2025 IEEE World Haptics Conference (WHC)
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

Investigation of the Effect of Auditory Stimulation on the Perceived Intensity of Short-Duration Airborne Ultrasonic Tactile Stimulation

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I. Introduction

Airborne ultrasound tactile displays (AUTDs), one of the mid-air haptic devices, generate tactile sensations by focusing ultrasound [1].There are studies on the combination of auditory and tactile stimuli [2], [3]. In a previous study [2], the authors played the sound of a cloth being rubbed simultaneously to change the perceived roughness of an ultrasound tactile stimulus. It has also been shown that white noise can enhance the roughness perception of ultrasound tactile stimuli [3].

In this paper, we investigate whether the tactile stimulation of airborne ultrasound is enhanced by sound. We conducted two experiments to investigate whether sound affects the perceived intensity of tactile stimuli. In Experiment 1, we evaluated whether presented sounds at different frequencies affects the perceived intensity of tactile stimuli. In experiment 2, we investigated whether the perceived intensity of tactile stimuli is enhanced by the driving sound from the AUTDs. As a result, no significant differences in perceived intensity were observed in either experiment.

II. Experimental Setup

We used six AUTD3 devices [1], with a phased array of aperture size $303\,\mathrm{mm} \times 576\,\mathrm{mm}$, mounted facing downward, positioned $300\,\mathrm{mm}$ above the table. During the experiment, participants placed one of their palms facing up beneath the device, and tactile stimuli without frequency modulation were presented (Fig. 1).

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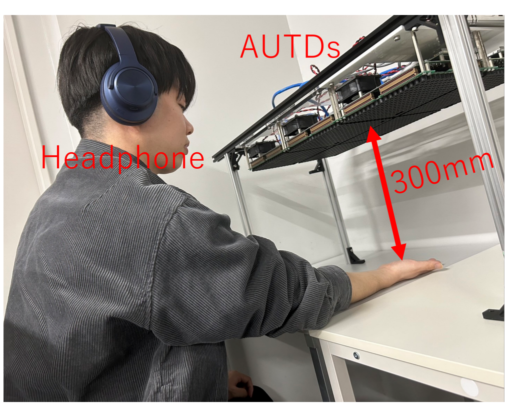


Fig. 1: Experimental setup

The AUTD allows the stimulus intensity to be set in 256 discrete levels ranging from 0 to 255. Nine participants (6 male, 3 female, mean age = 25.0 years, SD = 3.28) took part in the experiment.

III. Experiment 1: Effects of presented sound and Frequency on Tactile Perception

In Experiment 1, we tested whether presented sounds at different frequencies affect the perceived intensity of ultrasound tactile stimulation.

A. Auditory stimulation

The single-pulse sound used in Experiment 1 was selected as follows. First, we recorded the actual driving sound from the AUTD and performed a Fourier analysis to identify its dominant frequency components. The audible sound corresponds to the envelope waveform of the ultrasound, while the recorded waveform does not appear as a simple pure tone due to the nonlinearity of air. Therefore, several synthetic sounds were generated based on the peak frequencies, and the one perceived to be most similar to the actual driving sound was selected through auditory evaluation. As a result, the selected single-pulse sound was set at $523\,\mathrm{Hz}$ with a duration of $76\,\mathrm{ms}$. Additionally, to examine the effect of sound frequency, two additional sounds at $262\,\mathrm{Hz}$ and $1047\,\mathrm{Hz}$, corresponding to one octave below and above the reference, respectively, were used. In total, three types of sounds were prepared.

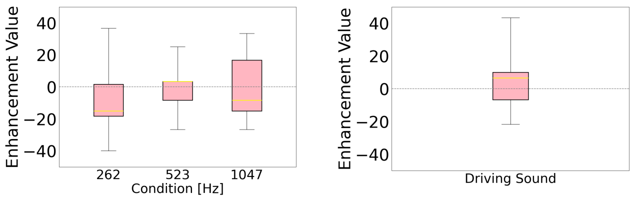
During Experiment 1, participants wore headphones playing white noise to mask the direct driving sound from the AUTDs.

Two types of stimulation were used: tactile-only stimulation delivered by ultrasound, and audio-tactile stimulation where sound was presented in synchrony with the tactile stimulus.

The intensity P_{only} for the tactile-only condition was fixed, and the intensity P_{hybrid} for the audio-tactile condition was adjusted so that the perceived intensities of the two conditions matched.

B. Procedure

To investigate the effects of auditory stimuli and frequency on tactile perception, we estimated the perceived tactile intensity for three different frequencies ($262\,\mathrm{Hz}$, $523\,\mathrm{Hz}$, and $1047\,\mathrm{Hz}$) using the up-and-down method with PEST [4], which efficiently estimates values by adjusting the stimulus based on participant responses. For each frequency, the



(a) Audio-tactile conditions. (b) Driving sound condition.

Fig. 2: Perceptual enhancement in estimated tactile strength under (a) audio-tactile conditions and (b) driving sound condition.

estimation was repeated three times, and the average of the three values was used as the representative intensity.

We searched for the ultrasound intensity at which audio-tactile stimulation was perceived as equivalent to the tactile-only stimulation. The search started from the maximum intensity of 255. In each trial, participants were asked to indicate which of the two stimuli felt stronger.

C. Results

Figure 2a shows a boxplot of the perceptual enhancement in estimated ultrasound stimulus intensity for each audio-tactile condition ($262\,\mathrm{Hz}$, $523\,\mathrm{Hz}$, and $1047\,\mathrm{Hz}$). The boxplot illustrates the distribution of enhancement values, calculated as the difference from the baseline intensity of 200 (i.e., $200 -$ estimated intensity). Positive values indicate that the presence of sound caused a lower actual intensity to be perceived as equivalent to the baseline, suggesting a perceptual enhancement effect.

To assess whether this enhancement was statistically significant, we first confirmed the normality of the data using the Shapiro-Wilk test. Subsequently, no significant differences from the baseline value of 200 were found in any of the frequency conditions based on one-sample t-tests(two-sided): 262 Hz: t(8) = 1.17, p = .277 (Bonferroni-corrected p = .831), 523 Hz: t(8) = 0.04, p = .969 (corrected p = 1.000), 1047 Hz: t(8) = 0.16, p = .877 (corrected p = 1.000)

IV. Experiment 2: Effect of the Driving Sound

In Experiment 2, we examined the effect of the driving sound from AUTDs on the perceived intensity of tactile stimulation.

A. Audio stimulus

The acoustic environment was varied depending on the condition. In the driving sound condition, participants did not wear headphones, allowing them to hear the natural driving sound from the AUTDs. In the tactile-only condition, participants wore headphones playing white noise to mask the driving sound.

B. Procedure

The up-and-down PEST procedure described in Experiment 1 was repeated for the driving sound condition to find the perceived-equivalent intensity relative to the fixed tactile-only baseline (P_{only}).

C. Results

Figure 2b shows a boxplot of the perceptual enhancement in estimated ultrasound stimulus intensity under the driving sound condition.

Similarly, for the driving sound condition, the Shapiro-Wilk test indicated no significant deviation from normality. A one-sample t-test revealed no significant difference from the baseline value of 200 in the perceived intensity: $t(8)$ = -0.671, p = .521.

V. Discussion

This study was motivated by the hypothesis that simultaneously presented auditory and tactile stimuli enhance the perceived intensity of tactile stimulation. To test this hypothesis, we compared a no-sound baseline to three audio-tactile conditions using synthetic sounds: one set at $523\,\mathrm{Hz}$, which matched the dominant frequency component of the natural driving sound from the AUTDs, and two additional sounds at $262\,\mathrm{Hz}$ and $1047\,\mathrm{Hz}$, corresponding to one octave below and above, respectively. However, statistical testing revealed no significant differences from the baseline value of 200 in any of the frequency conditions. To further isolate the effect of sound, we also compared tactile perception with and without the direct driving sound. Again, no significant difference was observed. These results do not support the hypothesis that the presence of sound enhances perceived tactile intensity. A post hoc power analysis showed that with nine participants, the study had 80% power to detect an effect size of $d = 1.07$. Therefore, smaller effects may have gone undetected, and auditory influence cannot be ruled out. Further investigation is needed to determine under what conditions, if any, concurrent sounds affect tactile perception.

VI. Conclusion

This study tested whether auditory stimuli, including both presented sounds and the natural driving sound from AUTDs, affect the perceived intensity of airborne ultrasound tactile stimulation. No significant effect was observed under any condition. While the results do not support the hypothesis that sound enhances perceived tactile intensity, they also do not exclude the possibility of auditory influence. Clarifying the conditions under which such influence occurs remains an open question for future research.

VII. Acknowledgment

This work was partially assisted by ChatGPT.

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