Effects of Auditory and Tactile Warning on Drivers' Response to Hazard Under Noisy Environment

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Abstract. If the warning signal is presented via visual or auditory stimulus, the auditory or visual interference with other information might arise. On the other hand, if vibrotactile cue is used, such interference would be surely reduced. Therefore, it is expected that a vibrotactile signal would be very promising as a warning signal especially under noisy environment. In order to clarify the most suitable modality of cue (warning) to a visual hazard under noisy environment, the following two cues were used in the experiment: (1) auditory cue and (2) vibrotactile cue. The condition of SOA (Stimulus Onset Asynchrony) was set to 0 s, 0.5 s, and 1 s. The outside noise under the real-driving environment was recorded and edited for the experiment. The noise level inside the experimental chamber was 60 dB(A), 70 dB(A), 80 dB(A), and 90 dB(A). As a result, it was verified that the vibrotactile warning was more effective than the auditory warning. When the outside noise under the real-driving environment was used as the noise inside the experimental chamber, the reaction time to the auditory warning was not affected by the noise level.

Keywords: Auditory warning · Vibrotactile warning · Automotive warning system · Outside noise under the real-driving environment · SOA

1 Introduction

Tactile interface is paid more and more attention for enhancing driving safety (Jones and Sarter [1]). Jones and Sarter [1] paid attention to the potential application of vibrotactile sense to the automotive warning system, and reviewed the utilization of sense of touch as a medium for information representation. They indicated that sense of touch represents a promising means for communication in human-vehicle system.

Recently, the tendencies of cross-modal information processing and design (Spence and Driver [2] and Driver and Spence [3]) have emerged as major research topics in the design of automotive warning system. Presenting information via multiple modalities such as vision, audition, and touch has been expected to be a promising means to reduce transmission errors and enhance safety. A better understanding of cross-modal spatial and temporal links is essential to ensure a better application of this property to the automotive warning design.

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The utilization of sense of touch as a medium for information representation is paid more and more attention. Ho et al. [4] showed that the presentation of spatially predictive vibrotactile warning signal can facilitate drivers response to driving event seen through the windscreen or rear mirror. Ho et al. [5] showed that auditory cue led to quicker response than vibrotactile cue under quiet laboratory environment. However, they did not compare the effectiveness as a warning signal between auditory and vibrotactile presentations under noisy environment.

If the warning signal is presented via visual or auditory stimulus, the auditory or visual interference with other information might arise. On the other hand, if vibtotactile cue is used, such interference would be surely reduced. Therefore, it is expected that a vibrotactile signal would be very promising as a warning signal especially under noisy environment.

Murata, Kuroda, and Kambayashi [6] showed that verified that the vibrotactile warning got more and more effective with the increase of noise level. The reaction time to the auditory warning was remarkably affected by the noise level, while the reaction time to the vibrotactile warning was not affected by the noise level at all. Moreover, the SOA condition did not remarkably affect the reaction time to the auditory or the vibrotactile warnings. Although they used a pure tone of 4 kHz as the noise surrounding the experimental chamber, it is desirable to use a noise recorded under the real-world driving environment. As their auditory cue was also a pure tone of 1 kHz, it is possible that the perceptibility of the auditory cue might be remarkably affected by the surrounding noise of the similar type. If the noise was different from the auditory cue, and the interference between the surrounding noise and the auditory cue was mitigated, it might be possible that the auditory cue is more effective even under the environment with high noise level.

In order to clarify the most suitable modality of cue (warning) to a visual hazard under noisy environment, and also in order to examine the effect of the type of surrounding noise on the processing speed of the auditory cue, the following four conditions were used in the experiment: (1) auditory cue and (2) tactile cue. In order to clarify the most suitable modality of cue (warning) to a visual hazard under noisy environment, the effects of the following three conditions on the reaction to the target (hazard) were examined: (1) cue modality (auditory or vibrotactile cue), (2) SOA (0 s, 0.5 s, and 1 s), and (3) noise level inside the experimental chamber (60 dB(A), 70 dB (A), 80 dB(A), and 90 dB(A)). The outside noise under the real-driving environment was recorded and edited for the experiment. It was explored whether similar results to Murata et al. [6] can be obtained when the outside noise under the real-driving environment was used as the noise in the experimental setting.

2 Method

2.1 Participants

Three healthy male aged from 21 to 24 years took part in the experiment. All had held a driver's license for 3–4 years. All signed the informed consent after receiving a brief explanation on the aim and the contents of the experiment.

2.2 Apparatus, Task, Design, and Procedure

The apparatus, task, design, and procedure were the same with that of Murata et al. [6]. The outline of the experiment is briefly explained below.

Using a driving simulator system, the participants were required to simultaneously carry out a simulated driving task (main task) and the reaction task to a hazard randomly presented on one of the four locations (front, back mirror, right monitor, and left monitor). In the main driving simulator task, the participant was required to minimize the deviation from the predetermined line and keep the lane location using a steering wheel. In the reaction task to a hazard, the participant was required to react to a visual hazard using an accelerator or a steering switch.

The warning was presented to the participant 0 s, 0.5 s, or 1 s before a visual hazard appeared to the front or the rear mirror using the following warning presentation method: (1) auditory cue (pure tone of 1 kHz) and (2) vibrotactile cue. The auditory cue was presented to the participant via two speakers placed (70 cm away from the participant) in front of and behind the participant. The vibrotactile cue was transmitted to the participant via four tactors (vibrotransducers) placed on the sitting surface so that these tactors contacted the left and the right thigh. The cue to the front target was presented via two tactors placed on the front part (one was on the left thigh, and another was on the right thigh). The cue to the rear target was presented via two tactors placed on the rear part (one was on the left thigh, and another was on the right thigh). Although the noise was presented to the participant with a pure tone of 4 kHz, the sound pressure level of which changed from 60 dB(A) to 90 dB (A) every 10 dB(A), in Murata et al. [6], the noise under the real-world driving environment was used as the noise presented to the participants during the experiment. The noises were recorded on a daytime moderately jammed road. These noises were edited, and presented to the participant with a sound level from 60 dB(A) to 90 dB(A) every 10 dB(A). This is the

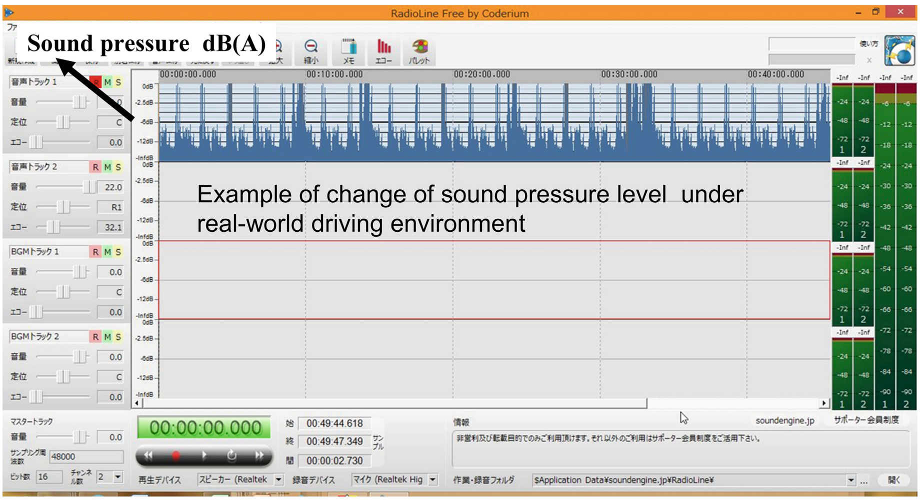

Fig. 1. Change of sound pressure level under real-world driving environment.

major difference from Murata et al. [6]. The change of sound pressure level under real-world driving environment is demonstrated in Fig. 1. This was used in this study.

The experimental conditions included the modality of cue ((1)-(2)) and the noise level (60 dB(A), 70 dB(A), 80 dB(A), and 90 dB(A)). The SOA was also an experimental variable (0 s, 0.5 s, and 1 s). All of these three experimental variables were within-subject factors.

3 Results

Figure 2 shows the reaction time as a function of SOA and noise level (auditory cue). In Fig. 3, the reaction time is plotted as a function of SOA and noise level (tactile cue). Figure 4 shows the reaction time as a function of noise level and cue (warning) modality (SOA: 0 ms). In Fig. 5, the reaction time is shown as a function of noise level and cue (warning) modality (SOA: 500 ms). Figure 6 shows the reaction time as a function of noise level and cue (warning) modality (SOA: 1000 ms).

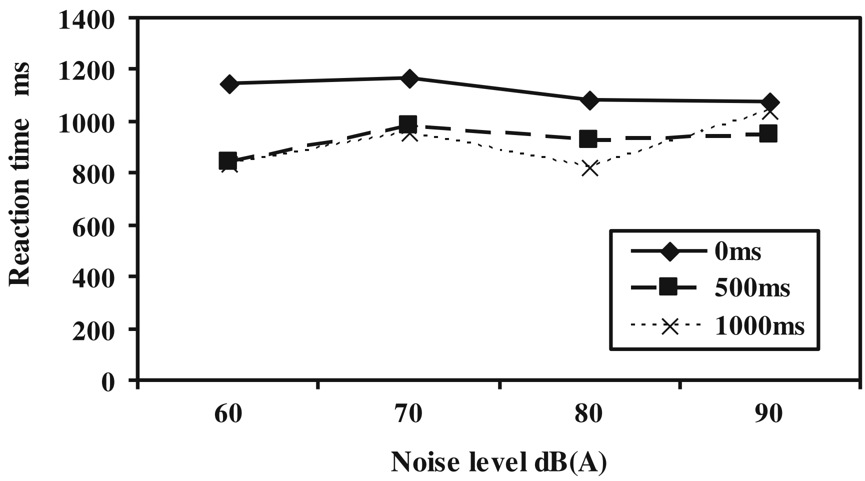

Fig. 2. Reaction time as a function of SOA and noise level (auditory cue).

In Fig. 7, the reaction time of the auditory warning is compared among noise levels and between Murata et al. [6] and this study (SOA: 0 ms). In Fig. 8, the reaction time of the auditory warning is compared among noise levels and between Murata et al. [6] and this study (SOA: 500 ms). In Fig. 9, the reaction time of the auditory warning compared among noise levels and between Murata et al. [6] and this study (SOA: 1000 ms). As for tactile warnings, the reaction time is compared among noise levels and between Murata et al. [6] and this study (SOA: 0 ms). Figure 11 shows the reaction time of the tactile warning compared among noise levels and between Murata et al. [6] and this study (SOA: 500 ms). Figure 12 shows the reaction time of the tactile warning compared among noise levels and between Murata et al. [6] and this study (SOA: 1000 ms).

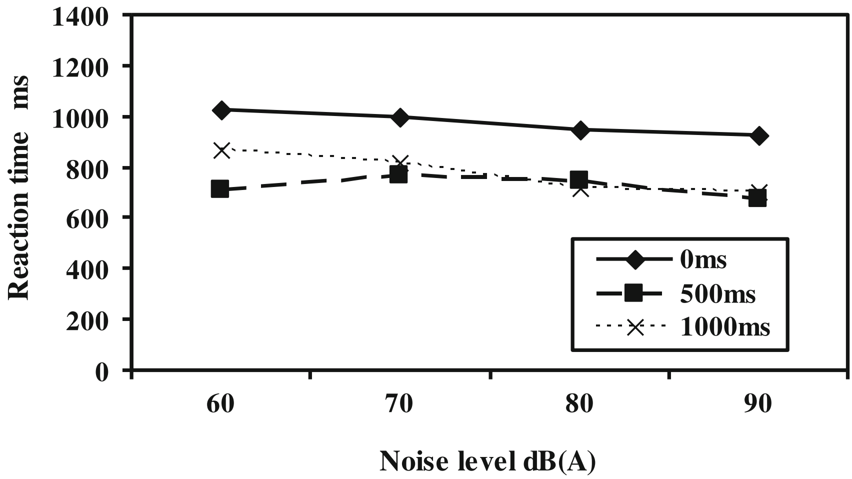

Fig. 3. Reaction time as a function of SOA and noise level (tactile cue).

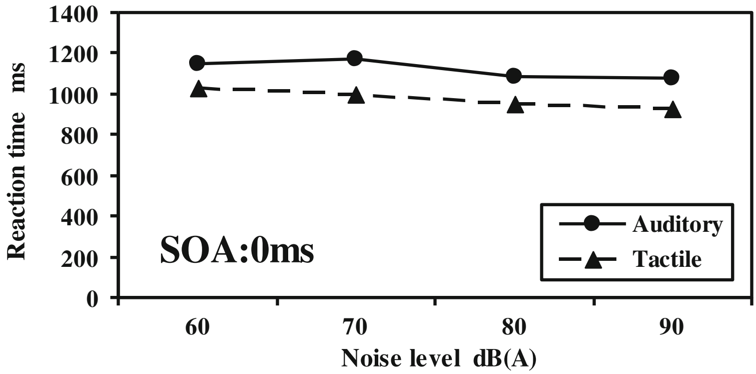

Fig. 4. Reaction time as a function of noise level and cue (warning) modality (SOA: 0 ms).

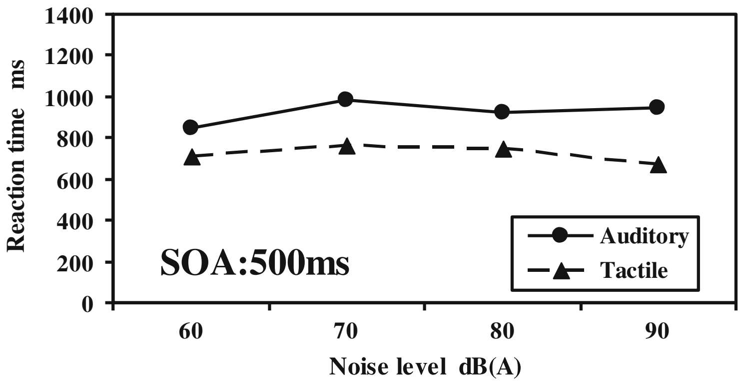

Fig. 5. Reaction time as a function of noise level and cue (warning) modality (SOA: 500 ms).

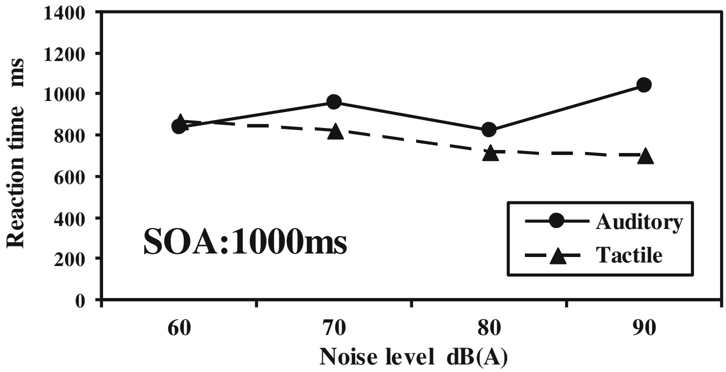

Fig. 6. Reaction time as a function of noise level and cue (warning) modality (SOA: 1000 ms).

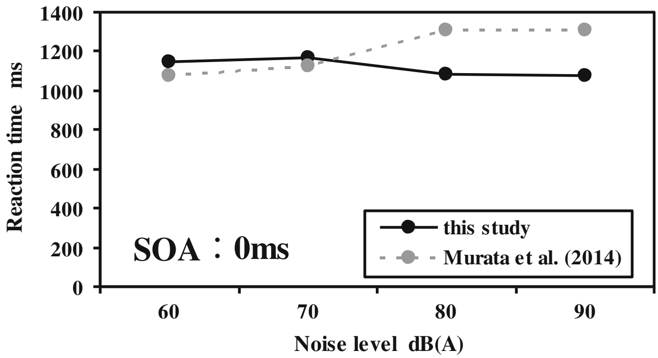

Fig. 7. Reaction time of the auditory warning compared among noise levels and between Murata et al. (2014) and this study (SOA: 0 ms).

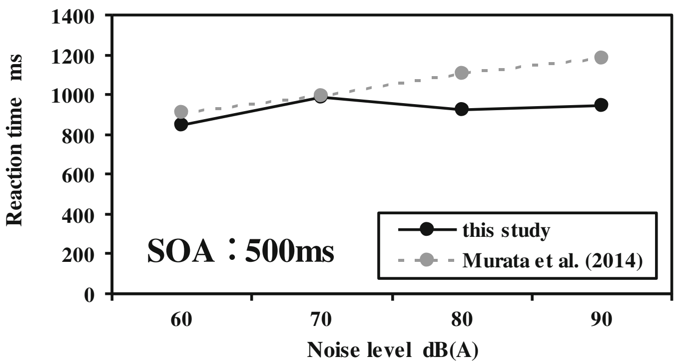

Fig. 8. Reaction time of the auditory warning compared among noise levels and between Murata et al. (2014)and this study (SOA: 500 ms).

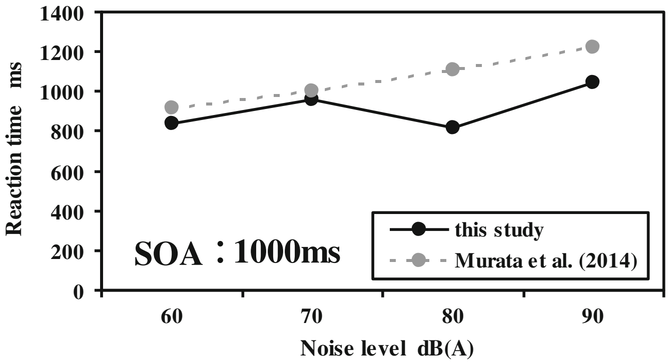

Fig. 9. Reaction time of the auditory warning compared among noise levels and between Murata et al. (2014) and this study (SOA: 1000 ms).

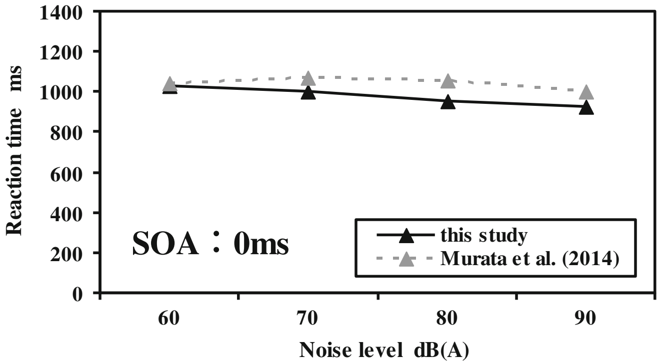

Fig. 10. Reaction time of the tactile warning compared among noise levels and between Murata et al. (2014) and this study (SOA: 0 ms).

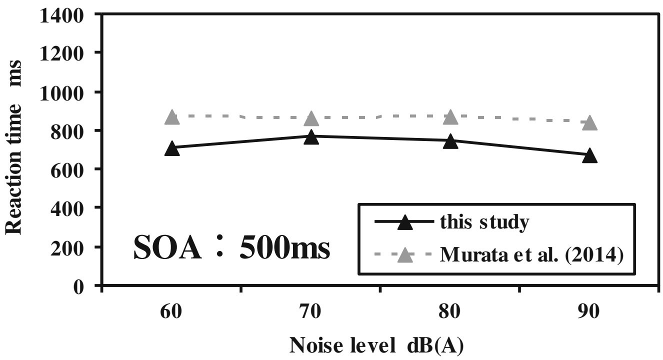

Fig. 11. Reaction time of the tactile warning compared among noise levels and between Murata et al. (2014) and this study (SOA: 500 ms).

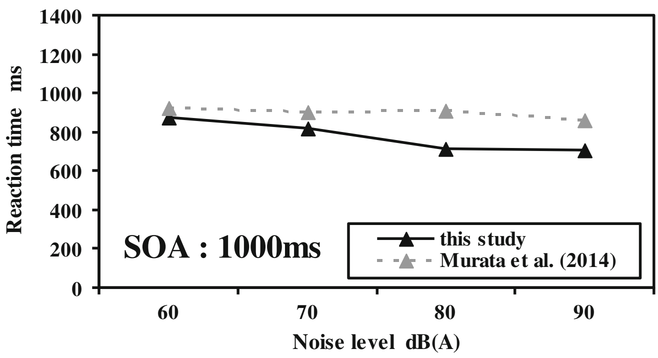

Fig. 12. Reaction time of the tactile warning compared among noise levels and between Murata et al. (2014) and this study (SOA: 1000 ms).

A two-way (warning modality by sound pressure level of noise) ANOVA conducted on the reaction time for SOA of 0 ms revealed only a significant main effect of warning modality ($\boldsymbol{F}(1,16) = 9.101$, $\boldsymbol{p} < 0.01$). A similar two-way ANOVA conducted on the reaction time for SOA of 500 ms revealed only a significant main effect of warning mode ($\boldsymbol{F}(1,16) = 14.271$, $\boldsymbol{p} < 0.01$). A similar two-way ANOVA conducted on the reaction time for SOA of 1000 ms revealed no significant main effect of warning mode ($\boldsymbol{F}(1,16) = 3.532$, $\boldsymbol{p} < 0.079$). A three-way (SOA by warning modality by sound pressure level of noise) conducted on the reaction time revealed only a main effect of SOA ($\boldsymbol{F}(2,12) = 84.755$, $\boldsymbol{p} < 0.01$).

4 Discussion

Under the nosy surrounding condition equal to or more than 70 dB(A), Murata et al. [6] showed that the reaction time of the auditory cue increased with the increase of the sound pressure level of the noise. As for the auditory modality, different from Murata et al. [6], the reaction time to the warning was not so remarkably affected by the noise level (see Figs. 7, 8 and 9). This must indicate that the auditory cue is effective irrespective of sound pressure level of the noise when the outside noise under the real-driving environment was used. Murata et al. [6] used the pure tone of 4 kHz, the sound pressure level of which ranged from 60 dB(A) to 90 dB(A) every 10 dB(A), as the surrounding noise. In this study, the noise under the real-world driving environment was used as the noise presented to the participants during the experiment. The sound type of the surrounding noise were the same (pure tone) with the auditory cue in Murata et al. [6], while the sound type of the surrounding noise was different from that of the auditory cue in this study (Fig. 10).

The interference between the surrounding noise and the auditory cue must be subtle in this study, which must lead to little effects of the sound pressure level of the surrounding noise on the perception and the reaction to the auditory cue. This must mean that the combination of sound types of auditory cue and surrounding noise affects the effectiveness of auditory cue. When the surrounding noise outside the vehicle was used as the surrounding noise inside the experiment chamber, the pure tone is effective as an auditory cue, because the reaction time to the auditory cue is not affected by the sound pressure level of the surrounding noise.

The reaction time of both auditory and vibrotactile modalities was nearly the same when the noise level was 60 dB(A) and when SOS was 500 ms or 1000 ms. Overall, the vibrotactile cue was more effective than the auditory cue (see Figs. 4, 5 and 6). In both this study and Murata et al. [6], the advantage of vibrotactile cues over the auditory cues was demonstrated.

The SOA condition remarkably affected the reaction time to the auditory or the vibrotactile warnings (see Figs. 2 and 3). When SOA was equal to 0 ms, it tended that the reaction time was prolonged for both auditory and vibrotactile cues. For SOA of 500 ms or 1000 ms, the reaction time decreased as compared with that for SOA of 0 ms. In summary, the SOA condition of 0 ms is not proper for the warning presentation. SOA should be selected to 500 ms or 1000 ms.

On the basis of the results, it is expected that a vibrotactile warning would be very promising as a warning signal under noisy environment. Moreover, the auditory cue was not affected by the surrounding noise when the noise was recorded from the real-world driving environment. Future research should explore the effectiveness of multisensory cuing (warning), or examine the effect of time interval between a cue and a target (hazard) appearance on the effectiveness of cue modality.

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