the tracking error (Figure 4) and the distance maintenance (Figure 5). While Owens *et al.* [27], Miller *et al.* [28], Alvarez *et al.* [29], and Jung *et al.* [31] demonstrated that voice command is effective under a dual-task condition, a few studies such as Lee *et al.* [5] and Ranney *et al.* [30] are skeptic about the effectiveness of voice command. This must indicate that voice command is not always effective and that the effectiveness depend on the situation. The future research should take the workload of a secondary GUI task into account and examine whether the advantage of voice command over manual input is observed when the workload of GUI task is higher than that in this study.

Tactile warnings contributed to more rapid and accurate responses to target cars irrespective of absence or presence of a secondary task (see Figures 7 and 8) and faster responses in a GUI task (Figure 9) according to Hypotheses 1 and 3, respectively. Hypothesis 3 is also regarded as representing an interaction between the main driving task and the secondary GUI task. While voice command contributed to reductions in tracking errors and increased the percentage of time spent at an appropriate distance from a leading car as shown according to Hypothesis 4, voice command did not contribute to the improvements of response speed and accuracy to target cars during the main driving task.

As already mentioned, tactile warning improved speed and accuracy of response to target cars and the speed of secondary GUI task and voice command improved tracking error and percentage of appropriate distance maintenance. In short, tactile warning and voice command differently contributed to improvements of impaired safety. It must be noted that unlike these results, both voice command and tactile warning contributed to enhance subjective ratings of concentration and situational awareness during driving.

As far as this study is concerned, appropriate countermeasures to prevent performance decrements potentially leading to a crash are to prevent competitions of stimulus modalities and competitions of central processing modalities by tactile warning (based on Hypotheses 1 and 3) and to prevent competition of response modalities by voice command (based on Hypothesis 4). This indicates that tactile warning and voice command should be used for different effects based on Hypotheses 1 and 3 (performance enhancement of responses to target cars and secondary GUI task by tactile warning) and Hypothesis 4 (performance enhancement of tracking and distance maintenance by voice command), respectively.

The limitations of this study can be summarized as follows. The detection of target cars in this study is different from real-world situations to detect hazards. As a hazard appears unexpectedly in a real-world situation, this study might not reflect such a situation. However, it must be noted that the decrement of response speed and accuracy to target cars potentially leads to slow and inaccurate responses to a hazard that appears unexpectedly. More realistic scenarios of hazard detection would be necessary in future research. Although the result of this study was obtained in a quiet experimental setting and without recognition error of voice command, the recognition accuracy of voice command is expected to decrease under noisy environment. Potentially dangerous situations can also occur even in front of vehicle. Future work should use both front and rear dangers (target cars) to enhance the generalizability of the results. As the actual workload in a real-world driving situation must be different from that in this study, we should investigate whether the results are applicable to a real-world situation. Increasing the sample size, future work should also be conducted to verify the results for other populations such as female participants or older adults.

VI. CONCLUSION

This study attempted to investigate how the performance decrements (such as increase of reaction time to a target car and detection error of target cars) resulting from the interference of a main driving task (tracking, distance maintenance, and response to target cars) and a secondary task were mitigated by tactile warning and voice command. The performance measures corresponded to (A) the detection speed and accuracy of target cars during the main driving task, (B) the tracking error during the main driving task, (C) the percentage of time spent at the appropriate distance during the main driving, and (D) the speed and accuracy of secondary GUI task.

(1) Tactile warning and voice command did not jointly but separately contributed to the improvement of these performance measures (A)–(D).

(2) Tactile warning contributed to the improvement of measures (A) and (D).

(3) Voice command enhanced the measures (B) and (C).

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