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Perceptual Matching of Electrotactile and Vibrotactile Stimulations*

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I. Introduction

Haptic feedback plays a vital role in virtual object interaction by conveying tactile information and thus enabling precise manipulation. While mechanotactile and vibrotactile stimulations are commonly used for haptic feedback [1], their bulky form factors and potentials for discomfort limit their use in mixed-reality (MR) applications. Transcutaneous electrotactile stimulation, delivered through skin-surface electrodes, offers a promising alternative due to its thin, lightweight, and low-power system characteristics [2]. Recent studies have explored its application in MR environments to provide effective tactile feedback [3]. For example, Withana et al. [4] developed a fingertip device capable of delivering electrotactile feedback without obstructing physical interaction, and Tanaka et al. [5] proposed a wearable electrotactile system offering whole-hand stimulation. However, these approaches are limited in the range of tactile sensations they can evoke.

Vibrotactile feedback, commonly used in haptic devices [6], can provide a wide range of tactile sensations by varying frequency, intensity, and duration. While Previous studies have investigated how electrotactile parameters affect perception [7, 8], direct comparisons of frequency perception between electrotactile and vibrotactile modalities remain less explored. Some studies, such as Yoshimoto et al. [9] and Yem & Kajimoto [10], addressed related issues, but focused primarily on intensity rather than frequency perception.

Prior research suggests that electrotactile stimulation is capable of inducing vibrotactile-like sensations and eliciting a range of perceptual frequencies [7, 8]. Nevertheless, understanding how the pulse frequency (PF) of electrical stimulation correlates with the perceived vibrational frequency is essential for accurately replicating targeted perception.

Therefore, this study aims to directly compare the perceived frequencies of transcutaneous electrotactile and vibrotactile stimulation in healthy adults. By examining the relationship between pulse frequency and perceived vibration we seek to inform the design of effective electrotactile feedback systems for MR applications.

II. Methods

A. Participants and Apparatus

Eleven right-handed participants (5 female, mean age 25.7 ± 3.35 years) with no hypersensitivity to electrical stimulation or hyperhidrosis participated. The study was approved by the Institutional Review Board of UNIST (UNISTIRB-23-054-C).

The tactile system comprised two modules: an electrotactile stimulator using a constant current pulse device (Model 2100, A-M Systems™, Washington, USA) and stainless-steel electrodes, and a vibrotactile actuator (PowerHap™, TDK, Tokyo, Japan) driven by a signal amplifier. Stimulus control was handled via MATLAB (MathWorks, Inc. MA, USA). Biphasic, cathodic-first square pulses (PW: 500 µs) were delivered to the left index finger (electrotactile) and right index finger (vibrotactile). Perceived intensity was controlled via pulse amplitude (PA).

B. Task Procedure

Detection thresholds (DTs) for electrotactile stimuli at 20, 40, and 60 Hz were measured using an adaptive staircase method. PA levels for each participant were set between their DT and their reported stinging or electrical sensation threshold.

The experiment consisted of three tasks: 1) Unimodal Frequency Discrimination (FD) Task where participants discriminated the frequency of either electrotactile or vibrotactile stimuli; 2) Frequency Matching (FM) Task where participants compared vibrotactile stimuli to electrotactile stimuli and adjusted parameters using an adaptive staircase method to identify vibrotactile stimuli that matched the electrotactile stimuli in perceived frequency and intensity; and 3) Cross-Modal Frequency Discrimination (CMFD) Task where participants compared matched pairs of electrotactile and vibrotactile stimuli to discriminate perceived frequency.

Each task was conducted following a two-interval forced-choice (2IFC) paradigm where two stimuli were presented serially in a random order, each lasting 2 seconds with a 2-second interval between them. In the FD and CMFD tasks, participants judged which stimulus had a higher perceived frequency.

C. Data Analysis

For the FD and CMFD tasks, each stimulus pair was presented 14 times in randomized order. Participants' responses were scored as ±1 depending on whether it was judged to vibrate higher or lower, and the scores were summed across trials. Statistical analysis was performed using a

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two-tailed Kruskal–Wallis test with Tukey–Kramer post hoc correction (KWTK) for multiple comparisons.

III. Results

As illustrated in Figs. 1(a) and 1(b), the participants demonstrated a consistent ability to differentiate between the three frequencies across both electrotactile and vibrotactile modalities (KWTK, $p<0.05$). Furthermore, stimuli with higher frequencies were generally perceived as having higher vibrational frequencies compared to lower-frequency stimuli (KWTK, $p < 0.05$). As illustrated in Fig. 1(c), the result of the FM task revealed that the participants perceptually matched the vibrotactile stimulus with frequency as approximately half of the frequency of the electrotactile stimulus: PF 20 Hz (electrotactile) → 12.19 Hz (vibrotactile); PF 40 Hz → 23.01 Hz; and PF 60 Hz → 32.06 Hz. For all tested PFs, the matched vibrotactile frequencies were consistently lower than the corresponding electrotactile PFs. Fig. 1(d) further validates the results from the matching task. When comparing the matched pairs of vibrotactile and electrotactile stimuli, the participants were unable to differentiate between the two modalities in terms of perceived frequency.

IV. Discussion and Conclusion

The findings of this study demonstrated that people could reliably discriminate between different stimulation frequencies across electrotactile and vibrotactile modalities. In the frequency matching task, participants exhibited a consistent tendency to select vibrotactile stimuli with frequencies approximately half of the corresponding electrotactile PFs. The CMFD task result further backs successful cross-modal frequency matching. These results support the viability of electrotactile stimulation in replicating vibrotactile stimulation with the perceptual scaling differences that must be considered in designing electrotactile haptic feedback.

The finding that the matched vibrotactile frequencies were approximately half of the corresponding electrotactile PFs may be related to the neural encoding mechanisms triggered by electrical pulses. Muniak *et al.* [11] have investigated the neural coding of vibratory stimuli in the mechanoreceptive afferents of non-human primates, showing that vibration frequency can be coded by the firing rate. For the vibratory stimuli used in the frequency range of the present study, it is likely that, above a certain intensity value, the evoked spike activity approximately doubles. However, it should also be noted that the perceived frequency can approximate the actual PF when stimulus intensity is low, indicating that perceived frequency may also depend on the strength of stimuli. Furthermore, considering that such electrical stimulation patterns are based on biomimetic approaches that mimic neural encoding strategies [12], it can be suggested electrotactile stimuli evoke vibratory sensations perceived at roughly half the applied PF.

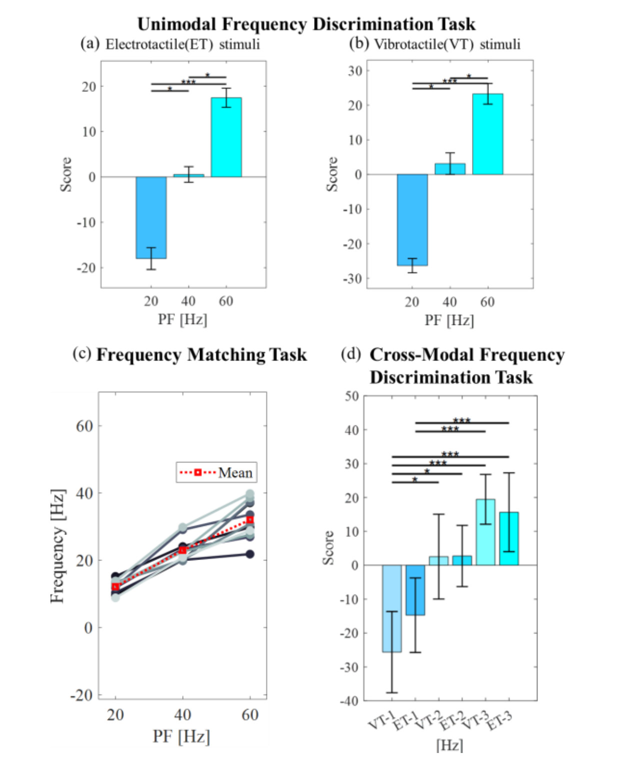

Figure 1. Experimental results from the three tasks. (a) Frequency discrimination performance for electrotactile (ET) stimuli. (b) Frequency discrimination performance for vibrotactile (VT) stimuli. (c) Results from the frequency matching task. Each dot represents data from an individual participant (n = 11). The red dash-dot line indicates the mean perceived frequency for each PF across participants. (d) Cross-modal frequency discrimination results between matched VT and ET stimuli. Data are represented as mean ± SD. (KWTK, $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.)

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