Perceptual Fusion of Combined Electrotactile and Vibrotactile Stimuli for Presenting Moving Textures

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Abstract. Vibrotactile feedback is widely used in handheld controllers to enhance user experience in interactive applications such as gaming. To overcome its limitations, particularly in spatial resolution, electrotactile stimulation can be combined with vibrotactile stimulation. When electrical and vibrotactile stimuli are presented simultaneously, their effectiveness depends on whether they are perceived as a single coherent sensation, referred to as "tactile fusion". However, the conditions that promote tactile fusion at the fingertip when using vibrotactile and electrotactile stimuli remain insufficiently understood, particularly with respect to the spatial characteristics of stimulation. This study investigates how the design factors of electrotactile and vibrotactile stimulus applied to the fingertip influence tactile fusion, when the electrotactile stimulus is moving while the vibrotactile stimulus is presented over the entire fingertip. Two experiments were conducted. Experiment 1 examined the effects of vibration frequency, vibration intensity, electrotactile stimulus area, movement speed, and electrotactile stimulus intensity on tactile fusion. Based on these results, Experiment 2 focused on the electrotactile stimulus area to identify an optimal area for maximizing fusion. The results showed that tactile fusion at the fingertip was significantly influenced by vibration frequency, electrotactile stimulus area, movement speed, and electrotactile stimulus intensity. These findings suggest that tactile fusion is enhanced when stimuli is spatially extensive, the intensity difference between electrotactile and vibrotactile stimuli is small, and stimuli can be easily tracked over space.

Keywords: Electrotactile, Tactile Fusion, Vibrotactile.

1 Introduction

In recent years, vibrotactile feedback has been widely adopted in handheld controllers and commercial devices such as smartphones and game controllers [1][2][3] due to its simple and low-cost implementation [4]. However, the limited size of vibrotactile actuators makes it difficult to convey detailed spatial information in limited surface areas such as the fingertip [5].

Electrotactile stimulation has attracted attention as an alternative approach because it can provide high spatial resolution through flexible electrode placement [6] and enables the design of compact, lightweight, and energy-efficient devices suitable for wearable and fingertip interfaces [7][8]. However, electrotactile feedback often feels artificial and can cause discomfort, which remains a significant challenge.

To address these issues, research has been conducted on combining vibrotactile and electrotactile stimulation to leverage complementary exploit the characteristics of each modality. Previous studies have reported that combining these two types of stimulation increases subjective perceptual intensity and lowers perceptual thresholds [9][10], that vibrotactile stimulation suppresses discomfort induced by electrotactile stimulation [11], and that the combination of the two improves pattern recognition performance compared to vibrotactile stimulation alone [12]. Consequently, it becomes possible to achieve haptic expressions that leverage the high spatial resolution of electrotactile stimulation while mitigating its inherent discomfort using vibrotactile stimulation.

However, many previous studies combining electrotactile and vibrotactile stimulation have treated both modalities as equivalent forms of haptic feedback, leaving their potential largely unexplored. In particular, it remains unclear how high–spatial-resolution electrotactile stimulation at the fingertip can be effectively combined with vibrotactile stimulation applied to the entire finger to produce coherent tactile fusion.

This study focuses on handheld controller applications and investigates the combination of high-density electrotactile stimulation and a single vibrotactile stimulus applied to one finger. We use fingertip motion perception as a representative case, as electrotactile stimulation can precisely convey motion but often yields an artificial sensation. By adding vibrotactile stimulation, we aim to achieve a more textured and natural motion sensation. We define "tactile fusion" as the perception that vibrotactile stimulation moves together with electrotactile stimulation, and we examine how spatial extent and stimulus intensity affect its strength. We hypothesize that tactile fusion increases when differences in spatial extent and intensity between the two modalities are minimized (or less perceptible).

2 Experimental Device

An overview of the device used in this study is shown in **Fig. 1** (A). The device consists of a vibrotactile actuator (a full-range loudspeaker, 50 mm in diameter, 25 W; **Fig. 1** (B)), and an electrotactile stimulation unit. The switching circuit and electrode unit of the electrotactile stimulation device (**Fig. 1** (C)) are attached to the speaker's diaphragm using double-sided adhesive tape. By placing a finger on the diaphragm, users can simultaneously perceive both electrotactile and vibrotactile stimulation. The intensity of vibration was calibrated in advance by attaching an accelerometer (BMX055, Bosch) to the diaphragm under no-load conditions (i.e., without finger contact).

The electrotactile stimulation system comprises a main board and a switching board connected via a flexible flat cable (FFC). The main board includes a microcontroller (ESP32-S3, Seeed Studio), a digital-to-analog converter (AD5452, Analog Devices), and an analog-to-digital converter (AD7476, Analog Devices). The switching board consists of high-voltage switches (HV513, Microchip) and is connected to a flexible electrode array. This array is composed of 64 electrodes (1.1 mm in diameter, 2.54 mm center-to-center spacing) arranged on a flexible substrate measuring 28.0 mm × 17.0 mm [13].

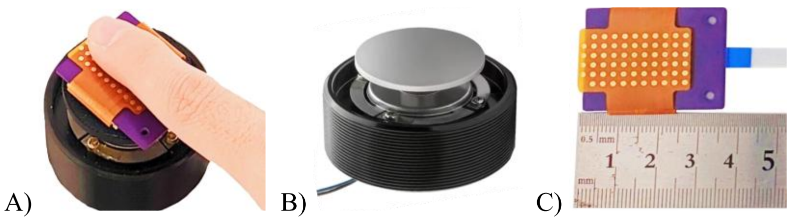

Fig. 1. Experimental Setup: (A) Overview, (B) Vibrotactile, (C) Electrotactile part.

3 Experiment1

The objective of this study is to investigate how stimulus parameters influence the perception of tactile fusion when vibrotactile stimulation is presented concurrently with electrotactile stimulation simulating motion. The experimental stimuli consist of electrotactile stimulation moving from the distal end of the finger toward the finger pad, superimposed with vibrotactile stimulation applied to the entire fingertip. While electrotactile stimulation alone evokes a sensation similar to being traced with a pen tip, the addition of vibrotactile stimulation is expected to elicit qualitatively different sensations, such as the "cutting" sensation experienced in video games.

The experiment involved 11 participants (8 male, 3 female; aged 21–24 years; including two left-handed individuals). All procedures were approved by the institutional ethics committee.

3.1 Conditions

The vibrotactile conditions comprised seven levels: three vibration frequencies (30 Hz, 60 Hz, and 200 Hz), two intensity levels (0.2 G and 1.0 G), and a no-vibration control. These frequencies were selected to target specific mechanoreceptors: 30 Hz primarily stimulates Meissner corpuscles, 60 Hz activates both Meissner and Pacinian corpuscles, and 200 Hz predominantly targets Pacinian corpuscles [14]. Due to these distinct receptor characteristics, the perceived spatial spread of the vibration is expected to vary by frequency. Intensity levels were defined as 0.2 G (weak but clearly perceivable) and 1.0 G (strong). To control temporal effects, vibrotactile stimulation was applied exclusively during the period of electrotactile stimulation.

The electrotactile stimulation was defined by three factors: stimulation area (2 × 2 and 4 × 4 arrays), motion speed (3.3 cm/s and 10 cm/s), and stimulus intensity (absolute and discomfort thresholds). As illustrated in **Fig. 2**, the stimulation area involved an electrode array moving from the top to the bottom of the grid. The motion speed was set to 10 cm/s to ensure the smoothest perception of motion, while 3.3 cm/s (one-third of the baseline) was selected for comparison. A higher speed of 30 cm/s was excluded as it proved too rapid for clear perception. Notably, the motion speed inherently dictates the duration of the stimulus presentation.

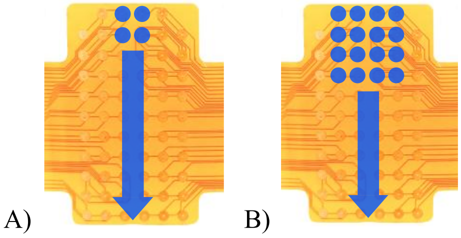

Fig. 2. Stimulation Area: (A) 2 × 2, (B) 4 × 4.

3.2 Procedure

Prior to the experiment, participants calibrated their electrotactile intensity thresholds. While placing the index finger of their dominant hand on the device, a sinusoidal vibrotactile stimulus (200 Hz, 1.0 G) was presented. Participants then adjusted the electrotactile intensity to determine their absolute threshold and the maximum threshold just prior to the onset of discomfort. The vibration was set to 1.0 G to correspond with the maximum intensity used in the experiment. To ensure consistency and minimize external noise, participants disinfected their fingers and wore earmuffs.

The experiment was divided into two phases. In the first phase, all 56 stimulus conditions were presented once in a randomized order without evaluation, allowing participants to establish internal rating criteria. In the second phase, each condition was presented again for formal evaluation. Upon completing all trials, participants provided qualitative feedback.

Three subjective measures were evaluated using a seven-point Likert scale:

- Tactile Fusion: The sensation of the electrotactile and vibrotactile stimuli moving together as a single integrated stimulus. (evaluated only for conditions including vibration).
- Smoothness: The perceived continuity of the electrotactile motion.
- Preference: The degree of subjective comfort, with higher scores indicating a stronger preference.

3.3 Result

Due to space limitations, this paper focuses exclusively on the results for tactile fusion, as shown in **Fig. 3** Based on the criteria that the strongest tactile fusion is characterized by the highest median score and the smallest interquartile range (IQR), the most robust fusion was observed under the following conditions: a vibration frequency of 60 Hz, an intensity of 0.2 G, an electrotactile stimulation area of 4 × 4 electrodes, a motion speed of 3.3 cm/s, and a stimulus intensity set to the maximum threshold.

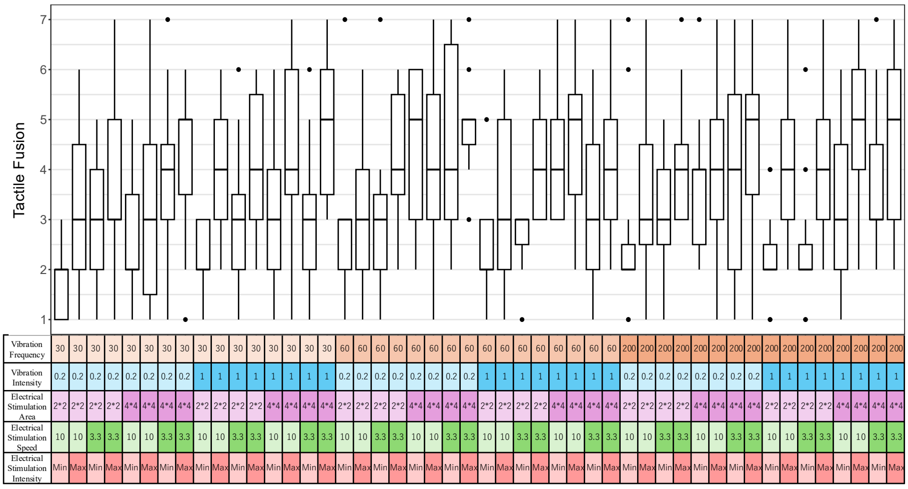

Fig. 3. Tactile Fusion for All Conditions in Experiment 1.

To examine the factors influencing tactile fusion, a linear mixed-effects model (LMM) was constructed with tactile fusion as the dependent variable. The model included all main effects and second-order interactions, with significance evaluated via Type III Analysis of Variance (ANOVA). No significant violations of model assumptions, such as normality or homoscedasticity, were observed.

The analysis revealed significant main effects for vibrotactile frequency ($p = 0.045$), electrotactile stimulation area ($p < 0.001$), motion speed ($p = 0.004$), and electrotactile stimulus intensity ($p < 0.001$). Furthermore, significant interaction effects were found between vibrotactile frequency and vibrotactile intensity ($p = 0.041$), vibrotactile intensity and electrotactile motion speed ($p = 0.012$), vibrotactile intensity and electrotactile stimulus intensity ($p = 0.005$), and electrotactile stimulation area and stimulus intensity ($p = 0.023$).

Fig. 4 illustrates the estimated marginal means (EMMs) and 95% confidence intervals (CIs) for each main effect, while **Fig. 5** presents the EMMs for significant interactions. Post-hoc pairwise comparisons for vibrotactile frequency showed that tactile fusion was significantly higher at 60 Hz compared to 30 Hz ($p = 0.045$), although the differences between 30–200 Hz ($p = 0.161$) and 60–200 Hz ($p = 0.843$) did not reach significance. Overall, fusion increased with a larger stimulation area, slower motion speed, and higher stimulus intensity.

Simple main effect analyses showed that vibrotactile frequency significantly affected tactile fusion only at 0.2 G (30 vs. 60 Hz: $p = 0.002$; 30 vs. 200 Hz: $p = 0.031$; 60 vs. 200 Hz: $p = 0.640$), with no differences at 1.0 G (all $p > 0.99$). Similarly, electrotactile motion speed was significant at 0.2 G ($p < 0.001$) but not at 1.0 G ($p = 0.818$).

Regarding the intensity interaction, vibration intensity had no effect when electrotactile stimulation was weak ($p = 0.099$), but significantly increased fusion under the stronger vibration condition when electrotactile stimulation was strong ($p = 0.022$). Notably, strong electrotactile stimulation consistently yielded higher fusion ratings regardless of vibration intensity (0.2 G: $p < 0.001$; 1.0 G: $p < 0.001$). Finally, while an interaction between electrotactile area and intensity was observed, the overall trends remained consistent with their main effects.

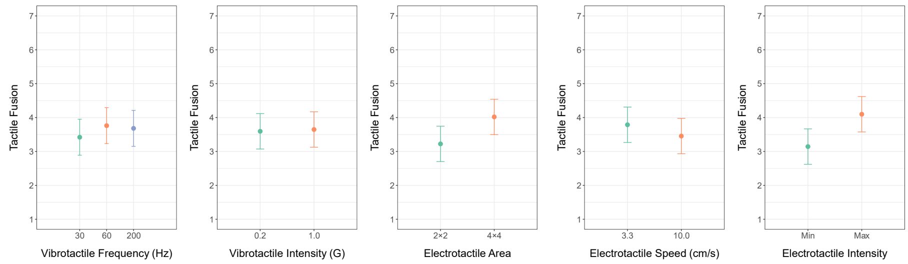

Fig. 4. Tactile Fusion for Each Factor

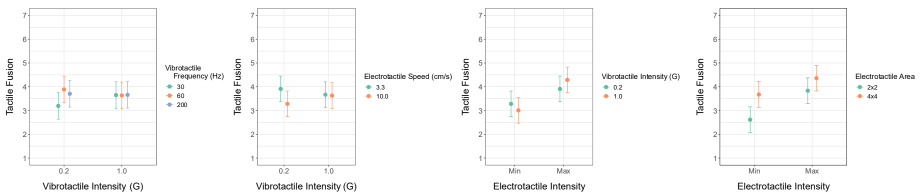

Fig. 5. Effects of Factor Pairs on Tactile Fusion

3.4 Discussion

Tactile fusion was most pronounced under the 60 Hz vibrotactile condition. We initially hypothesized that 200 Hz vibration, which primarily stimulates Pacinian corpuscles [14], would elicit the strongest fusion due to its more spatially diffuse percept. However, while fusion tended to be higher at 200 Hz than at 30 Hz, this difference was not statistically significant, suggesting that spatial diffusion alone is insufficient to enhance fusion. At 200 Hz, excessive spatial spread may have hindered the association of vibrotactile and electrotactile stimuli as a single event. Conversely, 60 Hz may have provided an optimal balance between spatial spread and localization, thereby facilitating perceptual fusion.

Tactile fusion also increased with a larger electrotactile stimulation area, supporting the hypothesis that spatial correspondence between the two modalities promotes fusion. Since vibrotactile stimulation was applied to the entire fingertip, a larger electrotactile area likely increased the spatial overlap, contributing to a unified percept.

Similarly, stronger electrotactile stimulation enhanced fusion, likely because increased intensity improved the perceptual salience of the stimulus's motion and location. Vibrotactile intensity alone had a negligible effect, possibly because it did not inherently convey motion information.

Regarding interactions, frequency-dependent differences in tactile fusion were observed only under low vibrotactile intensity. High-intensity vibration appeared to diminish frequency-specific effects, likely due to broadband receptor activation that obscured the distinct characteristics of each frequency. A similar trend was observed for motion speed. Although vibrotactile intensity was not a dominant factor on its own, its interaction with electrotactile intensity suggests that the relative balance between the two modalities is a key determinant of fusion. Overall, tactile fusion appears to be primarily driven by the perceptual strength and clarity of the electrotactile stimulus, with vibrotactile stimulation playing a complementary role in shaping the integrated sensation.

4 Experiment2

Based on the results of Experiment 1, this subsequent experiment focuses on the electrotactile stimulation area to further investigate its impact on tactile fusion, while maintaining all other parameters constant. Fourteen participants (10 males and 4 females; aged 21–24 years; including two left-handed individuals) took part in the study.

4.1 Conditions

The electrotactile stimulation area comprised four conditions: 1 × 1, 2 × 2, 3 × 3, and 4 × 4 electrode arrays. To more precisely characterize the effect of area on tactile fusion, 1 × 1 and 3 × 3 conditions were added to those used in Experiment 1. The 1 × 1 condition represents the minimum spatial extent, producing a point-like sensation, while areas exceeding 4 × 4 were excluded to avoid near-uniform stimulation that would diminish motion perception. All other stimulus parameters were fixed to the values that yielded the highest tactile fusion scores in Experiment 1.

4.2 Procedure

The experimental setup was identical to that of Experiment 1. To establish internal evaluation criteria, participants first experienced all conditions once in a randomized order without providing ratings. In the main trials, each condition was presented five times in a randomized order for evaluation. This repetition was implemented to minimize single-trial variability and enhance the reliability of the ratings. The evaluation metrics remained the same as in Experiment 1: tactile fusion, smoothness, and preference, each assessed on a seven-point Likert scale.

4.3 Result

For Experiment 2, each participant's median rating per condition was used to analyze tactile fusion, preference, and smoothness. To account for repeated trials, linear mixed-effects models (LMMs) were constructed with stimulation size as a fixed effect and participant as a random effect. Statistical significance was evaluated using Type III

Analysis of Variance (ANOVA). For all models, the normality of residuals and random effects, along with homoscedasticity, were confirmed. The results, including boxplots and significance levels, are presented in **Fig. 6**.

Tactile fusion showed a highly significant main effect of stimulation size ($p < 0.001$). Post-hoc comparisons using Tukey's method revealed that fusion ratings were significantly higher in the. A marginal difference was also observed between the 2 × 2 and 4 × 4 conditions ($p = 0.052$). In contrast, no significant main effects of stimulation size were found for preference ($p = 0.125$) or smoothness ($p = 0.113$).

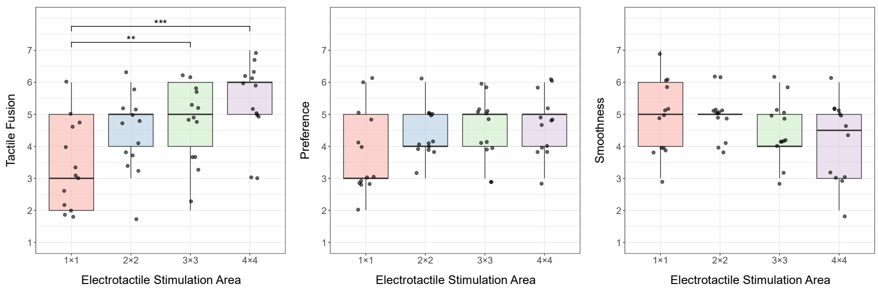

Fig. 6. Changes in Perception with Varying Stimulation Area.

4.4 Discussion

Overall, tactile fusion tended to increase with larger stimulation areas. Significant differences were observed between the 1 × 1 condition and both the 3 × 3 and 4 × 4 conditions; however, no significant differences were found among the other pairings. This pattern suggests that the effect of stimulation area on tactile fusion does not follow a linear progression but instead saturates beyond a certain spatial extent.

Furthermore, because the stimulation area had no significant impact on smoothness or preference, these findings indicate that area size does not directly influence perceived temporal continuity or subjective comfort.

5 Conclusion

This study investigated the conditions under which distributed electrotactile stimulation and fingertip-wide vibrotactile stimulation are perceived as a unified sensation. Specifically, we examined how various stimulus parameters influence subjective tactile fusion when electrotactile stimulation simulates motion accompanied by vibrotactile cues.

The results of Experiment 1 demonstrated that tactile fusion is enhanced by a greater perceived spatial spread of the stimulus and that the ability to continuously track the motion trajectory is a critical factor for perceptual fusion. Furthermore, fusion was most effective when the perceived intensities of the electrotactile and vibrotactile modalities were well-balanced. Experiment 2 further established that the spatial extent of the electrotactile stimulation plays a significant role in facilitating this fusion, though its effect appears to saturate beyond a certain area.

While this study primarily focused on manipulating the spatial parameters of electrotactile stimulation, future research should systematically vary the spatial extent of vibrotactile stimulation. Such investigations will provide a more comprehensive understanding of how spatio-temporal correspondence between distinct tactile modalities governs the fusion of complex haptic sensations.

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