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Improvement of Subjective Impact Perception in Airborne Ultrasound Tactile Display

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Abstract—The magnitude of the force due to acoustic radiation pressure that can be presented using airborne ultrasound is very small, approximately a few grams in weight. Therefore, especially when considering the application to tactile sensation presentation, research has been conducted on methods to make people subjectively feel a strong force even if the force is physically small. The objective of this study is to investigate the conditions necessary to induce an impact sensation that is conducive to a visual experience in which an object makes contact with the skin for approximately 50ms. The term ”impact sensation” is defined as a tactile stimulus that is characterized by its substantial subjective intensity and brief subjective duration. To elucidate this concept, two experiments were conducted.

In Experiment 1, the effective tactile stimuli duration and modulation method when only tactile sensations are presented was investigated. The results demonstrated that a tactile stimuli duration of 100ms-150ms and a modulation method of 200Hz AM were effective. In Experiment 2, we investigated the degree of agreement between the perceived tactile stimulus and the visual experience during tactile presentation while viewing a visual stimulus of a ball actually impacting the palm with a contact time of 50ms. As a result, it was confirmed that even if the visual stimulus was 50ms, a tactile stimuli duration of 100ms was acceptable as a suitable duration. This finding has implications for the presentation of virtual experiences and symbolic information using airborne ultrasound.

Index Terms—haptics, tactile, impact, intensity, duration, modulation, visual, visuotactile.

I. Introduction

An airborne tactile display technology using an ultrasonic phased array has been previously proposed [1], [2]. This method generates tactile sensations through acoustic radiation pressure by forming a high-pressure point in the air via phase-controlled ultrasonic transducers. The maximum force achievable with a single focal point is reported to be 0.027 N using six airborne ultrasound tactile display (AUTD3) devices ([3]), indicating that the presented force remains relatively weak [4].

To address this, various hardware and software approaches have been proposed to enhance perceptual intensity. In AUTD3, the system is designed to increase the aperture by minimizing delay when multiple units are combined, thereby enhancing the achievable intensity [3].

On the software side, research is advancing on enhancing perceived intensity through modulation techniques, primarily amplitude modulation (AM) [1], [5], [6] and spatiotemporal modulation (STM) [7] or lateral modulation (LM) [8], [9]. These methods leverage the perceptual characteristics of human tactile receptors to enhance stimulus intensity by inducing appropriate vibration sensations rather than static pressure stimulation. In AM, ultrasound amplitude is modulated to generate a vibration sensation around 100Hz, thereby increasing perceived intensity. STM and LM enhance intensity by dynamically shifting the focal point across the skin. Morisaki et al. further demonstrated that selecting appropriate frequency and movement range for LM enables the presentation of a pressure sensation without inducing vibration [10].

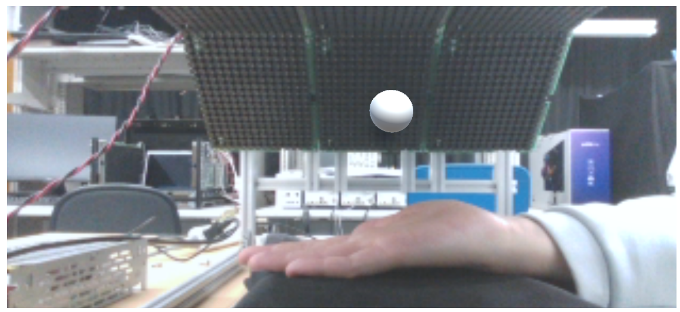

Fig. 1: Visual stimuli of colliding virtual spheres

Previous research on modulation for enhancing perceptual intensity has primarily focused on continuously presented stimuli. In contrast, this study examines optimal stimulation methods for increasing perceptual intensity in instantaneous stimuli. As an example, we consider a scenario in which a virtual object, such as a ping-pong ball, falls, makes contact with the palm for 50ms, and then bounces away (Fig. 1). Intuitively, synchronizing ultrasound presentation with the contact duration may seem to provide the highest consistency in experience. However, as we will demonstrate, stimulus intensity is influenced by stimuli duration, with shorter durations generally resulting in weaker perceived intensity. Therefore, this study examines the relationship between stimulus duration, modulation method, and perceived intensity to determine the optimal tactile presentation conditions for accurately conveying a 50ms contact sensation without perceptual incongruity.

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In this study, we conducted two main experiments. In the first experiment, we examined the effects of stimulus duration and modulation method on intensity. Regarding stimulus duration, we evaluated how much the perceived intensity and stimulus duration changed using the magnitude estimation method when 100ms was used as the reference. We also examined which stimulus was perceived as the strongest under various modulation methods. The results showed that stimuli with a duration of 50ms were perceived as significantly weaker than those of 100ms or more, with a perceived intensity of about three-quarters that of 100ms stimuli. For durations of 150ms or more, perceived intensity remained unchanged up to 300ms, indicating no further contribution from increased duration. Regarding modulation methods, 200Hz AM was perceived as the strongest among those compared.

In the second experiment, we evaluated the acceptable duration of a tactile stimulus when combined with a visual image. Based on Experiment 1, a 200Hz AM stimulus with a duration of 100-150ms was considered optimal. We therefore investigated its acceptability when paired with a 50ms visual stimulus. The stimulus frequency was fixed at 200Hz AM and only the duration was varied to assess its suitability for the visual image. The results indicated that durations up to approximately 100ms were acceptable. In summary, a 200Hz AM stimulus lasting 100ms was found to be appropriate for a 50ms collision image.

Enhancing the expression of instantaneous contact sensations through ultrasound stimulation could improve the realism of virtual experiences and expand the range of symbolic information presentation. Specifically, when presenting information via short, pulsed stimuli, it becomes possible to determine the necessary and sufficient stimulus duration for effective presentation.

II. Related Works

A. Relationship Between Tactile Stimulus Duration and Subjective Intensity

The relationship between tactile stimulus duration and subjective intensity has been studied. Bochereau et al. examined seven vibration patterns with durations increasing in 100ms increments from 100 to 700ms [11]. Participants repeatedly selected the stronger stimulus relative to a reference, enabling the determination of the vibration amplitude corresponding to the reference intensity for each duration.

It is possible that if the same phenomenon occurs in airborne ultrasound-based tactile presentation, extending the stimulus duration may enhance subjective intensity, enabling more effective impact presentation. Since the physical intensity of ultrasound from an AUTD reaches its peak in approximately 1 ms [12], the temporal variation between airborne ultrasound stimulation and vibration actuators is minimal. Airborne ultrasound also allows spatiotemporal modulation in addition to amplitude modulation and no-modulation conditions. This study aims to examine the optimal duration for tactile stimuli to maximize impact sensation.

B. Relationship Between Ultrasound Modulation Methods and Subjective Intensity

In airborne ultrasound tactile presentation, there are two modulation methods to increase subjective intensity: amplitude modulation (AM) and spatio-temporal modulation (STM) or lateral modulation (LM).

AM is a method of presenting vibrations to the skin at the focal point by periodically changing the amplitude of the generated ultrasound. This technique was applied in the study by Iwamoto et al [1]. Hasegawa et al. found that the modulation frequency minimizing the perceptual threshold is 200Hz when amplitude modulation is used [6].

STM or LM is a modulation technique that makes people feel a strong force by periodically moving the focal position of ultrasound. STM was proposed by Frier et al. [7], while LM was introduced by Takahashi et al. [8] in 2018. Ablert et al. showed that the tactile experience varies with the radius and frequency of the STM [13]. Plasencia et al. showed that a new algorithm allows for a multi-point STM [14]. In their paper on LM, Takahashi et al. demonstrated that the perceptual threshold of LM stimuli is lower than that of AM stimuli, particularly in the modulation frequency band above 50Hz. Morisaki et al. have shown that tactile stimuli physically measured at 0.027 N are perceived as equivalent to 0.21 N when LM is applied, and that LM at a low frequency of about 10Hz is effective for the presentation of static pressure sensations [4], [10].

Previous studies have suggested that modulation techniques can enhance perceived intensity even for instantaneous stimuli. However, most research on subjective intensity during modulation has focused on steady-state tactile sensations in stimuli lasting several seconds. The optimal modulation conditions for instantaneous tactile presentations remain unclear. The present study aims to fill this gap.

III. Experiment 1: Perceived Intensity and Duration in the Case of Solely Tactile Stimulation

A. Methods

1) Equipment: The experimental apparatus for this study was illustrated in Fig. 2. The apparatus was constructed with 12 AUTD3 units. A hand is inserted into the device, and tactile sensations are presented to the hand (Fig. 3). We determined the focus parameters based on the as-built device geometry and calculated the phase of each transducer from its propagation distance to the focal point. All transducers were driven at maximum acoustic pressure to maximize force.

2) Conditions: In this experiment, 10 tactile stimuli were prepared, each with varying durations and modulation methods. The specific values are given in Table I.

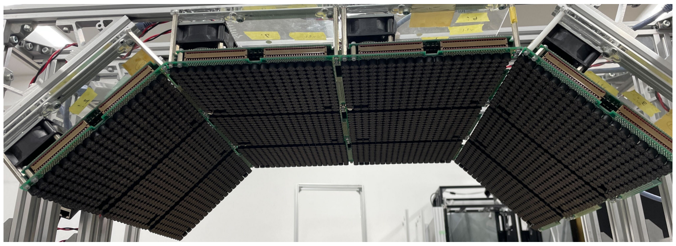


Fig. 2: Equipment

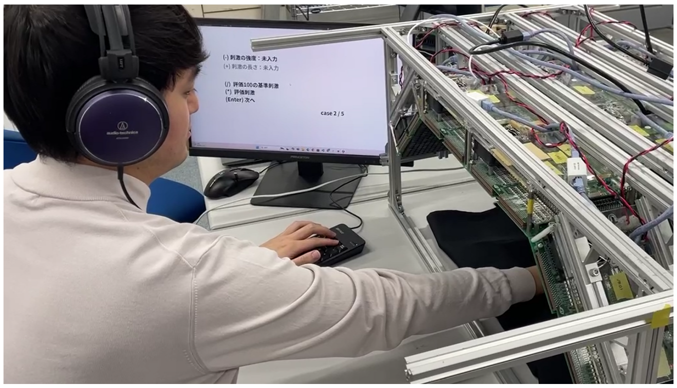


Fig. 3: Participants in the experiment

In a preliminary experiment, subjective intensity tended to vary when the tactile stimulus duration was less than 150ms. Based on this, two stimuli with durations shorter than 150ms and one stimulus with a duration longer than 150ms were prepared. Regarding the modulation, three stimuli were selected to correspond to each of the tactile mechanoreceptors: the Merkel cells, the Meissner corpuscles, and the Pacinian corpuscles. These four stimuli were selected in conjunction with no modulation. Regarding the modulation type, LM is commonly used at low frequencies (typically below several tens of Hz) for static pressure presentation [10], while AM minimizes the perceptual threshold at 200Hz [6]. Based on these findings, LM was set to 10Hz and 30Hz, and AM was set to 200Hz. The orbit of the focal point in the LM was a circle with a radius of 5 mm.

Although 16 types of stimuli could be generated from these combinations, 10 tactile stimuli, as shown in Table I, were selected to limit experiment duration and reduce subject fatigue. Using this set, the effect of tactile stimuli duration was examined for 200Hz AM, which was perceived as particularly strong, while the effect of modulation was investigated at the 100ms duration. Additionally, 30Hz LM and 200Hz AM were compared to examine the interaction between modulation and tactile stimuli duration.

3) Evaluation Method: The evaluation process was conducted using the magnitude estimation method. In each trial, participants were presented with two stimuli: a reference stimulus and an evaluation stimulus. The reference stimulus was a 100ms tactile stimulus with 200Hz AM, while the evaluation stimulus was one of the ten predefined tactile stimuli. Participants compared the two stimuli and assigned an integer rating to the evaluation stimulus. The intensity and duration of the reference stimulus were set to a baseline score of 100.

TABLE I: Conditions for Experiment 1. The tested conditions are indicated by circles. Blue: comparison of stimuli durations, Red: comparison of modulation, and Green: evaluate the interaction between the stimuli duration and modulation.

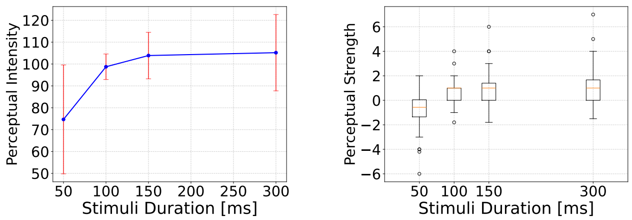
	No Modulation	10HzLM	30HzLM	200HzAM
50ms	-	-	○	○
100ms	○	○	○	○
150ms	-	-	○	○
300ms	-	-	○	○

Each participant evaluated intensity and duration five times for each experimental condition, for a total of 50 trials. The number of trials per condition was set to five based on previous studies [15], [16]. Similarly, following previous research [16], the randomization process was designed to prevent a specific condition from being consecutively selected as the evaluation stimulus. The stimuli were randomized such that a condition could only be presented for the $(n+1)$th time after all conditions had been presented n times.

4) Procedure: As shown in Fig. 3, participants received tactile stimuli on their right palm and provided ratings using a numeric keypad with their left hand. Before the experiment, each participant adjusted the ultrasound focus height in 2mm increments up and down using the numeric keypad, adjusting the focus to the position where they felt the strongest stimulation. The distance between the AUTD unit on the upper surface and the focus position ranged from 21 to 22 cm. To minimize the potential influence of AUTD drive noise on tactile perception, participants wore earplugs and over-ear headphones that delivered pink noise at a level sufficient to mask any audible drive noise.

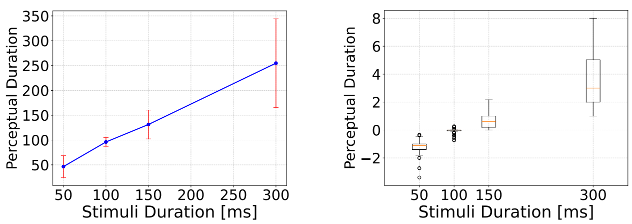
As shown in Fig. 3, the left-side monitor displayed instructions for operating the numeric keypad, with specific keys assigned to the reference and evaluation stimuli. Participants were allowed to freely experience these stimuli by pressing the assigned keys, with no restrictions on the number of presentations or the time interval between them. They were then instructed to compare the two stimuli and enter their evaluation values for intensity and duration. All operations were performed independently by the participants using a numeric keypad.

Sixteen participants (13 males and 3 females) in their 20s took part in Experiment 1. Stimuli were presented to their right hand, regardless of dominant hand. The exper-



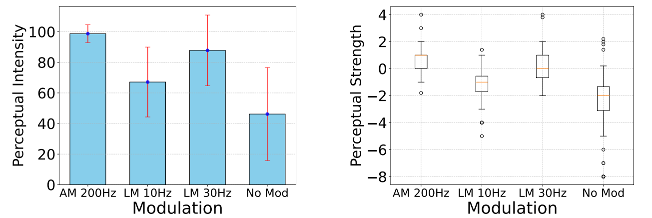
(a) Mean (b) MAD scaled boxplot

Fig. 4: Relationship between tactile stimuli duration and perceived intensity (modulation fixed at 200Hz AM)



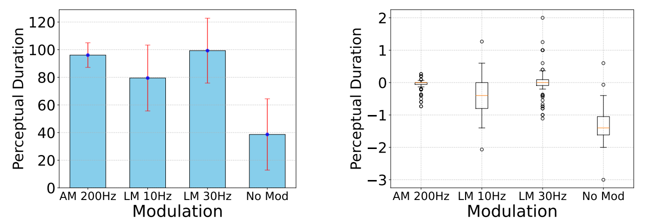
(a) Mean (b) MAD scaled boxplot

Fig. 5: Relationship between tactile stimuli duration and perceived duration (modulation fixed at 200Hz AM)



(a) Mean (b) MAD scaled boxplot

Fig. 6: Relationship between modulation method and perceived intensity (duration fixed at 100ms)



(a) Mean (b) MAD scaled Boxplot

Fig. 7: Relationship between modulation method and perceived duration (duration fixed at 100ms)

iment was approved by the Ethics Review Committee of the University of Tokyo (Review No. 24-369).

5) Data Processing and Analysis: The following procedure was employed in this study to analyze the data obtained by the magnitude estimation method.

The median absolute deviation (MAD) normalization technique was employed to standardize the response scale for each experimental participant. For 50 data points of subjective intensity and duration obtained from one experimental participant, MAD normalization is performed using the following equation:

$$Score = \frac{x_i - Median(\boldsymbol{x})}{MAD}, \tag{1}$$

$$MAD = Median(|x_i - Median(\boldsymbol{x})|), \tag{2}$$

where $\boldsymbol{x}$ represents the set of all data points, and x_i denotes an individual data point.

The normalized data were aggregated for each condition, resulting in 80 data points (5 trials $\times$ 16 participants per condition). The median was subsequently calculated from these 80 normalized data points, and the normalized medians were compared across conditions.

The determination of significant differences was conducted through the implementation of either the ART-ANOVA or the Wilcoxon signed-rank test. Considering that the data might not meet the normality assumption, we used nonparametric tests throughout (Wilcoxon signed-rank test with Holm's adjustment and ART-ANOVA).

B. Results

1) Relationship between tactile stimuli duration and subjective intensity or subjective duration: The response averages for subjective intensity under fixed modulation condition (200 Hz AM) with varying tactile stimulus durations are shown in Fig. 4a and their MAD normalized values are shown in Fig. 4b. Similarly, the response averages for subjective duration are plotted in Fig. 5a and their MAD normalized values are shown in Fig. 5b. Averaged data plots show the mean and standard deviation, while MAD-normalized plots represent the data using box plots.

The effects of varying tactile stimulus duration were compared across the four levels using the Wilcoxon signed-rank test, with p-values adjusted via Holm's method. The statistical test on MAD-normalized data indicated a significant difference in all conditions, with $p = 0.0013$ for the 100 ms–300 ms comparison and $p < 0.001$ for all others, except for the 150 ms–300 ms comparison ($p = 0.25$). On the other hand, there was a significant difference in subjective duration between all conditions when the tactile stimuli duration was changed ($p < 0.001$).

The results showed that subjective intensity increased with stimulus duration up to 150 ms, but no further enhancement was observed beyond this point up to 300 ms. In the context of a 50 ms collision, the intensity of the 50 ms stimulus, which had the same duration as the collision, decreased to an average of approximately 0.75 relative to the 100 ms reference stimulus.

2) Relationship between modulation method and subjective intensity or subjective duration: Fig. 6a presents

the response averages for subjective intensity with a fixed tactile stimulus duration of 100 ms under different modulation methods, while Fig. 6b shows the corresponding MAD-normalized values. Similarly, Fig. 7a displays the mean response values for subjective duration, with their MAD-normalized values shown in Fig. 7b.

The Wilcoxon signed-rank test was employed on MAD-normalized data to compare the four levels of modulation (no modulation, 10Hz LM, 30Hz LM, and 200Hz AM). This analysis applied Holm's method to adjust the p-values for significance testing. The results indicated a significant difference across all conditions ($p < 0.001$).

The Wilcoxon signed-rank test on MAD-normalized data for subjective duration under different modulation conditions showed a significant difference between all condition pairs ($p < 0.001$), except for the 30 Hz LM – 200 Hz AM pair, which exhibited no significant difference ($p = 0.29$).

Thus, differences in modulation conditions resulted in changes in subjective intensity, following the order 200Hz AM > 30Hz LM > 10Hz LM > No-modulation. Meanwhile, subjective duration was perceived as longer in the order 200Hz AM, 30Hz LM > 10Hz LM > No-modulation.

3) Interaction between tactile stimulus duration and modulation method: ART-ANOVA on MAD-normalized data tested the interaction effect of the two factors on subjective intensity and duration for the eight conditions enclosed by the green line in Fig. I. No significant interaction was found ($p = 0.98$, $p = 0.56$).

IV. Experiment 2: Allowable tactile stimuli duration when combining visual and tactile sensations

A. Methods

1) Conditions: In this experiment, an image of a virtual sphere impacting on the palmar region, remaining stationary for 50ms, and then rebounding is presented along with tactile stimuli. The overall experimental situation is the same as in Experiment 1; however, a collision image of the virtual sphere is presented on the monitor, as shown in Fig. 1. This image is a composite of the virtual sphere using Unity on the image of the right hand of the experiment participant. The refresh rate of the monitor is 60 fps, and the sphere on the video comes into contact with the skin for 3 frames and remains still. Although the hands on the image were synchronized in real time, the subjects did not move their hands during the experiment. Therefore, the fall position were fixed at predetermined values.

Based on previous research [17], the time difference between visual and tactile stimuli caused by the experimental setup was measured. The results showed that the visual stimulus was delayed by 10 ms relative to the tactile stimulus, so the following experiment was conducted after making the necessary adjustment.

In this experiment, five duration conditions were prepared: 25ms, 50ms, 100ms, 150ms, and 200 ms. The purpose of this experiment is to examine perceptual differences between tactile stimulus durations, while the sphere was contacted for 50 ms.

In all patterns, the onset time of the visuotactile stimulation coincided with the moment of contact of the virtual sphere on the image. The modulation was all 200Hz AM, based on the results of Experiment 1.

2) Evaluation Method: The experimental procedure was as follows: After pressing a key to present a stimulus, a virtual ball appeared above the participant's palm. The ball took approximately 0.5 seconds to fall and collide with the palm, at which point a tactile stimulus was presented. On each trial, participants could experience the stimulus repeatedly by pressing the buttons at their discretion. Participants experienced the tactile stimuli, assessed whether the stimulus duration felt appropriate in relation to the visual images, and selected one of three options: "short", "appropriate", or "long". Each of the five experimental conditions was presented 10 times, resulting in a total of 50 responses per participant.

3) Procedure: The difference from Experiment 1 is that there is no reference stimulus and the response options are different. Six participants took part in Experiment 2, five of whom had previously participated in Experiment 1, while one participated only in this experiment. The real-time camera feed of the hand and the superimposed virtual sphere were displayed on the monitor, and participants were instructed to consistently look at the screen.

B. Results

As shown in Fig. 8, the responses regarding the perceived duration of the tactile stimulus relative to the video are presented for the five experimental conditions of tactile stimulus duration. The percentage of participants who perceived the stimulus as shorter is represented in green, those who considered it appropriate in blue, and those who judged it to be longer than the video in yellow.

A chi-square test was conducted to ascertain whether one option was selected with a significantly higher frequency than the other two options in each condition. The test results confirmed that the "short" option was selected with a significantly higher frequency in the 25 ms condition ($p < 0.001$). The "appropriate" option was also chosen significantly more often in the 50ms ($p < 0.001$) and 100ms ($p < 0.01$) conditions. For the 150ms and 200ms conditions, the "long" option was significantly preferred in both cases ($p < 0.001$, $p < 0.001$).

There was no significant difference in the response of "appropriate" between 50-100ms ($p \simeq 0.85$), indicating that they were judged to be appropriate to the same extent.

V. Discussion

The main findings of this study are as follows: (1) For tactile impact presentation, changes in duration are

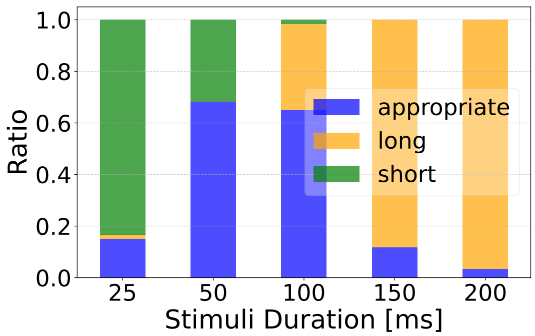


Fig. 8: Responses about the adequacy of tactile stimuli duration

perceived as changes in intensity up to approximately 150ms, but beyond this point, variations in intensity are no longer strongly perceived. (2) For a 50ms visual stimulus, a tactile stimulus duration of up to approximately 100ms is perceived without any sense of incongruity.

Regarding finding (1), the subjective intensity increases up to a stimuli duration of approximately 150ms and does not increase beyond that time. This phenomenon is independent of the vibration characteristics of the ultrasound. According to previous studies, the time it takes for the physical intensity of ultrasound emitted from the AUTD to reach its peak is about 1 ms [12]. It has also been reported that when the vibration is transmitted to the skin surface of the hand, the vibration amplitude at the skin surface reaches its peak in a few ms [18]. The available evidence suggests that the increase in subjective intensity from 100 ms to 150 ms is not attributed to the vibration characteristics of the ultrasound device. Rather, it is hypothesized that this phenomenon originates from the perceptual characteristics of tactile sensation.

While we confirmed that subjective intensity changes with stimulus duration, an interesting observation is that conditions in which stimulus intensity is perceived as weak also tend to result in a shorter perceived duration. This implies that for durations up to approximately 150ms, stimulus intensity and duration may not be perceived independently. Further investigation is required to clarify the underlying mechanisms.

In Experiment 1, 200 Hz AM produced higher subjective intensity than other LM conditions. However, since LM conditions at 200 Hz were not tested, it remains unclear how the results would compare under identical frequency conditions. Previous studies have shown that LM stimuli are perceived as stronger for tactile presentations lasting several seconds or longer [4], [8], [19]. Therefore, it is crucial to investigate whether this effect extends to short-duration tactile presentations, which requires a comparison under the same modulation frequency conditions.

In this experiment, the visual stimulus was fixed at 50ms, which was chosen as a relatively long duration within the range perceived as an instantaneous contact event. Changing this condition could potentially alter the results. However, based on the authors' subjective perception, the 50ms visual stimulus was short enough to be perceived as a collision event.

In this experiment, the tactile and visual stimuli were presented simultaneously. However, presenting the tactile stimulus before the visual stimulus could potentially allow for a longer perceived duration. To investigate this possibility, we conducted a preliminary experiment. The results indicated that the most natural perception of the tactile stimulus occurred when its onset time coincided with that of the visual stimulus. Therefore, we did not further investigate conditions in which the tactile stimulus preceded the visual stimulus. This finding is consistent with previous studies [20], [21] and supports its validity.

Experiment 2 involved only six participants (five of whom also participated in Experiment 1), which may limit the generalizability of the visuo-haptic synchrony findings. Future work should recruit a larger and more diverse sample to validate the robustness of the observed duration–perception alignment and to explore potential individual differences in cross-modal timing.

VI. Conclusions

In this study, we investigated the optimal conditions for presenting a strong, instantaneous tactile sensation using ultrasound haptic stimulation, with a focus on stimulus duration and modulation methods.

Experiment 1 revealed that a stimuli duration of 100–150ms with 200Hz AM is optimal for tactile-only stimulation. This finding has potential applications in various scenarios where tactile feedback is provided independently. For instance, it can be used to warn individuals entering hazardous areas [22], facilitate haptic guidance [23], [24], or present symbolic stimuli, such as Morse code. In addition, the observed correlation between perceived intensity and stimulus duration up to 150ms, beyond which intensity remained constant, highlights an intriguing feature of human tactile perception.

Experiment 2 showed that pairing a 50 ms collision image with a 50–100 ms tactile stimulus yields a natural visuotactile experience. Extending the tactile stimulus 50 ms beyond the visual one did not reduce naturalness. Thus, 100 ms is optimal for strong yet natural haptics, though optimal duration may depend on how long the virtual sphere remains stationary.

The experimental results indicate that a tactile stimuli duration of 100-150ms with a 200Hz AM is optimal for tactile stimulation. However, in a visuo-haptic system, it is preferable to align the onset timing of visual and tactile stimuli while limiting the tactile tactile stimuli duration to 100ms to ensure a natural experience.

References

[1] Takayuki Iwamoto, Mari Tatezono, and Hiroyuki Shinoda. Non-contact method for producing tactile sensation using airborne ultrasound. In Haptics: Perception, Devices and Scenarios:

6th International Conference, EuroHaptics 2008 Madrid, Spain, June 10-13, 2008 Proceedings 6, pp. 504–513. Springer, 2008.

[2] Ismo Rakkolainen, Euan Freeman, Antti Sand, Roope Raisamo, and Stephen Brewster. A survey of mid-air ultrasound haptics and its applications. IEEE Transactions on Haptics, Vol. 14, No. 1, pp. 2–19, 2020.

[3] Shun Suzuki, Seki Inoue, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. Autd3: Scalable airborne ultrasound tactile display. IEEE Transactions on Haptics, Vol. 14, No. 4, pp. 740–749, 2021.

[4] Tao Morisaki, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. Non-vibratory pressure sensation produced by ultrasound focus moving laterally and repetitively with fine spatial step width. IEEE Transactions on Haptics, Vol. 15, No. 2, pp. 441–450, 2021.

[5] Takayuki Hoshi, Masafumi Takahashi, Takayuki Iwamoto, and Hiroyuki Shinoda. Noncontact tactile display based on radiation pressure of airborne ultrasound. IEEE Transactions on Haptics, Vol. 3, No. 3, pp. 155–165, 2010.

[6] Keisuke Hasegawa and Hiroyuki Shinoda. Aerial vibrotactile display based on multiunit ultrasound phased array. IEEE transactions on haptics, Vol. 11, No. 3, pp. 367–377, 2018.

[7] William Frier, Damien Ablart, Jamie Chilles, Benjamin Long, Marcello Giordano, Marianna Obrist, and Sriram Subramanian. Using spatiotemporal modulation to draw tactile patterns in mid-air. In Haptics: Science, Technology, and Applications: 11th International Conference, EuroHaptics 2018, Pisa, Italy, June 13-16, 2018, Proceedings, Part I 11, pp. 270–281. Springer, 2018.

[8] Ryoko Takahashi, Keisuke Hasegawa, and Hiroyuki Shinoda. Lateral modulation of midair ultrasound focus for intensified vibrotactile stimuli. In Haptics: Science, Technology, and Applications: 11th International Conference, EuroHaptics 2018, Pisa, Italy, June 13-16, 2018, Proceedings, Part II 11, pp. 276–288. Springer, 2018.

[9] Ryoko Takahashi, Keisuke Hasegawa, and Hiroyuki Shinoda. Tactile stimulation by repetitive lateral movement of midair ultrasound focus. IEEE transactions on haptics, Vol. 13, No. 2, pp. 334–342, 2019.

[10] Tao Morisaki, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. Noncontact haptic rendering of static contact with convex surface using circular movement of ultrasound focus on a finger pad. IEEE Transactions on Haptics, 2023.

[11] Séréna Bochereau, Alexander Terekhov, and Vincent Hayward. Amplitude and duration interdependence in the perceived intensity of complex tactile signals. In International Conference on Human Haptic Sensing and Touch Enabled Computer Applications, pp. 93–100. Springer, 2014.

[12] Shun Suzuki, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. Reducing amplitude fluctuation by gradual phase shift in midair ultrasound haptics. IEEE transactions on haptics, Vol. 13, No. 1, pp. 87–93, 2020.

[13] Damien Ablart, William Frier, Hannah Limerick, Orestis Georgiou, and Marianna Obrist. Using ultrasonic mid-air haptic patterns in multi-modal user experiences. In 2019 IEEE International Symposium on Haptic, Audio and visual Environments and games (HAVE), pp. 1–6. IEEE, 2019.

[14] Diego Martinez Plasencia, Ryuji Hirayama, Roberto Montano-Murillo, and Sriram Subramanian. Gs-pat: high-speed multipoint sound-fields for phased arrays of transducers. ACM Transactions on Graphics (TOG), Vol. 39, No. 4, pp. 138–1, 2020.

[15] Kan Arai and Katsunori Okajima. Tactile force perception depends on the visual speed of the collision object. Journal of vision, Vol. 9, No. 11, pp. 19–19, 2009.

[16] Femke E Van Beek, Wouter M Bergmann Tiest, Winfred Mugge, and Astrid ML Kappers. Haptic perception of force magnitude and its relation to postural arm dynamics in 3d. Scientific reports, Vol. 5, No. 1, p. 18004, 2015.

[17] Morgan Le Chénéchal and Jonas Chatel-Goldman. Htc vive pro time performance benchmark for scientific research. In Icat-Egve 2018, 2018.

[18] Yitian Shao, Vincent Hayward, and Yon Visell. Spatial patterns of cutaneous vibration during whole-hand haptic interactions. Proceedings of the National Academy of Sciences, Vol. 113, No. 15, pp. 4188–4193, 2016.

[19] Tao Morisaki and Yusuke Ujitoko. Towards intensifying perceived pressure in midair haptics: Comparing perceived pressure intensity and skin displacement between lm and am stimuli. In International Conference on Human Haptic Sensing and Touch Enabled Computer Applications, pp. 107–119. Springer, 2024.

[20] Charles Spence, David I Shore, and Raymond M Klein. Multisensory prior entry. Journal of Experimental Psychology: General, Vol. 130, No. 4, p. 799, 2001.

[21] Massimiliano Di Luca and Arash Mahnan. Perceptual limits of visual-haptic simultaneity in virtual reality interactions. In 2019 IEEE World Haptics Conference (WHC), pp. 67–72. IEEE, 2019.

[22] Saya Mizutani, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. Thresholds of haptic and auditory perception in midair facial stimulation. In 2019 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE), pp. 1–6. IEEE, 2019.

[23] Shun Suzuki, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. Midair hand guidance by an ultrasound virtual handrail. In 2019 IEEE World Haptics Conference (WHC), pp. 271–276. IEEE, 2019.

[24] Euan Freeman, Dong-Bach Vo, and Stephen Brewster. Haptiglow: helping users position their hands for better mid-air gestures and ultrasound haptic feedback. In 2019 IEEE World haptics conference (WHC), pp. 289–294. IEEE, 2019.