Minimally Allowable Inconsistency between Visual and Synthetic Tactile Grating Textures for Surface Tactile Displays

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***Abstract*—For surface tactile displays, it is believed that visual and haptic contents need to be consistent with each other. However, some inconsistency between them can be unrecognized by humans. We investigated the minimally allowable inconsistency between visual and synthetic tactile textures. Participants adjusted the surface wavelength of virtual grating scales to match the visual and tactile grating scales. The minimally allowable inconsistencies in the wavelength were 0.335 mm and 0.412 mm for gratings' wavelengths of 1.0 mm and 2.0 mm, respectively. This information is valuable for designers of haptic content, as it facilitates a reduction in accuracy requirements for stimulus presentation, a decrease in costs while maintaining user satisfaction.**

***Index Terms*—electrostatic texture display, surface display, discrimination, gratings**

I. INTRODUCTION

Touch panels are among the most popular human-computer interfaces. Surface tactile display, a haptic feedback technique for touch panels, has been extensively studied by researchers [1]–[4]. Implementing tactile feedback functions on touch panels enhances the entertainment value [5] and usability [6] of computer applications.

For developing effective interfaces, it is crucial that visual and tactile contents align with each other; however, a certain degree of inconsistency is permissible [7], [8]. Previous research using actual tactile textures suggested that some inconsistencies in surface wavelength are less likely to be recognized when using grating textures, which feature periodic surface patterns.

This study aims to determine the allowable inconsistency between visual and tactile texture stimuli for surface texture displays that deliver electrostatic friction. Such display devices present less physically realistic tactile stimuli than actual textures; hence, the allowable inconsistency may differ from the values previously reported using actual textures [8]. Identifying the acceptable level of inconsistency between visual and tactile stimuli will assist developers in creating cost-effective haptic contents.

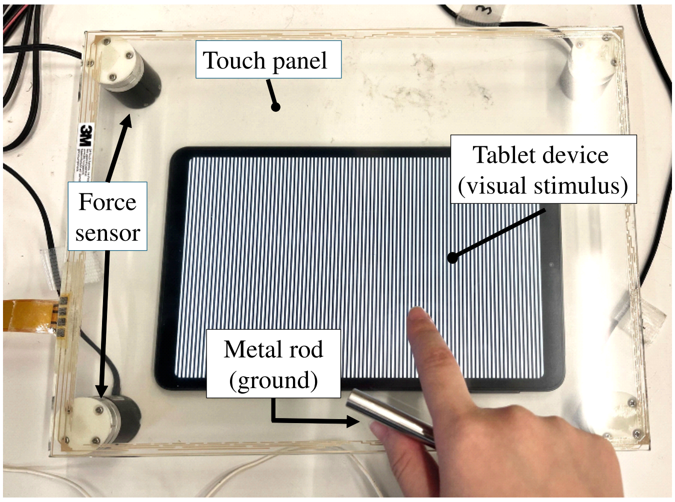

Fig. 1. Electrostatic friction display. Images of the grating texture was shown on a tablet PC beneath the touch panel.

II. METHODS

A. Apparatus: Electrostatic tactile texture display

An electrostatic tactile display, as shown in Fig. 1, was used in the study. The same apparatus was also used in [9], [10]. Voltages of up to ±20 V were applied to the indium tin oxide touch panel (3M Touch Systems, Inc.,, MN), over which the participant directly slid their finger. The voltage was adjusted for individuals as described in Section II-B. The electric charges between the finger and touch panel produced an adhesive frictional force, leading to the increase in friction. The intensity of this force is controlled by changing the level of applied voltage. To stabilize the stimuli, participants gripped a grounded metal rod. A force sensor was placed beneath each corner of the panel and they were used to calculate the center of the load on the panel, corresponding to the finger position. The control frequency of the surface display system was 2 kHz.

B. Stimuli: Visual and tactile gratings

The relationship between the shear frictional force $F_e(t)$ and the applied voltage $V_e(t)$ is determined according to the

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law of electrostatic force and Coulomb friction as follows:

$$F_e(t) = \mu\{W + kV_e{}^2(t)\} \tag{1}$$

where μ, W, and k are the coefficients of friction, the load of the finger, and the constant about electrostatic force. In the experiment, virtual textures of gratings with wavelengths ranging from 0.5 mm to 5.0 mm were presented. Thus, the applied voltage $V_e(t)$ could be expressed as follows:

$$V_e(t) = \begin{cases} 0 & \sin\frac{2\pi x(t)}{2\lambda} > 0 \\ a & \sin\frac{2\pi x(t)}{2\lambda} \leq 0 \end{cases} \tag{2}$$

where $x(t)$, a, and λ are the position of the finger pad on the panel, the applied voltage that was determined by individuals, and the surface wavelength of the grating scale, respectively. This method to present virtual grating scales follows earlier studies [11]–[13].

As shown in Fig. 1, visual stimuli with wavelengths of 1.0 mm or 2.0 mm were presented. They had alternating white and black bars of equal widths on the surface, and its surface wavelength is the sum of the width of the two bars.

C. Participants

Seven university students in their 20s, who were unaware of the objectives of the study, participated in the study.

D. Procedures

In the training session, each participant adjusted the intensity of the electrostatic stimuli until they could clearly feel the tactile gratings. During this session, they were presented with both visual and tactile gratings whose surface wavelengths matched.

In the main session, the participant slid their finger on the panel and compared the wavelengths of the visual and tactile grating scales. The wavelength of the visual scale was fixed at either 1.0 mm or 2.0 mm. The wavelength of the tactile scale was variable, starting with a random value ranging from 0.5 mm to 2.5 mm at the beginning of each trial. The participant adjusted the wavelength of the tactile scale in 0.1 mm increments or decrements until the tactile scale felt equal to the visual scale. Each participant repeated this trial 10 times for each of the two visual wavelength levels, with no time limit.

E. Data analysis

For each participant, we calculated the 95% confidence interval of the mean adjusted tactile wavelengths. Only cases where the wavelength of the visual stimulus fell within this interval were included in the subsequent statistical analysis. For the 1.0 mm visual stimulus, six out of seven participants met this criterion. For the 2.0 mm visual stimulus, a different set of six participants met the criterion.

We used the Shapiro-Wilk test to check the normality of the samples for each of 1.0 mm and 2.0 mm wavelengths of visual stimuli, respectively. For the wavelength of 1.0 mm, the p-value was 0.2917 and the W statistic was 0.9763. For the wavelength of 2.0 mm, the p-value was 0.7587 and the W statistic was 0.9867. Therefore, we treated the obtained samples, regarding them following normal distributions.

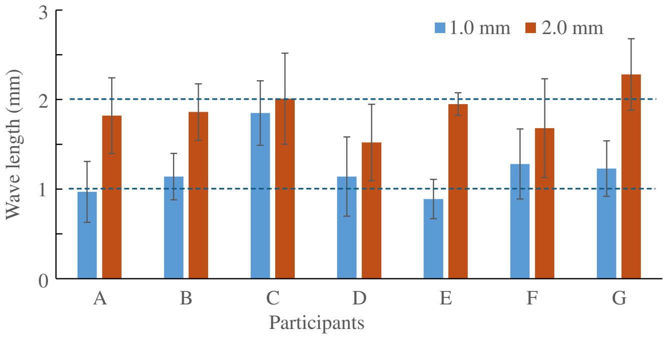

Fig. 2. Mean and standard deviation of all participants' responses.

TABLE I
POOLED STANDARD DEVIATIONS AND THEIR 95% CONFIDENCE INTERVALS

Visual texture (mm)	Standard deviation	95% confidence interval
1.0	0.335	0.282–0.413
2.0	0.412	0.347–0.508

We used the Shapiro-Wilk test to check the normality of the samples for each of the 1.0 mm and 2.0 mm wavelengths of visual stimuli. For the 1.0=mm wavelength, the p-value was 0.2917 and the W statistic was 0.9763. For the 2.0 mm wavelength, the p-value was 0.7587 and the W statistic was 0.9867. Therefore, we treated the obtained samples as following normal distributions.

Instead of using the 86% discrimination threshold, we employed the standard deviation of the participants' responses. The pooled standard deviation among all participants was calculated for each visual stimulus.

III. RESULTS

Figure 2 displays the averages and standard deviations of individual participants. Due to previously mentioned reasons, data for Participant C at a wavelength of 1.0 mm and Participant D at a wavelength of 2.0 mm were excluded from the statistical analysis.

Table I presents the pooled standard deviations and 95% confidence intervals across all participants. The pooled standard deviation of tactile stimuli wavelengths was 0.335 mm for the visual wavelength of 1.0 mm. The value was 0.412 mm for the visual wavelength of 2.0 mm.

IV. DISCUSSIONS

The acceptable difference in wavelengths between the visual and tactile grating scales was 0.282–0.413 mm and 0.347–0.508 mm for $\lambda = 1$ mm and 2 mm, respectively. We converted the permissible errors reported in [8] to be comparable with the values in this study. The values converted from [8] were 0.414 mm, 0.511 mm, and 0.554 mm for $\lambda = 1$ mm, 1.8 mm, and 2.2 mm, respectively. These values are greater than those found in this study.

The major difference between the two studies lies in whether the tactile stimuli were actual or virtual. We speculated that virtual tactile textures would increase the permissible ranges because they are less distinct than actual textural stimuli. However, the results were contrary to this expectation. One potential explanation is that in our setup, participants could directly see their finger sliding on the visual textures, making them more sensitive to the difference between the visual and tactile textures. In contrast, participants could not do so in the setup of [8].

V. CONCLUSIONS

In this study, we determined the error tolerances between visual and tactile grating stimuli presented by electrostatic friction displays. The obtained results contribute to the optimization of texture presentation with electrostatic friction tactile displays. Designers of haptic content can now understand the required consistency between visual and tactile stimuli, which helps them determine the necessary specifications for their content and texture displays.

In the future, it will be important to investigate wavelengths greater and smaller than those used in this study to provide comprehensive design guidelines for haptic content. Additionally, since the presentation of three-dimensional shapes by modulated friction is a feature of electrostatic texture displays [14], [15], it will be intriguing to test the error tolerance when virtual shapes and gratings are combined [9].

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