The Influence of Auditory Feedback on Vibrotactile Intensity Perception for a Virtual Button

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Introduction

In modern times, the paradigm of technology development is changing from the product-oriented design to the human-centered design. Accordingly, the development of Human-Machine Interface (HMI) has become much more important in various devices and applications in order to improve user's convenience and satisfaction [1][2]. For instance, in the automobile industry, as advanced driver-assistance systems are paid attention and are commercialized, it is required to develop a useful and comfortable interface that delivers infotainment functions and provides pleasant driving environment [3][4].

In this regard, touch-sensitive displays have been integrated into many products, such as control consoles in automobiles or kiosks, by virtue of its advantages in terms of spatiality, programmability, and informational connectivity. And the developers have intentionally made touch feedback (or haptic feedback) in several ways so that the user can notice a touch event properly [5][6]. For this purpose, tactile intensity perception of feedback stimuli has been considered as one of the most important design factors because it is directly connected to the user's feelings on products [7][8].

From this perspective, several studies have been carried out to understand the tactile intensity perception according to the change of tactile stimuli for a long time [9–12]. However, it is still not well-identified how auditory feedback has an influence on tactile intensity perception. Therefore, this study aims to investigate the effect of auditory feedback on tactile intensity perception and to find equally perceived intensity levels taking into account the presence and absence of auditory feedback effect.

Psychophysical Experiment

Experimental Apparatus

In order to evaluate the tactile intensity perception, an experimental apparatus was built as shown in Figure 1. Two virtual buttons were displayed on a touchscreen tablet. Then it was programmed to produce tactile and auditory feedback when the buttons are pressed. The tactile feedback was generated by an electrodynamic shaker and the auditory feedback was given by a closed headphone. The tactile and auditory feedback was created simultaneously to stimulate the subject's senses at the same time.

Touch Feedback Stimuli

An underdamped harmonic waveform, which emulates the natural response of touch buttons, was adopted for the base waveform of tactile and auditory feedback stimuli (Figure 2). The exponential decaying ratio and the duration of waveform were determined by referring to the sound and vibration of physical buttons. For tactile feedback stimuli, the frequency of waveform was used as 50, 100, 150, and 200 Hz, and the amplitude was set to generate the RMS (Root-Mean-Square) level of 115, 125, and 135 dB (re 1 μm/s^2) over the waveform duration. Note that the just-noticeable threshold level measured at the finger is approximately known as 105 dB in the frequency range of 50 to 200 Hz. Namely, it can be said that 115 dB is a weak level, 125 dB is a normal level, and 135 dB is a strong level. On the other hand, eight different frequency conditions between 50 and 8000 Hz were used for auditory feedback stimuli, and the amplitude of each stimulus was set to have the loudness level of 65 phons.

Figure 1: An experimental apparatus that consists of a touchscreen tablet and an electric dynamic shaker. A graphical user interface was designed by MATLAB and was displayed on the screen for the evaluation task.

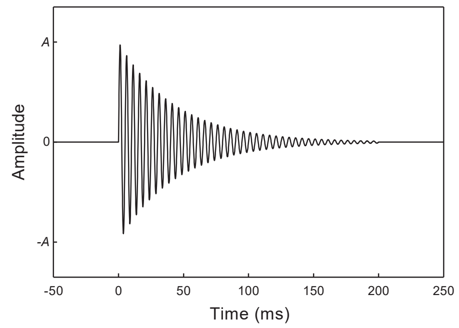

Figure 2: A base waveform of feedback stimuli that emulates the natural response of touch buttons. The frequency and amplitude were determined by considering the threshold level of the human tactile and auditory senses. Twelve tactile feedback stimuli and eight auditory feedback stimuli were created for the psychophysical experiment.

Evaluation Method

The magnitude estimation method, developed by S.S. Stevens [00], was used for the evaluation of tactile intensity perception.

This technique is usually recommended to the psychophysical experiment that requires to estimate the perceived strength of a stimulus by letting subjects assign a number proportional to the stimulus magnitude they perceive. In this study, a standard stimulus (so-called a modulus) was given by the reference button throughout the experiment, and its perceived intensity level was assumed to be 100. Then the subsequent stimuli were given by the test button, and subjects were asked to judge the perceived tactile intensity level by comparing them with a modulus. For example, if they felt the tactile intensity from the test button is two times stronger than that from the reference button, they would have assigned 200. On the contrary, if they felt that from the test button is two times weaker than that from the reference button, they would have assigned 50.

Evaluation Procedure

Twenty-two subjects (12 female and 10 male participants aged 20 to 40) took part in the experiment. The experiment consisted of a training session and the main session. In the training session, subjects learned the magnitude estimation method then they were accustomed to the evaluation task. And in the main session, subjects evaluated the perceived tactile intensity of twelve tactile feedback stimuli, introduced above, in the absence and presence of auditory feedback stimuli. Namely, the tactile feedback stimuli were presented in combination with and without auditory feedback stimuli. Specifically, a tactile feedback stimulus having a level of 125 dB and a frequency of 200 Hz was used as a modulus. The evaluation order was sorted randomly to avoid the sequence effect, and each audio-tactile feedback stimulus was given two times in one experiment. The properties of audio-tactile feedback stimuli were not known to subjects in order to prevent prejudice against intensity perception.

Results and Discussions

Analysis of Tactile Intensity Perception

Evaluation data of tactile intensity perception, collected from the psychophysical experiment, were analyzed in a statistical way. Firstly, the perceived intensity scores, answered by subjects, were classified according to the level and frequency of tactile feedback stimuli. Next, after eliminating outlier points by drawing a box plot (Figure 3a), the perceived intensity scores were transformed to the mean of resultant scores (Figure 3b).

In this manner, the perceived intensity scores for all tactile feedback stimuli were re-evaluated and differences of tactile intensity perception due to auditory feedback were analyzed. Figure 4a–d show the results for the tactile feedback stimuli of 50, 100, 150, and 200 Hz, respectively. And the grouped bars in each figure represent the results for the tactile feedback stimuli of 115, 125, and 135 dB from the left. Black bars are corresponding to the cases for the absence of auditory feedback, whereas hatched red bars are corresponding to the cases for the presence of auditory feedback. As can be seen in Figure 4, regardless of the frequency of tactile feedback stimuli, if auditory feedback is given, perceived intensity scores go down at 115 dB and they go up at 135 dB. Besides, perceived intensity scores do not seem to be changed by auditory feedback at 125 dB.

To make these inferences clear, the statistical significance of changes in perceived intensity scores was examined by calculating the p-value in each group as summarized in Table 1. It is shown that all p-values for the changes in perceived intensity scores at 115 dB and 135 dB are less than 0.05 (the most common significance level) whereas all p-values for the changes in perceived intensity scores at 125 dB are greater than 0.05. In other words, it is statistically reasonable to say as follows: When the level of tactile feedback stimulus is relatively weak, such as 115 dB, perceived tactile intensity decreases with the influence of auditory feedback (herein, called intensity masking). On the contrary, when the level of tactile feedback stimulus is relatively strong, such as 135 dB, perceived tactile intensity increases with the influence of auditory feedback (herein, called intensity enhancing). Exceptionally, only when the level of tactile feedback stimulus is normal, such as 125 dB, perceived tactile intensity is not affected by auditory feedback and does not change.

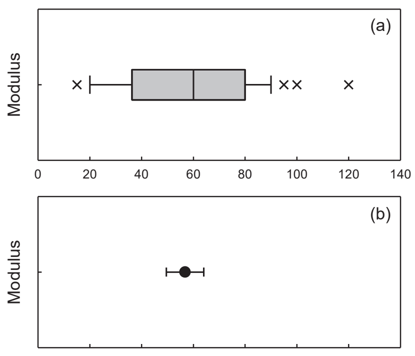

Figure 3: An example of statistical analysis results: (a) a box plot and (b) the mean value with 95 % confidence interval for perceived intensity scores corresponding to the tactile feedback stimulus of 115 dB and 200 Hz.

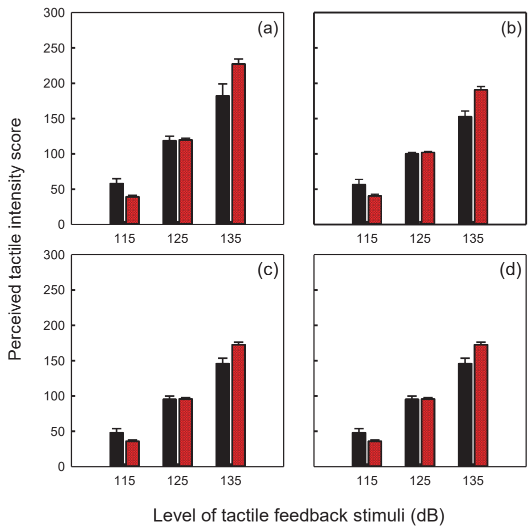

Figure 4: Differences of perceived intensity scores due to auditory feedback, for the frequency of tactile feedback stimuli: (a) 50, (b) 100, (c) 150, and (d) 200 Hz. Black and hatched red bars represent the cases for the absence and presence of auditory feedback, respectively.

Table 1: Probability values for statistical significance of changes in perceived intensity scores according to the presence or absence of auditory feedback.

Tactile feedback		Change of mean values	*p*-value
Level	Frequency		
115 dB	50 Hz	18.84 ↘	< 0.05
115 dB	100 Hz	16.04 ↘	< 0.05
115 dB	150 Hz	12.06 ↘	< 0.05
115 dB	200 Hz	13.87 ↘	< 0.05
125 dB	50 Hz	1.235 ↗	0.529
125 dB	100 Hz	1.846 ↗	0.346
125 dB	150 Hz	0.560 ↗	0.853
125 dB	200 Hz	2.877 ↘	0.587
135 dB	50 Hz	45.17 ↗	< 0.05
135 dB	100 Hz	37.71 ↗	< 0.05
135 dB	150 Hz	26.90 ↗	< 0.05
135 dB	200 Hz	39.37 ↗	< 0.05

Compensation of Auditory Feedback Effect

It would be necessary for haptic feedback designers to compensate the effect of auditory feedback, if they wish to selectively use tactile feedback or audio-tactile feedback, in order to provide the perceived tactile intensity of haptic feedback constantly. So, for this purpose, perceived intensity scores according to the presence or absence of auditory feedback effect were compared, then the levels of tactile feedback stimuli that provide the same perceived tactile intensity were investigated as follows.

Firstly, perceived intensity scores between 115 dB and 135 dB were calculated using the linear interpolation method based on the scores at 115, 125, and 135 dB. The resultant scores for the tactile feedback stimuli of 50, 100, 150, and 200 Hz are drawn in Figure 5a–d, respectively. Herein, black lines are corresponding to the cases for the absence of auditory feedback, whereas dotted red lines are corresponding to the cases for the presence of auditory feedback. Next, for each line in each figure, the level of tactile feedback stimulus that matches with a pre-specified perceived intensity score was picked up. For example, if a pre-specified perceived intensity score is 60, 115.3 dB and 117.6 dB can be selected for the black and dotted red lines in Figure 5a, respectively.

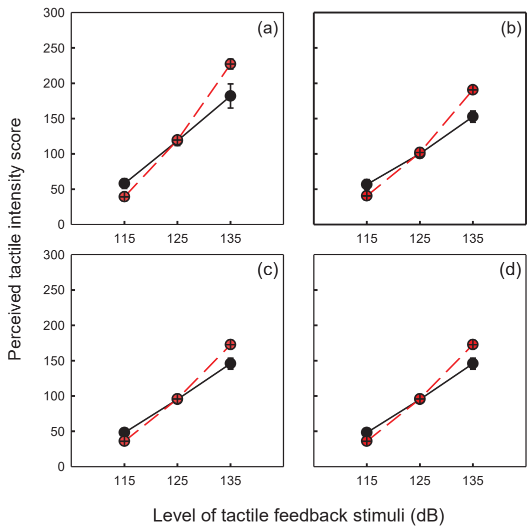

Figure 5: Perceived intensity scores between 115 and 135 dB, for the frequency of tactile feedback stimuli: (a) 50, (b) 100, (c) 150, and (d) 200 Hz. Black and dotted red lines represent the resultant scores for the absence and presence of auditory feedback, respectively.

In the same way, the levels of tactile feedback stimuli, for pre-specified perceived intensity scores of 60, 100, and 140, were selected as summarized in Table 2. Accordingly, the subset levels of tactile feedback stimuli, corresponding to each perceived intensity score, provide the same perceived tactile intensity. It is shown that, to provide the perceived tactile intensity scored as 60 (relatively weak intensity), the level of tactile feedback stimulus should be increased if auditory feedback is given with tactile feedback together; because of the intensity masking effect. Conversely, to provide the perceived tactile intensity scored as 140 (relatively strong intensity), the level of tactile feedback stimulus should be decreased if auditory feedback is given with tactile feedback together; because of the intensity enhancing effect. On the other hand, in the case of the perceived tactile intensity scored as 100 (normal intensity), the level of tactile feedback stimulus does not need to be compensated substantially for by the effect of auditory feedback. Likewise, the levels of tactile feedback stimuli that provide a constant tactile intensity perception with or without auditory feedback can be determined, and it may be of benefit to haptic feedback designers.

Table 2: Levels of tactile feedback stimuli for pre-specified perceived intensity scores of 60, 100, and 140 according to the presence or absence of auditory feedback

PIS	Frequency	Auditory feedback		
		Absence	Presence	Δ
60	50 Hz	115.3 dB	117.6 dB	+2.3
60	100 Hz	115.8 dB	118.1 dB	+2.3
60	150 Hz	117.6 dB	119.0 dB	+1.4
60	200 Hz	120.7 dB	122.6 dB	+1.9
100	50 Hz	122.0 dB	122.6 dB	+0.6
100	100 Hz	124.9 dB	124.7 dB	–0.2
100	150 Hz	126.0 dB	125.6 dB	–0.4
100	200 Hz	128.6 dB	127.8 dB	–0.8
140	50 Hz	128.4 dB	126.9 dB	–1.5
140	100 Hz	132.6 dB	129.3 dB	–3.3
140	150 Hz	133.8 dB	130.8 dB	–3.0
140	200 Hz	135.0 dB	131.4 dB	–3.6

※ PIS: Perceived Intensity Score, Δ: Difference

Conclusion

The influence of auditory feedback on vibrotactile intensity perception for a virtual button has been investigated, in this study, by performing the psychophysical experiment. An experimental apparatus, which consists of a touchscreen display and an electrodynamic shaker, was built for the evaluation of tactile intensity perception. They were programmed to provide tactile and auditory feedback in response to the user's touch. Then, based on the magnitude estimation method, twenty-two participants evaluated perceived tactile intensity with respect to twelve tactile feedback stimuli in combination with and without auditory feedback stimuli. The evaluated data were analyzed in a statistical way, and it was found that the presence of auditory feedback can affect perceived tactile intensity. The influence of auditory feedback on tactile intensity perception, investigated in this experiment, can be summarized as follows:

If the tactile feedback stimulus is relatively weak (such as 115 dB), auditory feedback interferes tactile intensity perception. It means that the level of tactile feedback stimulus should be increased if auditory feedback is given with tactile feedback together. Contrarily, if the tactile feedback stimulus is relatively strong (such as 135 dB), auditory feedback enhances tactile intensity perception. It means that the level of tactile feedback stimulus should be decreased if auditory feedback is given with tactile feedback together. In particular, only if the level of tactile feedback stimulus is normal (such as 125 dB), the influence of auditory feedback on tactile intensity perception can be negligible, meaning that the level of tactile feedback stimulus should not be adjusted depending on the absence or presence of auditory feedback.

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