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Tactile Enhancement of Mid-Air Ultrasonic Stimulation by Wrist Vibration: Perceived Intensity and Pattern Recognition

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***Abstract*—This study investigates methods to enhance the perceived intensity of mid-air ultrasonic tactile stimuli through the perceptual phenomenon of tactile enhancement. By presenting a brief vibrotactile stimulus to the wrist before stimulating the palm with a mid-air ultrasonic stimulus of the same frequency, we demonstrated that the perceived intensity could be increased by up to 1.7 times. A second user study further examined the effectiveness of this method, revealing that recognition of number-patterned mid-air stimuli was significantly improved by 7.8 % with the presence of wrist vibration. These findings offer promising directions for improving the usability of mid-air haptic devices using common wearable technology.**

***Index Terms*—Mid-air ultrasonic tactile stimulation, Tactile enhancement, Perceived intensity, Wearable haptics, Recognition.**

I. Introduction

The technology of mid-air haptics excites a user's skin using a stimulus transmitted through the air and elicits a tactile sensation from the user, without requiring physical contact. Since the introduction of focused ultrasound for this purpose [1, 2], mid-air haptics has marked a significant milestone in the development of human interaction technologies and applications. Although some alternatives, such as laser-based methods [3, 4], were tested, the ultrasound approach remains the predominant technology for mid-air haptics. However, this approach has suffered from two primary weaknesses that significantly limit its usability: limited energy transmission distance and weak perceptual intensity [5]. Improving upon these problems is essential to advance the mid-air haptics technologies and expedite its adoption in diverse practical applications.

In this paper, we explore methods to enhance the perceptual strength of mid-air focused ultrasonic stimuli while preserving usability for mid-air applications. Our approach leverages a perceptual phenomenon known as *tactile enhancement* [6]. As depicted in Fig. 1 (top), if two vibrations are sequentially applied to the same location on the hand, the second vibration is perceived as more intense than when presented alone; i.e., its perceptual strength is enhanced. In our method (Fig. 1, bottom), a brief vibration generated by an electromagnetic actuator is applied to the wrist, e.g., using a device like a smartwatch. It is followed by a mid-air ultrasound stimulus stimulating the palm. This method differs from the typical conditions in which tactile enhancement is observed in two aspects: 1) the locations of the preceding and following stimuli are different, and 2) the following stimulus is produced by focusing ultrasounds. We demonstrate that tactile enhancement occurs in such conditions; that is, the mid-air ultrasonic stimuli feel stronger than when they are presented alone.

After reviewing related work (Sec. II), we describe the experimental setup used to examine the tactile enhancement effect for midair ultrasonic displays (Sec. III). In User Study 1 (Sec. IV)[1], we quantify the extent of tactile enhancement of the perceived intensity of a focused ultrasound stimulus enabled by a preceding contact stimulus. This study examines the degrees to which four preceding contact vibrations combining two frequencies (50 and 200 Hz) and two amplitude levels (weak and strong) increases the perceptual strengths of the following ultrasound stimuli. In User Study 2 (Sec. V), we consider a pattern recognition task for ten focused ultrasonic spatiotemporal patterns representing digits. The goal was to evaluate the amount of increase in pattern recognition accuracy that our tactile enhancement technique using an additional contact stimulus can achieve. The main findings from the two user studies are summarized in Sec. VI discussion ideas for future work. To our knowledge, this paper reports the first demonstration that improves the perceptual performance of focused ultrasound stimuli by applying an additional tactile stimulus to a body spot near the palm, relying on the concept of tactile enhancement.

II. Related Works

A. Mid-air Haptics

Mid-air haptics utilizes focused ultrasound to enable free-hand interactions and present intricate tactile patterns on the hand without requiring physical contact [1]. This unique and vital advantage can significantly broaden the scope of haptic interaction and enhances immersion in VR/AR environments [8, 9], motivating numerous studies on applications of mid-air haptics. Researchers have explored ways to use ultrasonic stimuli for automobiles, public displays, artistic and scientific

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[1]User study 1 was presented earlier in Eurohaptics 2024 [7]. This paper extends it with another study about human recognition of tactile spatiotemporal patterns.

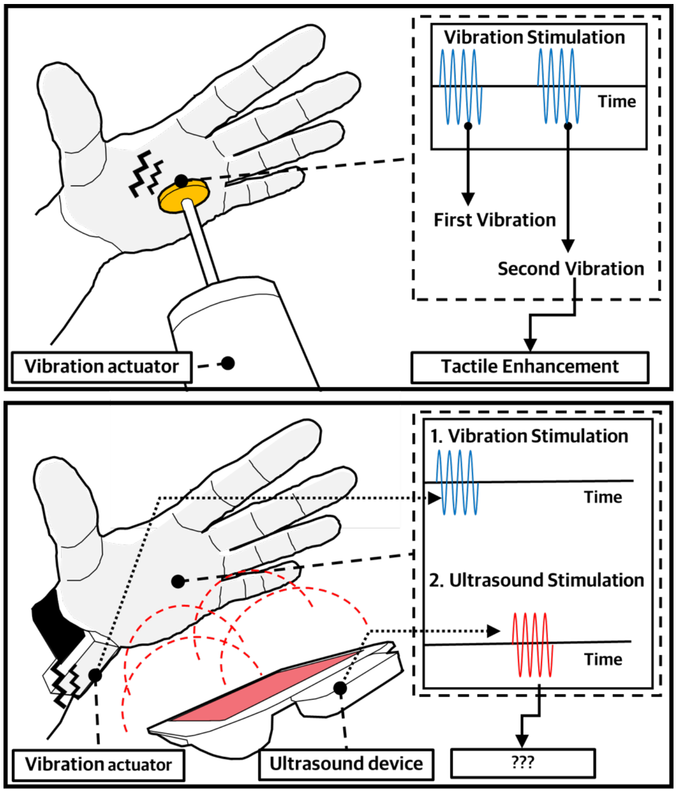

Fig. 1. Illustration of tactile enhancement. (Top) Typical situation of two successive mechanical vibration stimulating the palm (reproduced from [6]; see Sec. II-B for more details). (Bottom) Our setup tested in this paper for mid-air ultrasound haptics.

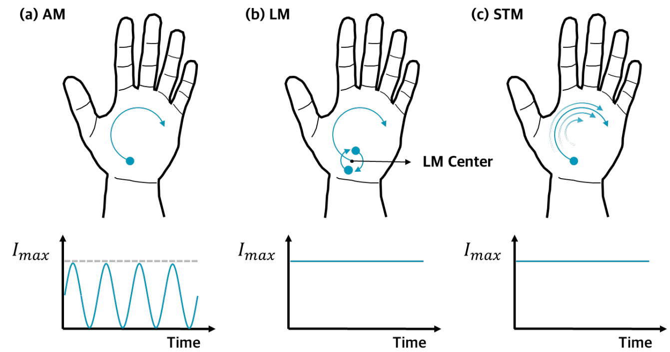

Fig. 2. Ultrasonic modulation techniques: focal point trajectories (top) and intensity variations over time (bottom). (a) Amplitude modulation (AM); (b) Lateral modulation (LM); (c) Spatiotemporal modulation (STM). In STM, the focal point is rapidly and repeatedly (e.g., at a few hundred Hz) moved along the target path.

exhibits, training and simulation, and hospitals; see a detailed review in Georgiou et al. [10].

To develop such applications, it is critical to understand how the haptic quality of ultrasonic stimuli varies with key parameters, such as sampling rate [11], focal point speed [12], and pattern size [13]. Depending on the application, the stimulation site itself can also serve as a variable [14]. For instance, the fingertips are commonly used for delivering point stimuli [2], while the palm is often preferred for transferring moving stimuli [15] or pattern stimuli [16] due to its larger surface area and stability. In this study, the palm was selected as the stimulation site, as it is closer to the wrist to which a contact preceding stimulus is applied and advantageous for pattern stimulus recognition.

However, mid-air haptics must overcome a critical challenge—the weak intensity of tactile feedback—in order for broader adoption in practical applications [5, 17]. Researchers proposed several methods to address this issue. For example, Driller et al. showed that increasing the duration of mid-air haptic stimuli can enhance their perceived intensity [18]. However, this method may not be suitable for applications with strict temporal constraints. Georgiou et al. demonstrated that a larger stimulus size increases the perceived intensity, but it comes at the cost of reduced radiation pressure, requiring a trade-off between size and intensity [10].

A more effective approach involves modulating the ultrasonic stimuli. Three major modulation techniques, illustrated in Fig. 2, have been proposed and extensively tested so far. Among them, *amplitude modulation (AM)* periodically changes the intensity at the ultrasonic focal point over time (Fig. 2(a)). Its AM frequency is determined within the vibrotactile perceptual band (a few ten to a few hundred Hz). Contrarily, *lateral modulation (LM)* repeatedly and quickly moves the focal point along a short path (e.g., less than 1 cm) on the hand (e.g., at 1000 Hz) while keeping the intensity constant at the maximum level [19]. This technique doubles the stimulus energy compared to AM and also triggers the spatial summation effect of tactile perception, thereby improving the perceptual intensity. When applied to rendering a long path (Fig. 2(b)), LM generates strong and continuous sensations. Whereas AM and LM are effective for rendering both stationary points and moving patterns, the last method, *spatiotemporal modulation (STM)*, is specialized for rendering static patterns [20]. STM moves the focal point rapidly and repeatedly (e.g., at 200 Hz) along the target path while maintaining the maximum intensity (Fig. 2(c)) in order to elicit a sensation of patterned pressure on the hand. Recently, a new technique named *spatio-temporally modulated tactile pointers (STP)* was proposed, which divides a target shape into short segments and sequentially renders each using STM [21]. STP preserves the high perceptual intensity of STM while improving the shape rendering clarity.

Among these techniques, LM, STM and STP were specifically designed to improve the weak intensity of mid-air haptic feedback. In comparison, AM exhibits a relative weakness in intensity, but it provides a unique advantage: it enables dynamic *vibrational* experiences, much like traditional vibrotactile stimuli, within the perceptible frequency range of skin mechanoreceptors (40–200 Hz). As such, AM is better suited than STM to tasks involving the recognition of diverse tactile patterns, achieving higher accuracy in pattern recognition tasks [22]. Based on these findings, AM has been adopted in studies on ultrasonic haptic pattern recognition [23]. STP enables strong and clear rendering of static shapes, but it does not produce vibrotactile stimuli with clearly defined frequencies. Since our study required presenting mid-air vibrations at specific frequencies to induce tactile enhancement, AM was considered more appropriate for this purpose.

Despite its lower perceived intensity, dynamic haptic feedback rendered through AM provides versatility across a wide range of applications. To address the method's inherent limitations in perceived intensity, this study proposes a novel approach that integrates wrist-applied vibrotactile stimuli with mid-air ultrasounds. This hybrid technique is designed to enhance tactile perception and pattern recognition while maintaining the flexibility and dynamic capability of AM.

B. Tactile Enhancement

In human perception, loudness enhancement refers to a phenomenon where a sound following another sound is perceived louder without an increase in its actual intensity. This effect has been observed across various auditory stimuli and is influenced by factors such as timing, frequency, and intensity [24, 25]. Loudness enhancement can increase the perceived intensity of an auditory stimulus by up to 10 dB [24].

Verrillo and Gescheider [6] discovered a similar phenomenon in tactile perception and termed it *tactile enhancement*. Their study demonstrated that when two vibrotactile stimuli are presented consecutively under specific conditions, the perceived intensity of the second stimulus is amplified. This effect is most pronounced when the two stimuli share the same frequency, are delivered to the same body site, and are separated by a short inter-stimulus interval (ISI) of less than 500 ms. Furthermore, tactile enhancement requires the first stimulus to be more intense than the second stimulus, typically with a difference of around 10 dB. Under these conditions, the perceived intensity of the following stimulus can be nearly doubled.

Tactile enhancement is fundamentally different from tactile masking, another perceptual phenomenon observed with consecutive vibrotactile stimuli. In tactile masking, the presence of one stimulus diminishes the perceived intensity or detectability of a subsequent stimulus due to interference or sensory overload [26], which involves interference and competition for neural resources. In contrast, tactile enhancement is a facilitative process in which the first stimulus primes the sensory system, enabling the second stimulus to be perceived as more intense than its physical intensity would suggest.

Building on this principle, this study extends tactile enhancement to mid-air ultrasonic stimuli. This approach aims to overcome the inherent limitation of low perceived intensity of the amplitude modulation technique, thereby providing improved usability for diverse tactile applications while retaining the method's flexibility and pattern-rendering capability.

III. General Methods

This paper investigates the tactile enhancement of mid-air ultrasonic stimuli by examining the perceptual strength of mid-air haptic stimuli (User Study 1) and the recognition accuracy of tactile patterns rendered using focused ultrasound (User Study 2). The two studies, along with a preliminary experiment for perceived intensity calibration, were approved by the Institutional Review Board at POSTECH (No. PIRB-2023-E037). This section describes the methods used in both studies.

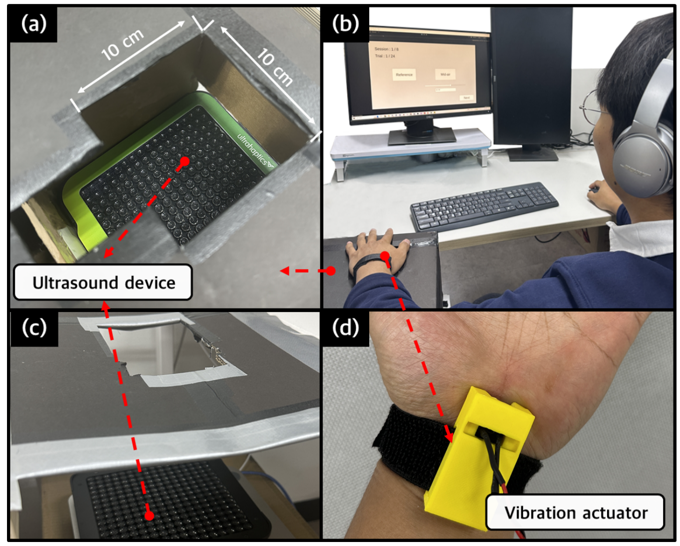

Fig. 3. Experimental setup. (a) A mid-air ultrasonic haptic interface enclosed in a box for user study 1. (b) A participant wearing the wrist band , while conducting the experiment. (c) A mid-air ultrasonic haptic interface for user study 2, without the box walls to preclude any interference caused by the walls. (d) Vibration actuator attached to the wrist. Both mid-air and contact vibrations are applied to the same hand: palm and palmar wrist, respectively.

A. Experimental Setup

Fig. 3 shows an experimental setup used to evaluate tactile enhancement of mid-air ultrasonic stimulation. A participant wore a wristband equipped with a vibration actuator while conducting the experiment. In User Study 1, a mid-air ultrasonic haptic interface (STRATOS™ Explore Development Kit, Ultraleap) was enclosed in a box to ensure controlled conditions (Fig. 3(a)). Participants were instructed to place their left palms over an aperture in the box's top cover to perceive mid-air tactile stimuli (Fig. 3(b)). In User Study 2, the interface setup was changed by removing the box walls (Fig 3(c)).[2] This adjustment was made to ensure that the tactile patterns would be perceived accurately without any interference that wall reflections might introduce.

Additionally, a vibration actuator (HapCoil-One, Actronika) was attached to the participant's wrist to provide contact-type stimuli (Fig. 3(d)). The vibration actuator was housed in a custom-designed 3D-printed case. This case was securely attached to the wrist using an adjustable band, as shown in Fig. 3(d), ensuring a tight fit. The vibration actuator was positioned to make direct contact with the soft tissue below the thenar eminence. This setup was designed to provide precise and consistent tactile stimuli to the same anatomical region across participants regardless of their palm size differences. It also allowed us to minimize variability in the distance between the wrist vibration and the mid-air ultrasonic stimulus, thereby enhancing the reliability of the tactile enhancement effects observed in this research.

In both experiments, participants perceived the two types of stimuli on the left hands (Fig. 1, right) to evaluate the extent of tactile enhancement. The distance from the ultrasound device to participants' hands was maintained as 20 cm. Participants controlled the experiment program's GUI using their right

TABLE I
EXPERIMENTAL CONDITIONS FOR USER STUDY 1.

Experimental Condition	50WN	50WW	50WS	50SN	50SW	50SS	200WN	200WW	200WS	200SN	200SW	200SS
Frequency (Hz)	50	50	50	50	50	50	200	200	200	200	200	200
Mid-air Vibration Intensity	WK	WK	WK	SR	SR	SR	WK	WK	WK	SR	SR	SR
Contact Vibration Intensity	NO	WK	SR	NO	WK	SR	NO	WK	SR	NO	WK	SR

hands while focusing visually on the screen. They also wore headphones that played white noise to block out sounds generated by the actuators.

B. *Perceived Intensity Matching*

The perceived intensity of a vibration is influenced by both its amplitude and frequency [27, 28]. Hence, we conducted a calibration procedure in both user studies to equalize the perceived intensities of the vibrations applied at the wrist with two different frequencies (50 and 200 Hz in User Study 1 and 80 and 200 Hz in User Study 2). Each vibration frequency was paired with two amplitudes eliciting weak and strong levels of perceptual strengths denoted by WEAK and STRONG. The amplitude values were determined by a pilot study. Six members of our research group, all experienced in vibrotactile perception and rendering, participated in the task. For 200-Hz vibrations, the STRONG level was set to the maximum output of the actuator, and the WEAK level was set to half of the maximum value. Next, participants were instructed to adjust the amplitude of 50-Hz (User Study 1) and 80-Hz (User Study 2) vibrations to match their perceived intensities to the 200-Hz vibrations at the corresponding WEAK or STRONG level. This process was conducted using a graphical interface, allowing participants to fine-tune the amplitude of the lower-frequency vibrations. The final amplitude value for each frequency was determined by averaging the estimates made by the six participants. This calibration procedure ensured that the contact vibrations applied at the wrist elicit the same, or at least very similar, perceptual strengths across frequencies.

IV. USER STUDY 1

In this user study, we tested whether the perceptual intensity of mid-air tactile stimuli could be enhanced by applying contact tactile stimuli beforehand.

A. *Methods*

1) Participants: Twenty participants (9 females and 11 males; aged between 20 and 32 years, with an average age of 24.5) took part in the study. None of the participants reported any sensorimotor impairments.

Before the experiment began, informed consent was obtained from each participant. Each participant received KRW 15,000 upon completion of the experiment. The experiment lasted about one hour.

[2]We appreciate a reviewer of our earlier conference paper who recommended this arrangement.

[2]The unit G represents gravitational acceleration (9.8 $\mathrm{m/s^2}$), which is commonly used to quantify vibrational amplitude.

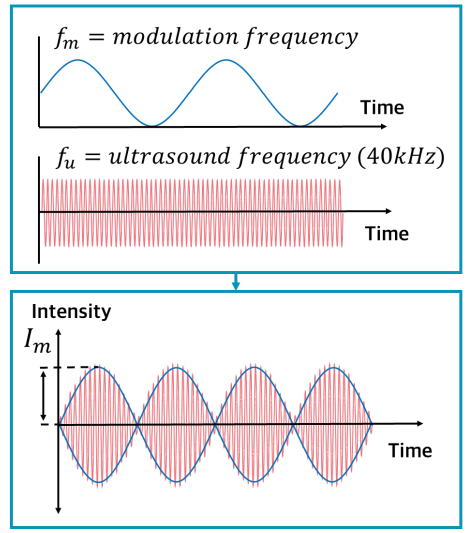

Fig. 4. Ultrasound stimulation method using amplitude modulation.

2) Stimuli: Tactile enhancement between two consecutive vibrations is maximized if they share the same frequency [6]. We selected two frequencies (50 and 200 Hz) for this experiment, which elicit relatively low, fluttering and smooth vibrational sensations, respectively [29]. Tactile enhancement also depends on the intensities of the two vibrations [6]. Thus, we combined the two frequencies factorially with three intensity levels (NONE, WEAK, and STRONG) of contact vibrations. In NONE, no contact vibration was presented, so participants perceived only mid-air tactile stimuli.

For the WEAK and STRONG conditions, the amplitudes were determined following the calibration procedure described in Sec. III-B. The amplitudes for the 50-Hz vibrations were 1.3 G and 2.9 G for WEAK and STRONG. They were 6.2 G and 8.8 G for the 200-Hz vibrations.

As shown in Fig. 4, a mid-air vibration signal was generated using amplitude modulation:

$$p(t) = \frac{I_m}{2}\left(1 + \sin\left(2\pi f_m t\right)\right)\sin\left(2\pi f_u t\right), \quad (1)$$

where I_m is the normalized amplitude, f_m is the modulation frequency, and f_u is the carrier frequency of ultrasound (40 kHz). f_m corresponds to the frequency of focal point vibration employing amplitude modulation, which is what the user perceives [11]. The mid-air stimuli were presented in two intensity levels, WEAK and STRONG. They were implemented by commanding the ultrasonic haptic device using 0.2 and 0.5 of its maximum intensity. These values are ratios and denoted using a unit AU (arbitrary unit) hereafter. Their perceptual effects were characterized by a follow-up experiment

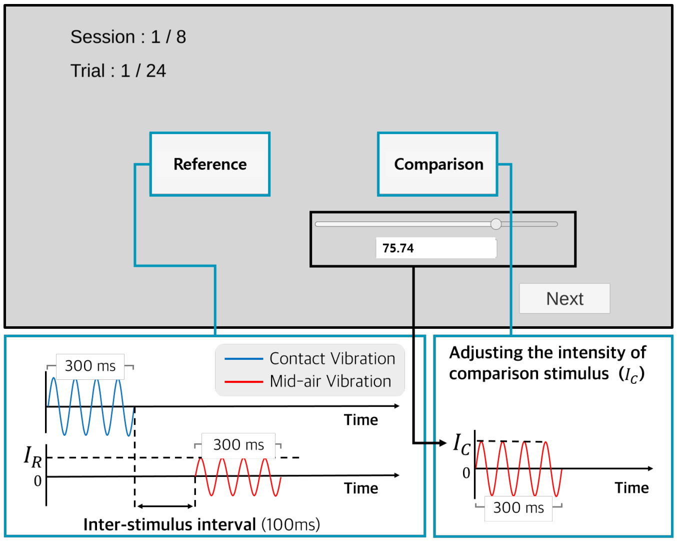

Fig. 5. Experimental program interface for User Study 1 (top). When a button (reference or comparison) was pressed, the corresponding stimulus (mid-air + contact or mid-air only) was generated (bottom). The slider below the comparison button allowed participants to adjust the comparison stimulus intensity.

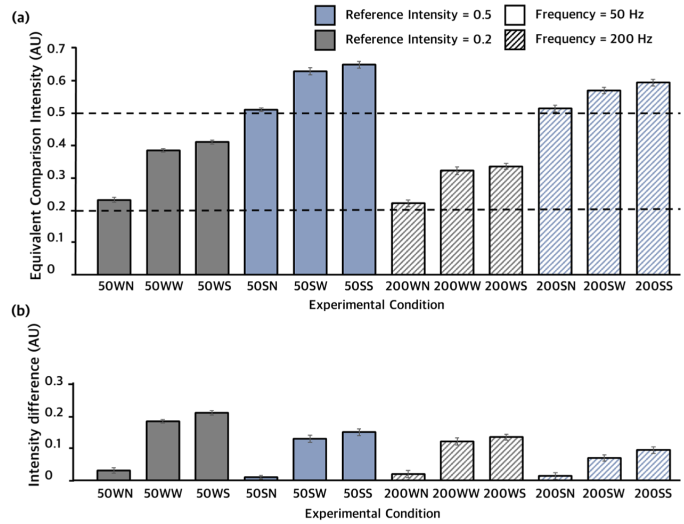

Fig. 6. (a) Mean intensities $\overline{I_C}$ of mid-air ultrasonic stimuli required to match the perceived intensities under the 12 experimental conditions. Error bars represent standard errors. (b) Mean intensity differences $\overline{\Delta I}$ of the perceived intensity thresholds I_C from the reference intensities I_R.

(Sec. IV-D). The distance between the stimulation point and the device was maintained at 20 cm. The last critical parameters were the stimulus durations and the inter-stimulus interval (ISI). Previous research on tactile enhancement showed that a shorter ISI resulted in a more pronounced effect [6]. In this study, we set the duration of both contact and mid-air vibrations to 300 ms and the ISI to 100 ms, as illustrated in Fig. 5 (bottom). The durations were empirically determined through repeated tests.

Table I summarizes the 12 experimental conditions of this study. Note that no preceding contact stimulus was presented in Conditions 1–4 (baselines).

3) Task and Procedure: The experiment consisted of eight sessions. The first session was for training, helping participants become familiar with the experimental procedure. Its data was excluded from data analysis. Each session included 24 trials, presenting the 12 experimental conditions twice in a random order. Hence, each experimental condition was evaluated using the data of 14 repetitions (7 sessions $\times$ 2 times).

In each trial, participants clicked the "reference" button on the GUI (Fig. 4, top). Then, a pair of two consecutive stimuli, a contact tactile stimulus followed by a mid-air stimulus after the ISI, were presented. Participants also perceived a mid-air tactile stimulus with a varying amplitude by clicking the "comparison" button. The amplitude was adjusted in AU between 0 and 1 using a slider on the GUI. Participants repeated to perceive the reference and comparison stimuli while changing the comparison stimulus amplitude. They stopped the comparisons when the two stimuli were perceived as equally strong and clicked the "Next" button to proceed to the next trial. This procedure followed the method of adjustment, and the initial comparison amplitude was randomly set in every trial.

After completing the main session, participants were interviewed to reflect on their experiences with the different haptic conditions. This interview aimed to gather qualitative insights into the participants' experiences and to better understand the perceptual relationship between wrist-applied vibrations and mid-air tactile stimuli. Participants were given open-ended questions to explore their perception of the tactile stimuli, including specific inquiries about how the wrist vibrations felt and how those vibrations influenced their perception of the palm stimuli.

4) Data Analysis: For each experimental condition, we evaluated the extent of tactile enhancement by comparing the intensity I_R of the reference mid-air stimulus with the intensity I_C of a comparison mid-air stimulus at which participants perceived as strong as the reference (contact + mid-air) stimulus. I_R and I_C are graphically illustrated in Fig 5 (bottom). Each experimental condition was repeated 14 times per participant, and we averaged the 14 values of I_C to obtain the threshold estimate $\overline{I_C}$ of the condition.

B. Results

Fig. 6 (a) presents all thresholds of $\overline{I_C}$ for equivalent perceived intensity estimated under the 12 experimental conditions. To better understand the enhancement effects, we computed the difference between the reference intensity and the intensity threshold, $\Delta I = I_C - I_R$, where I_R is a constant (0.5 or 0.2 AU), for every response. Their means, $\overline{\Delta I}$, are shown in Fig. 6(b).

Three-way repeated-measures ANOVA showed that ΔI was significantly affected by all three independent factors: vibration frequency ($F(1, 19) = 10.97, p = 0.0037$), contact stimulus intensity ($F(2, 38) = 65.53, p < 0.001$), and mid-air stimulus intensity ($F(1, 19) = 13.27, p = 0.0017$). Tukey's HSD tests were conducted on each factor for post-hoc multiple comparisons, and Fig. 7 shows their results. Using the vibration frequency of 50 Hz resulted in significantly greater increases in perceived intensity than 200 Hz. The mid-air stimuli with lower

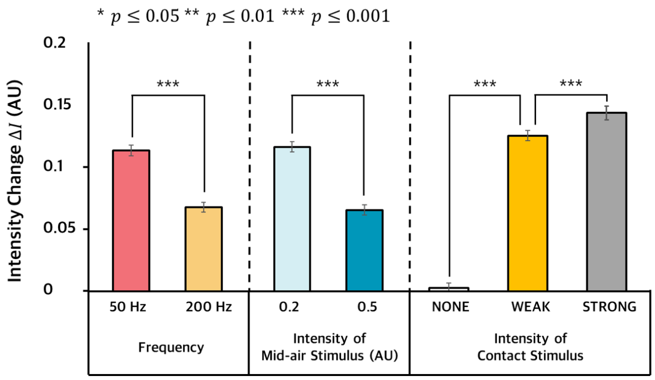

Fig. 7. Main factor effects for the perceived intensity difference ΔI. Error bars show standard errors. The factor means that had significant differences are denoted using asterisks.

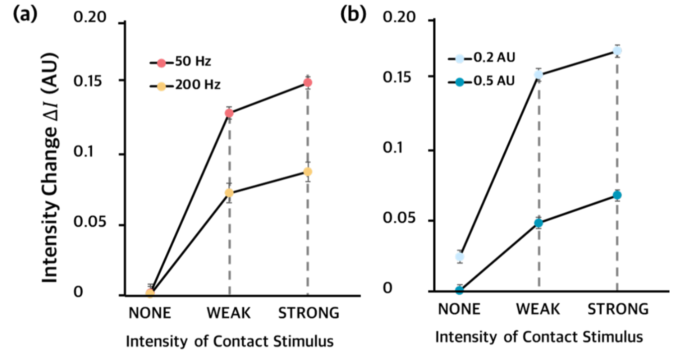

Fig. 8. Interaction plots (a) between contact stimulus intensity and vibration frequency and (b) between contact stimulus intensity and mid-air stimulus intensity. Error bars show standard errors.

intensity obtained significantly more pronounced enhancements than those with higher intensity. Finally, the enhancement effect was significant when the contact tactile stimulus was present (WEAK and STRONG), with STRONG exhibiting significantly better enhancement than WEAK.

Furthermore, interaction effects among the three factors were analyzed to better understand their combined influence on ΔI. The interaction term between vibration frequency and contact stimulus intensity was significant ($F(2, 38) = 4.39, p = 0.0193$). This effect can be understood using the interaction plot in Fig. 8(a). When the vibration frequency was 50 Hz, the perceived intensity increase was 0.002 AU at the contact vibration intensity of NONE, 0.130 AU at WEAK, and 0.150 AU at STRONG. Post-hoc comparisons confirmed that the difference between NONE and WEAK was significant ($p < 0.0001$), as was the difference between WEAK and STRONG ($p = 0.0222$). In contrast, at 200 Hz, tactile enhancement was still observed, but increasing contact stimulus intensity beyond the weak level did not yield additional benefits. The perceived intensity increase was 0.001 AU at NONE, 0.073 AU at WEAK, and 0.088 AU at STRONG. The difference between NONE and WEAK was significant ($p < 0.0001$), while the difference between WEAK and STRONG was not ($p = 0.2329$).

The interaction between contact stimulus intensity and mid-air stimulus intensity was also significant ($F(2, 38) = 5.11, p = 0.0108$). As shown in Fig. 8(b), the enhancement effect was greatest when the contact stimulus was strong and the mid-air intensity was low (0.2 AU). The perceived intensity increase at the mid-air intensity of 0.2 AU was 0.026 AU at NONE, 0.154 AU at WEAK, and 0.171 AU at STRONG. Post-hoc comparisons showed that the difference between NONE and WEAK was significant ($p < 0.0001$), as well as the difference between WEAK and STRONG ($p < 0.0001$). When the mid-air intensity was 0.5 AU, the enhancement effect was still observed but slightly reduced. The perceived intensity increase was 0.004 AU at NONE, 0.049 AU at WEAK, and 0.068 AU at STRONG. The difference between NONE and WEAK was significant ($p < 0.0001$), as was the difference between WEAK and STRONG ($p < 0.0001$).

Finally, the interaction between vibration frequency and mid-air stimulus intensity was not significant ($F(1, 19) = 0.16, p = 0.6901$), nor was the three-way interaction ($F(2, 38) = 2.26, p = 0.1185$).

C. Discussion

1) Effects of Independent Factors: In the absence of a preceding contact vibration, the perceived intensity differences between the mid-air stimuli experienced by participants averaged 0.0018 AU, which did not significantly differ from zero. In contrast, when a leading contact vibration was present, participants reported stronger intensities by 0.14 AU[3] on average than the actual intensities of mid-air stimuli. This result provides solid evidence that presenting a brief contact tactile stimulus on the wrist followed by a mid-air tactile stimulus on the palm improves the perceptual strength of the mid-air stimulus, confirming the existence of tactile enhancement effect.

As depicted in Fig. 7, the overall increase in perceived intensity depended on the independent factors. When comparing vibration frequencies, the increase was greater at 50 Hz (0.11 AU) than at 200 Hz (0.07 AU), indicating that tactile enhancement was more pronounced at lower frequencies. One possible explanation is that mid-air vibrations involving the RA1 channel may facilitate stronger enhancement than those mediated primarily by the RA2 channel, but this hypothesis needs a further confirmation.

Regarding mid-air stimulus intensity, the enhancement effect was greater when the stimulus intensity was lower. At an intensity of 0.2 AU, the increase in perceived intensity was 0.12 AU, whereas at 0.5 AU, the increase was 0.07 AU. Thus, it appears that mid-air tactile enhancement is more effective at lower intensities, possibly due to a ceiling effect that higher intensities provide diminishing perceptual benefits. This observation is in line with a prior finding on tactile enhancement that a pronounced intensity contrast between the first and second stimuli is critical for the effect [6]. In our case, weaker mid-air vibrations may have increased the relative disparity from the preceding contact stimulus, thereby facilitating stronger enhancement.

[3]The perceptual meanings of the intensity changes are clarified by a follow-up experiment described in Sec. IV-D.

Lastly, the influence of contact stimulus intensity followed a similar trend. When no contact stimulus was present, there was no noticeable increase in perceived intensity (0.003 AU). With a weak contact stimulus, the enhancement effect increased significantly to 0.13 AU, and with a strong contact stimulus, it reached 0.14 AU. Post-hoc analysis confirmed that all three conditions (NONE, WEAK, and STRONG) were significantly different from each other ($p < 0.001$), demonstrating that a preceding contact stimulus plays a crucial role in enhancement, and increasing its intensity further amplifies the effect.

2) Participants' Comments: We also analyzed the participants' comments and interviews. Many participants reported that the contact vibrations stimulating the wrist also propagated to the palm, and it seems to be relevant to the tactile enhancement of ultrasonic vibrations. For example, 17 participants who perceived a higher intensity increase in the 50-Hz conditions than in the 200-Hz conditions commented that the lower-frequency contact vibrations spread more effectively across the palm. One participant described this sensation as "The low-frequency vibrations felt as if they spread widely across the palm from the wrist." This broader propagation characteristic can be a necessary condition for tactile enhancement; low-frequency vibrations are generally better transmitted through the palm [30]. The higher frequency vibrations of 200 Hz should spread less widely across the palm than the 50-Hz vibrations. Eight participants who showed less enhancement effect mentioned that the vibration did not fully transmit to their palms.

Six participants with smaller hands reported a unique effect that their entire palms became sensitive by the contact vibrations. They noted that after the vibrations were sufficiently felt across the palm, their overall tactile perception seemed to become more sensitive. This result suggests that hand size may modulate the propagation and reception of tactile vibrations, impacting the overall enhancement effect.

These comments suggest that the degree of enhancement is related to how well a contact vibration stimulating the wrist propagates to the palm. Control of contact vibration propagation from the wrist to the palm might be a key for the effective intensity enhancement of mid-air ultrasound stimuli, handling the individual differences.

D. Perceptual Characterization of Intensity Increases

User Study 1 demonstrated that tactile enhancement increased the perceived intensity of mid-air ultrasound stimuli. This increase was measured using AU, an arbitrary proportional unit used for programming, which does not carry direct physical or perceptual meaning. To more clearly confirm the enhancement effect, a comparison based on physically or perceptually interpretable quantities is required. Although physical measurement would offer a more direct interpretation, it is technically challenging due to the complexity of ultrasound interactions with the skin. Therefore, we conducted an additional experiment using magnitude ratio scaling [31] to evaluate the relationship from the AU-level changes observed under the enhancement conditions to actual perceptual differences. This perceptual quantification allowed us to determine whether the enhancement effect observed in Study 1 was accompanied by a meaningful increase in perceived intensity.

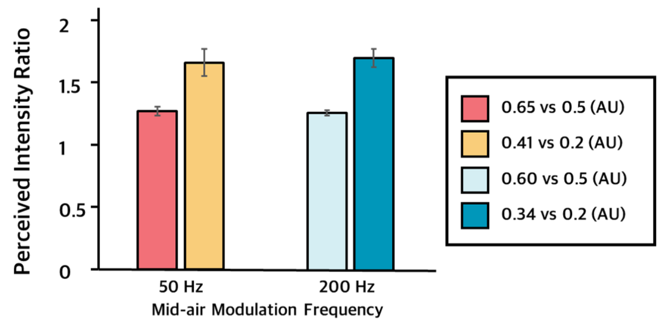

Fig. 9. Perceived intensity ratios validating the extents of tactile enhancement. Error bars represent standard errors.

1) Methods: We measured how many times the perceived intensity increased when the mid-air ultrasound strength was increased in the AU unit. We chose to compare (0.20, 0.41 AU) and (0.50, 0.65 AU) for 50-Hz stimuli, and (0.20, 0.34 AU) and (0.50, 0.60 AU) for 200 Hz stimuli. These numbers corresponded to the cases where the strongest perceptual enhancement was observed in User Study 1 (50SS, 50WS, 200SS, and 200WS).

Each participant experienced the four pairs of mid-air stimuli across multiple sessions. In each session, one vibration in the pair was designated as the reference stimulus (e.g., 50 Hz and 0.20 AU), and the other vibration as the comparison stimulus (e.g., 50 Hz and 0.41 AU). Participants could freely perceive the two ultrasonic vibrations using a GUI and were asked to enter a ratio indicating how many times the comparison stimulus felt stronger or weaker than the reference. Each session consisted of eight trials, where participants experienced each vibration pair twice. The experiment was completed over four sessions.

This experiment was conducted with five participants who were all experienced in haptics research and the members of our research group.

2) Results: The results are shown in Fig. 9. For the four experimental conditions of 50SS, 50WS, 200SS, and 200WS, the perceived intensity ratios were 1.23, 1.67, 1.27, and 1.71, respectively. On average, the perceived intensity gain was 1.69 for the WEAK mid-air vibrations (0.20 AU) and 1.25 for STRONG (0.50 AU). These findings validate the tactile enhancement effect observed in User Study 1, confirming that the enhancement mechanism produces consistent perceptual gains across multiple conditions.

V. User Study 2

User Study 1 demonstrated the positive effect of tactile enhancement in improving the perceived intensity of mid-air ultrasonic stimuli using brief preceding mechanical vibrations. Inspired by this finding, we conducted User Study 2 to investigate the benefits that tactile enhancement can provide to the recognition of spatiotemporal mid-air tactile patterns drawn on the palm.

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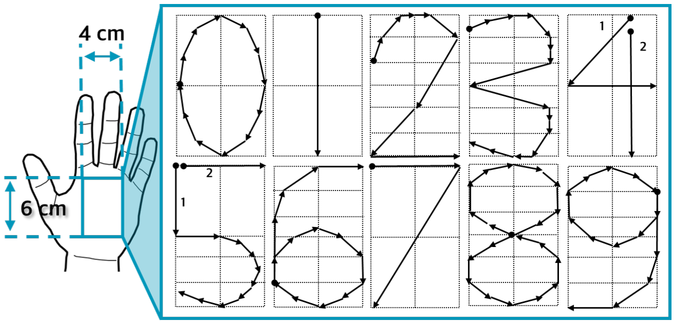

Fig. 10. Stimulus patterns used in User Study 2. For each pattern, the black circle represents the starting point, while the arrows indicate the middle points with the directions of progression. Pattern 4 and 5 consist of two segments, and small numbers next to the segments represent the drawing sequence.

A. Methods

1) Participants: Twenty individuals (10 males and 10 females) participated in this study. Their ages ranged from 21 to 53 years, with a mean age of 28.2 years. Upon completing the experiment, which lasted approximately one hour, each participant was compensated with KRW 20,000. Other details about participants were identical to those of User Study 1.

2) Stimuli: As illustrated in Fig. 10, we designed ten spatiotemporal mid-air stimuli that represented numeric digits referring to a previous study on tactile recognition [23]. Each pattern consisted of a starting point and a series of via points that defined the overall trajectory. The focal point of the ultrasound stimulus was continuously moved along this trajectory at a constant speed of 0.1 m/s, controlled by the update rate of the ultrasound board. Amplitude modulation was applied dynamically to the ultrasound stimulus, ensuring that the tactile sensation was rendered smoothly as the focal point passed through the via points. This method allowed participants to perceive the spatial patterns as a continuous tactile shape rather than discrete points.

We selected two frequencies, 80 and 200 Hz, which represent a low and high frequency, respectively. Initially, we tested pattern recognition using the same frequencies (50 and 200 Hz) as in User Study 1. However, using 50 Hz resulted in very low recognition accuracy due to its weak perceptual strength. Thus, we replaced it with 80 Hz, which still presents a clearly lower frequency sensation than 200 Hz.

The intensities of the mid-air stimuli were set to the maximum level provided by the ultrasonic haptic device. For contact vibrations, we used only the STRONG intensity level, and their amplitudes were 3.1 and 8.8 G for 80 and 200 Hz, respectively.

The ultrasonic stimuli had different durations from 600 to 1910 ms. These durations were considerably longer than that (300 ms) of User Study 1. This change required us to use a longer contact vibration to prevent a reduction in the tactile enhancement effect [32]. We increased the duration of a contact vibration to 500 ms after conducting internal tests. The ISI remained the same (100 ms). In our pilot tests, we observed that using wrist vibration durations longer than 300 ms (used in User Study 1) tended to improve the perceptual clarity of ultrsonic pattern stimuli. However, extending the vibration duration beyond 500 ms did not yield noticeable improvements in perceived intensity or clarity. It is noted that prior research on tactile loudness enhancement identified ISI as the most critical factor [24, 33], but the effects of stimulus durations have not been studied in detail.

Finally, we combined the ten patterns (digit 0 to 9), the two frequencies (80 and 200 Hz), and the two contact vibration intensities (NONE and STRONG), which resulted in 40 experimental conditions.

3) Task and Procedure: The experiment began with a training session designed to help participants familiarize themselves with the pattern stimuli. During this session, participants were guided on how to position their hands above the ultrasonic haptic device to ensure that the stimuli were accurately focused on the center of their palms. Participants were instructed to adjust their hand positions while perceiving the stimuli until they confirmed that the sensation was centered on their palms. In this session, participants experienced all the experimental conditions once, with one stimulus provided per trial. After selecting a response, correct answer feedback was given, allowing participants to know whether their selection was correct.

Following the training session, eight main sessions were conducted, each consisting of 40 trials. In each main session, all experimental conditions were presented once in a random order. Thus, each pattern stimulus was repeated eight times per participant. A one-minute break was provided between sessions to prevent fatigue.

In each trial, participants clicked the “stimuli” button on the GUI (Fig. 11) to experience the contact stimulus followed by the pattern stimulus after ISI. After perceiving the stimulus only once, they selected the digit that they believed they had perceived using the GUI. No correct answer feedback was provided during the main sessions. The participants then clicked the “Next” button to proceed to the next trial.

After the main session, participants took part in an interview to share their experiences with the haptic conditions. The discussion included open-ended questions aimed at understanding their perception of the tactile stimuli, with a focus on the sensations produced by the wrist vibrations and their impact on the recognition of mid-air patterns. Participants were also asked to describe specific scenarios in which patterns felt more distinct or easier to identify, providing deeper insight into the conditions that enhanced pattern recognition. This qualitative feedback was gathered to further explore the interplay between wrist-applied vibrations and mid-air tactile stimuli in dynamic pattern scenarios.

4) Data Analysis: We evaluated the recognition accuracy using the percent correct (PC) score. The PC score was determined by averaging the number of correct responses collected in the eight main sessions across all participants.

B. Results

Fig. 12 presents the average PC scores for the two independent variables of vibration frequency and contact vibration intensity. The average PC scores for the 80-Hz and 200-Hz conditions were 43.8% and 53.3%, respectively. The

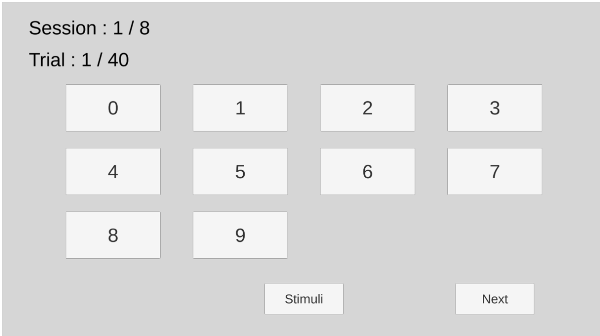

Fig. 11. Experimental program interface for User Study 2. When the "stimuli" button was pressed, the contact and mid-air stimuli were presented sequentially.

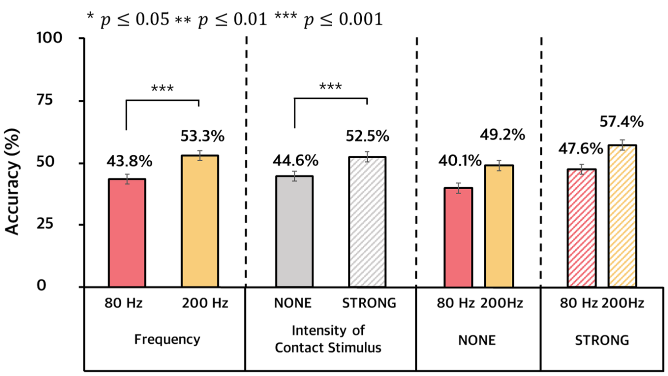

Fig. 12. Average PC scores indicating the main factor effects. Error bars represent standard errors.

average PC scores for the two contact vibration intensities, NONE and STRONG, were 44.6% and 52.5%, respectively. We performed a two-way repeated-measures ANOVA on the PC score for the two independent variables. Both factors showed significant effects ($F(1, 19) = 46.19, p < 0.0001$; $F(1, 19) = 17.08, p = 0.0006$), but the interaction term was not significant ($F(1, 19) = 0.08, p = 0.7842$).

The recognition accuracy was higher when pattern stimuli were presented using the 200-Hz vibrations than the lower frequency vibrations. Also, tactile enhancement significantly improved the recognition accuracy, as indicated by the higher PC scores in the STRONG contact stimulus condition than NONE. The non-significant interaction term suggests that the improvements caused by each main factor were consistent regardless of the other main factor.

Interested readers may also refer to the entire stimulus-response confusion matrices reported in the Appendix.

C. Discussion

1) Tactile Enhancement: The experimental results in Fig. 12 indicate that a tactile enhancement effect enabled by a short tactile stimulus applied to the wrist improved the recognition performance of the ten mid-air ultrasonic patterns of digits by approximately 8%. The improvement was statistically significant, and it provides clear evidence that a contact vibrotactile stimulus applied to the wrist can enhance the recognition performance of midair ultrasound patterns. Interestingly, the average pattern recognition accuracy increase of 8% attained through tactile enhancement is comparable to that (8%) obtained by providing a ten-minute long mindful meditation phase before a ultrasound pattern recognition task of ten digits [23]. These two methods can be used selectively or in combination depending on the adequacy to application contexts.

2) Effect of Vibration Frequency: As depicted in Fig. 12, the average PC score was significantly higher when the vibration frequency was 200 Hz than 80 Hz. When a mechanical vibration propagates on the skin, lowering its frequency increases its propagation distance [34]. As in User Study 1, ten participants in this study noted that the lower frequency vibrations at 80 Hz seemed to spread more effectively across the palm.

However, despite the effective propagation, lower-frequency vibrations showed less improvements in pattern recognition accuracy. This result indicates that while lower-frequency vibrations may enhance the perceived intensity across the palm, it does not necessarily lead to better pattern recognition. In other words, an increase in perceived intensity across the palm may not enhance spatial acuity; instead, it might reduce the ability to discern fine spatial details in the tactile patterns. The trend of higher PC scores observed with the 200-Hz vibration patterns may reflect a trade-off between perceived intensity and spatial acuity. This trade-off suggests that overly strong tactile feedback could potentially interfere with accurate pattern recognition, as higher intensity may overwhelm the subtle tactile cues required for distinguishing intricate patterns. Therefore, the relationship between tactile enhancement and pattern recognition demands a careful consideration of these trade-offs. Future studies should investigate these dynamics in greater depth to determine the optimal balance between perceived intensity and spatial acuity.

Finally, it is noted that the average correct recognition score for the ten digit patterns ranged from 40.1% (no preceding contact stimulus and 80 Hz) to 57.4% (tactile enhancement by a preceding contact stimulus and 200 Hz), as shown in Fig. 12.

3) Effects of Patterns: The PC scores for the ten digit patterns are shown in Fig. 13. Theses results indicate that the effects of preceding contact stimulus and frequency on pattern recognition depended on the specific pattern. For the simplest numeric pattern for digit 1, the recognition accuracy was consistently high around 90% across all conditions. For the other patterns, the recognition accuracy varied across the conditions, ranging from 20% to 69%.

In most cases, the tactile enhancement effect improved the recognition accuracy, and its extent ranged from -0.6% to 18.1%. Noteworthy exceptions were observed with digits 4, 8, and 9 at the frequency of 80 Hz, where the recognition rates were very similar regardless of the presence of a preceding contact stimulus. Even for these three digits, the recognition accuracies were improved by 5.0%, 18.1%, and 9.4%, respectively, when the 200 Hz preceding contact vibration was provided. This suggests that for more complex mid-air patterns, using a high-frequency vibration along with tactile enhancement by a preceding contact stimulus can afford the best pattern recognition performance.

Furthermore, the recognition accuracy differences across the patterns can stem from spatial resolution limitations in mid-air haptics. Howard et al. [35] reported that two closely-

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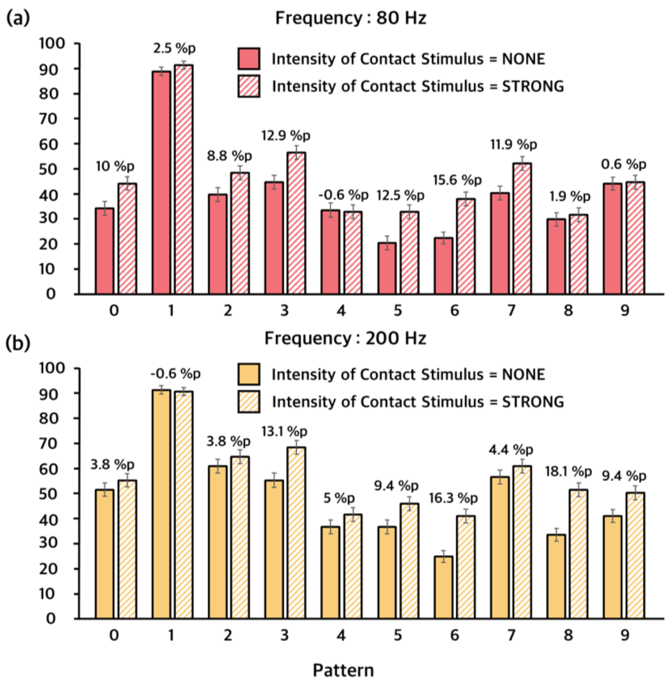

Fig. 13. (a) Graph showing the PC scores for each digit pattern at a vibration frequency of 80 Hz. (b) Graph for 200 Hz. The numbers above the bars indicate the percentage difference in accuracy with and without contact stimuli.

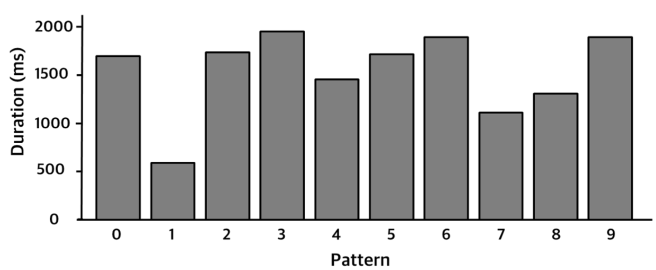

Fig. 14. Ultrasound stimulus durations for the ten digit patterns.

spaced ultrasonic focal points could be perceived as a single stimulus rather than distinct sensations. It may explain why some patterns exhibited lower recognition accuracies despite their similar durations and drawing paths. The close spacing of focal points within these patterns could have could have diminished the effectiveness of tactile enhancement. Ensuring adequate spatial separation in mid-air haptic patterns may be crucial for maximizing the benefits of tactile enhancement in recognition tasks.

4) Effects of Stimulus Duration: In general, a time gap between preceding and following vibrations has a critical effect on tactile enhancement. This fact raises a question whether the duration of the following vibration may also influence the effectiveness of tactile enhancement. In our case, the durations of the ten tactile digit patterns varied in a large range from 600 ms to 1910 ms, as shown in Fig. 14. We computed the correlation coefficient between the pattern duration and the recognition accuracy difference with and without tactile enhancement. The correlation coefficient was 0.574, indicating a moderate correlation between the pattern duration and the degree of tactile enhancement. It implies that the tactile enhancement effect of a preceding contact stimulus for pattern recognition persists better for a longer following ultrasonic stimulus. This interpretation is somewhat counterintuitive, as any positive effects of the preceding contact stimulus should decay over time. This intriguing issue deserves further attention in future work.

In addition, the positive effect of ultrasound stimulus duration seems to be interfered by the complexity of tactile pattern. For example, digit six, which had the longest vibration duration (1910 ms), showed the greatest recognition accuracy improvement (Fig. 13). This pattern was the most difficult to recognize without the preceding contact stimulus. It can be compared with digit nine, which had the same duration as and a similar drawing path to digit six. However, the recognition accuracy improvement of digit nine by tactile enhancement was not as pronounced as for digit six (Fig. 13). It is noted that digit six had greater ambiguity with digit zero than digit nine. Digit six and zero had very similar shapes and drawing paths. In comparison, digit nine had a similar shape to digit zero, but their drawing paths were quite different. This closer similarity in both shape and drawing trajectory may have contributed to the lowest initial recognition accuracy and the greatest enhancement effect observed for digit six.

In summary, the duration of ultrasound pattern appears to have a positive effect for tactile enhancement, but it is affected by other factors, such as the complexity of a vibration pattern.

VI. Conclusions and Future Work

A. *Summary of Main Findings*

Mid-air ultrasonic haptic interfaces have immense potential, but their weak perceptual output has blocked their way to wider dissemination. In this paper, we presented a method to enhance the perceptual strength of mid-air ultrasound stimuli while maintaining free-hand usage. In this method, a vibrotactile stimulus stimulates the user's wrist, and it is followed by an ultrasound stimulus focused on the palm after an inter-stimulus interval. We demonstrated that this method could increase the perceived intensity of a mid-air stimulus by up to 1.7 times. This perceptual phenomenon reminds us of tactile enhancement, which was reported for two successive tactile stimuli applied to the same body site in the literature. The enhancement effect for perceived intensity was more pronounced when the vibration frequency was low or the mid-air stimulus had a low intensity. Building on these findings, User Study 2 explored the effects of tactile enhancement on the recognition of ten midair ultrasound patterns representing digits. The results showed that the presence of a preceding contact stimulus on the wrist significantly improved the recognition performance, and its extent was more evident for more complex patterns or a high vibration frequency. Combined together, we conclude that additional tactile feedback from contact stimuli can improve the usability of mid-air haptic interfaces by enhancing both perceived intensity and pattern recognition accuracy. These findings can contribute to expanding the interaction methods and applications of midair ultrasonic haptic displays.

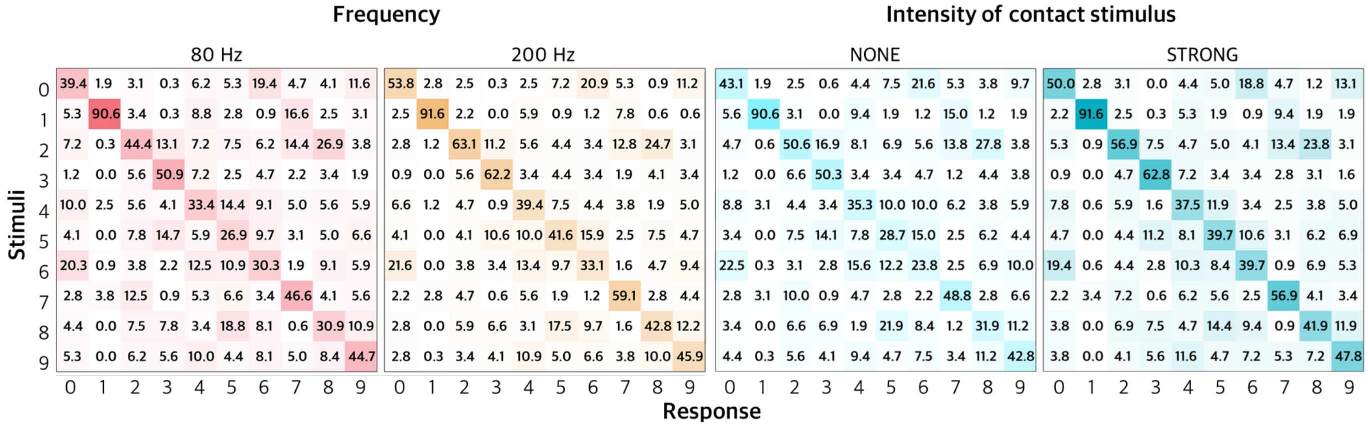

Fig. 15. Stimulus-response confusion matrices for the two independent variables of frequency (left) and contact stimulus intensity (right) measured in User Study 2.

B. Limitations and Future Work

This work merely proves the feasibility of utilizing additional tactile stimuli to enhance the perceptual performance of midair ultrasonic haptic devices, thereby opening a large space for future research. For example, our technique has a few important variables, but we tested the effects of vibration frequency and amplitude in the present study. Other variables that deserve further attention include the ISI between a preceding contact stimulus and a following ultrasonic stimulus and the durations and relative intensities of the two stimuli.

Furthermore, we focused on unveiling perceptual effects and did not measure the physical characteristics of the skin vibrations induced by the wrist actuator or their interaction with mid-air ultrasonic stimuli. Understanding how these two stimuli interact on the skin surface can provide deeper insights into the mechanisms underlying tactile enhancement. As the perception of mid-air ultrasound is influenced by factors such as propagation dynamics and skin vibration resonance, future work should involve the physical characterization of the combined stimuli.

Exploring different forms of contact stimuli and body sites for stimulation is also necessary to determine optimal configurations for usability. Also, this study fixed the distance between the wrist actuator and the ultrasonic focus on the palm. However, the distance may also influence the effectiveness of tactile enhancement, and its effects needs to be investigated in future work. Another promising direction for future work is to explore the possibility of replacing a contact vibration on the wrist with shear shock waves generated by ultrasonic stimulation itself [36, 37]. If the shear shock waves can induce a similar tactile enhancement effect on the palm, this approach could eliminate the need for additional devices, thereby simplifying the system and improving the overall usability and user comfort.

Finally, the new midair configuration tested in this work using two different types of tactile stimulation is likely to open new application scenarios exceeding the basic perceptual benefits instantiated in this paper. For example, we can also vary the preceding contact vibration and use it as another design variable. This approach can improve the information transmission capacity of the combined tactile stimulus, as in [38, 39], leading to an intuitive and effective contact-midair tactile vocabulary that is easy to learn, memorize, and recognize. Such tactile signal sets can contribute to improving the usability of gesture-based interfaces, e.g., those used in surgery environments to control medical equipment without physical contact [40, 41, 42] and in gesture-based automotive interfaces that do not require visual attention [43, 44].

APPENDIX

Fig. 15 shows four stimulus-response confusion matrices of the ten digit patterns for the two vibration frequencies (80 and 200 Hz) and the two contact vibration intensities (NONE and STRONG), collected in User Study 2.

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