2025 IEEE/SICE International Symposium on System Integration (SII)
January 21-24, 2025, Munich, Germany

Influence of Longterm Duration and Damping Shapes to Perceived Intensity for Vibrotactile Stimulation

Takumi Kuhara[1], Hikari Yukawa[1], and Yoshihiro Tanaka[1,2]

Abstract— **Haptic information has been shown to improve various experiences and accuracy of movement. However, the perceived intensity is known to be influenced by various parameters of the vibrotactile stimuli. Not only the amplitude but also the length of a short-term duration, the presence of a decaying factor, and the shape of the waveform affect the subjective intensity. In this paper, we investigated the influence of different damping shapes and duration on the perceived intensity. We prepared four different shaped waves as stimuli; a constant sinusoidal wave, an exponential decaying shaped wave, a linear decaying shaped wave, and a logarithmic decaying shaped wave, and six different long-term durations of up to 3 seconds for each waveform. Ten participants took part in the experiment to see how strong the intensity was perceived for each stimulus. The results indicated that the damping shape of the samples affects the perceived intensity in the order of a constant sinusoidal wave, a logarithmic decaying shaped wave, a linear decaying shaped wave, and an exponential decaying shaped wave. Also, the results suggest the representation of the time-averaged energy to the perceived intensity.**

I. INTRODUCTION

Haptic information has been investigated in various fields to improve the experience and accuracy of operations and guiding movements. For example, in the field of virtual reality, adding haptic information to the visual and auditory environments improves the sense of presence and immersion [1], as well as reducing the awkwardness stemming from a disconnect with reality [2]. In 2D navigation, changes to the frequency and amplitude of vibrotactile stimuli directly affect performance and comfort [3]. As an example of substituting different sensory information, Cancar et al. [4] demonstrated that using vibrotactile stimuli as feedback to manipulate a robot allowed the users to perceive time-to-contact properties in real environments, which also improved performance.

Vibrotactile stimuli are a common method adopted to present haptic information. For example, Culbertson et al. [5] demonstrated that presenting friction and texture using a vibrotactile stimulus improves the realism of virtual surfaces. Yamazaki et al. [6] indicated that transforming the auditorial signals into perceivable vibrotactile stimuli and presenting them to the upper body improves the music experience. One reason vibrotactile stimuli are commonly used is their ease of presenting spatiotemporal differences and characteristics—such as feedback, cues, and haptic information —by changing different parameters of the waveform. For example, Lylykangas et al. [7] demonstrated that different vibrotactile stimuli can be intuitively interpreted as different speed regulation instructions. Cipriani et al. [8] showed that presenting short-duration stimuli to convey different levels of force and frequency is effective in providing sensory feedback to upper limb amputees. Nakada et al. [9] reported that presenting vibrotactile stimulation using amplitude and frequency modulation improves the discrimination sensitivity for the force information compared with conventional single modulations. Vibrotactile stimuli can also be used to reproduce environmental vibrations, allowing the sharing of tactile sensations and experiences. For example, Yukawa et al. [10] reported that presenting the measured skin-propagating vibration on the fingertip of an advanced skill holder to a beginner can improve the beginner's learning speed. Vibration can also be reproduced in remote communication, and haptic information can be shared via vibrotactile stimuli as an additional dimension for telepresence, enhancing traditional audiovisual communications [11]. Vibrotactile stimuli have a variety of parameters that can be adjusted; however, some parameters exhibit mutual interference.

Although intensity is a direct factor that affects the cognition and comfort associated with vibrotactile stimuli, multiple additional parameters aside from amplitude have been reported to affect the intensity perception. Verillo [12] reported that the shape of the waveforms affects the perceived intensity in the order of square, sawtooth, and sinusoidal waves. Gescheider et al. [13] discussed the presence of damping, expecting it to reduce perceived intensity owing to rapid adaptation. Bochereau et al. [14] reported that lengthening the duration of a Gabor wave from 0.1 s to 0.7 s increases the perceived intensity for frequencies within 10-300 Hz. Bensmaïa et al. [15] reported that frequency power spectra relate to perceived intensity using constant sinusoidal waves. However, many of these studies used stimuli shorter than 1 s, restricted experiments to a specific type of waveform, and failed to address waveform decay. Consequently, the possibility that decaying the waveform into different shapes or extending the duration in the long term may affect perceived intensity has not been investigated. We believe that revealing the influences of different parameters on the perceived intensity can extend the use of vibrotactile stimulation by allowing a more precise prediction of the perceived difference for the presented vibrotactile stimuli.

The appliance of vibrotactile stimuli to different applications erupt many limitations such as design specifications and the perceived difference between individuals. For example, the maximum output voltage is relevant to the adopted

---

[1] Takumi Kuhara, Hikari Yukawa, and Yoshihiro Tanaka are with the Department of Electrical and Mechanical Engineering, Graduate School of Engineering, Nagoya Institute of Technology, Japan `t.kuhara.538@nitech.jp`

[2] Yoshihiro Tanaka is also with Inamori Research Institute for Science, Japan

979-8-3315-3161-4/25/$31.00 ©2025 IEEE

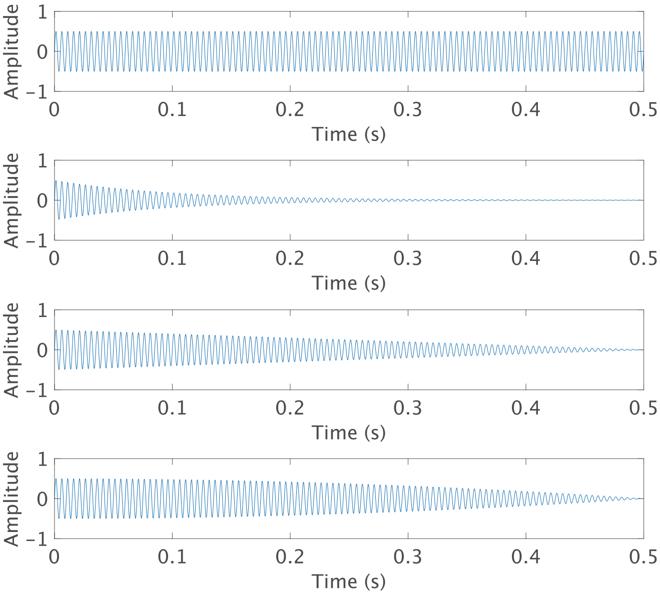


Fig. 1. Waveform shape with the duration of 0.5 s; From the top shows a constant sinusoidal waveform, an exponential damping shaped waveform, a linear damping shaped waveform, and a logarithmic damping shaped waveform.

interface. If the maximum output amplitude of a vibrotactile stimulus falls short of the desired intensity, other parameters can be used to enhance perceived intensity instead. In addition, the influence between the perceived intensity and perceived duration is bidirectional, as a stronger presentation of vibration intensity can make the duration seem longer which allows more possible choices to be adopted [16]. Although the shape of the waveform is capable of providing different tactile textures [17], various applications can use vibrotactile stimuli as cues or substitute sensory information as feedback. For example, the usage of vibrotactile stimuli in 2D navigation was to present direction and cues [3]. The usage in manipulating a remote robot arm was to present the timing the arm was about to contact something [4].

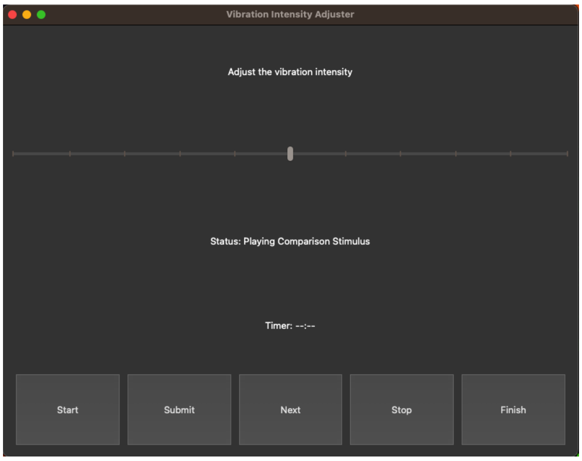
As introduced above, vibrotactile stimuli have a wide range of presentable information with a perceivable difference thanks to multiple parameters configuring the waveform. In this study, we conducted an experiment to reveal the influence of different decaying shapes and long-term durations on the perceived intensity of vibrotactile stimulation.

II. EXPERIMENT SETUP

A. *Stimuli*

For the stimuli, we used six different durations (0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 s), three different damping shapes (linear, exponential, and logarithmic), and a constant wave for a total of 24 samples. A frequency of 200 Hz was adopted for all samples, as it is considered easy to perceive [18]. For damping waves, the damping factor was calculated using Eq. (1) where t denotes time, T denotes duration, and a denotes the exponent.

$$y = (1 - (t/T)^a)\sin(2\pi f t) \tag{1}$$


Vibration Intensity Adjuster

Adjust the vibration intensity

Status: Playing Comparison Stimulus

Timer: --:--

Fig. 2. The GUI presented to the participants; the top part is a slider to adjust the test stimulus output amplitude, the status shows which stimulus is being presented or whether the participants should be taking a break, and the timer starts a countdown from 3 minutes when the break is needed.

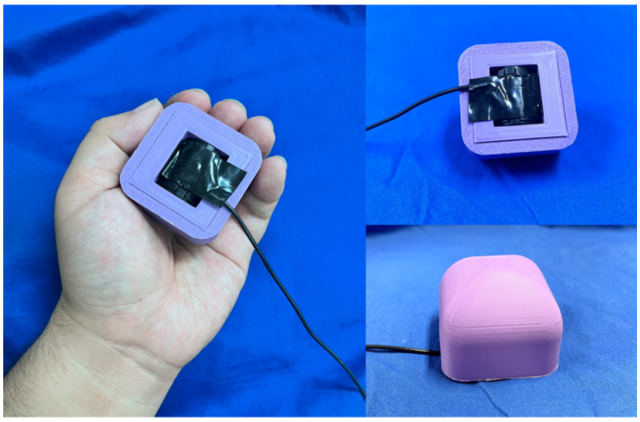


Fig. 3. The posture the participants held the vibrator; to provide vibration to the whole hand, we put the vibrotactile actuator in a rounded cube case sized 45x45x40 mm shown in the right side of the figure

The adopted damping shapes with a duration of 0.5 s are shown in Fig. 1, where the exponent is set to $a = 1$ for linear, $a = 0.5$ for exponential, and $a = 2$ for logarithmic. Given that the maximum input amplitude determined by the audio output system was 100, all waves were initially set with an input amplitude of 50, corresponding to an output amplitude of 7.79 µm. All samples were prepared at a sampling frequency of 44.1 kHz.

B. *Presentation System*

We prepared a GUI that allowed the participants to proceed with the experiment independently, as shown in Fig. 2. In the experiment, the participants compared two different vibrotactile stimuli (reference and test stimuli). The GUI, which controlled the presentation of both stimuli, included a slider to adjust the output amplitude of the test stimulus. The stimuli were presented by using a vibrotactile actuator (Foster, 646752) connected to an amplifier (Foster, ap05 mk2), as shown in Fig. 3. The vibrotactile actuator was also placed inside a top-rounded cube composed of PLA using a

3D printer to present the vibration to the entire hand.

III. METHOD

A. Procedure

We conducted a psychophysical experiment using the adjustment method to determine the effect of each parameter on perceived intensity. As a reference stimulus, we presented the prepared 24 samples in a random order for each participant. For the test stimulus, we adopted a constant sinusoidal wave of 200 Hz, along with a duration of 0.25 s to minimize potential stress stemming from prolonged vibrotactile stimulation. When the test stimulus was presented, the initial input amplitude was set to 50, with a maximum of 100. The reference stimuli were also presented at an input amplitude of 50.

Ten participants (nine male, one female, aged 21-24, nine right-handed, and one left-handed) participated in the experiment. The dominant hand of each participant was identified using a questionnaire [19]. Participants were asked to hold the vibrating device, weighing 61.5 g, with their left hand, as shown in Fig. 3, and handle the GUI using a mouse with their right hand. During the experiment, the participants were presented with stimuli passively, which should leave any influence of the friction coming from the device design low. After the reference stimulus was presented five times, the test stimulus was presented was repeated at 0.1 s intervals until the participants submitted their answers by pressing the submit button shown at the bottom left of Fig. 2. Once the test stimulus started repeating, the participants were asked to control a slider bar that changed the output amplitude of the test stimulus, ensuring that its perceived intensity matched that of the reference stimulus. To exclude the effects of auditorial information, the participants were presented with white noise using noise-canceling headphones throughout the experiment. In addition, to reduce the effect of potential stress caused by prolonged vibration, we set a three-minute break for every six trials. The experiment took approximately 30 minutes for each participant.

B. Analysis

Because the collected data did not follow a normal distribution, we performed an aligned rank transform [20] and then conducted a two-way repeated measures analysis of variance (ANOVA). The aligned rank transform allowed us to handle non-parametric data as parametric data, between the answers for different waveform shapes. When a significant difference was observed, the Wilcoxon signed-rank test with Bonferroni correction was conducted for post-hoc multiple comparisons.

Previously, the perceived vibrotactile intensity has been reported to relate to the Pacinian weighted power spectrum [15] and the time-averaged energy [14]. In the present study, the energy was calculated using Eq. (2) for each waveform. According to Parseval's theorem, the energy in the time domain is equal to the sum of the squared magnitudes of its Fourier coefficients in the frequency domain.

TABLE I

ADJ. P VALUE BETWEEN THE WAVEFORM SHAPES

Shape 1	Shape 2	Adj. P Value
Constant Sinusoidal	Exponential Decay	$<.001$
Constant Sinusoidal	Linear Decay	$<.001$
Exponential Decay	Linear Decay	$<.001$
Exponential Decay	Logarithmic Decay	$<.001$
Linear Decay	Logarithmic Decay	0.022

$$E = \sum_{n=0}^{N-1} |y[n]|^2 \tag{2}$$

Here, E represents the calculated energy, and $y[n]$ represents the discrete samples of the signal in the time domain. According to Bensmia et al. [15], the Pacinian weighted power is modulated by the sensitivity for each frequency and represents the perception of each participant. However, we adopted a simple vibrotactile stimulation with a single frequency of 200 Hz. Therefore, we examined the energy calculated for each stimulus using Eq. (2).

We also measured the acceleration for every four values from 0 to 100 and calculated the amplitude to determine the relationship between the audio system's input and output amplitudes. A linear regression model was created from the measured accelerations and the coefficient of determination R^2 was calculated. The coefficient of determination R^2 was 0.99, indicating a strong linear relationship. Therefore, the experiment and analysis were conducted under the assumption of linearity. The linear regression model between the input and the output amplitude calculated from the acceleration is shown in Eq. (3).

$$A_{out} = 0.083A_{in} + 3.63 \tag{3}$$

Here, A_{out} represents the output amplitude in µm and Ain represents the input amplitude value that was answered equivalent.

IV. RESULTS

The results of the experiment are illustrated as box plots in Fig. 4, where each waveform is denoted by color and the amplitude that yielded the same perceived intensity for the test stimulus as the reference stimulus is shown for each duration. Compared to the input amplitude of 50 for the test stimulus, the perceived intensities of the constant sinusoidal wave and logarithmic decaying-shaped wave were close to or slightly lower. For the exponential and linear decaying-shaped waves, most of the perceived intensities were all answered lower than the input amplitude of 50 for the test stimulus.

Although the two-way repeated measures ANOVA revealed a significant difference in both the duration factor ($F(5,45) = 5.01, p < .001$) and the waveform factor ($F(3,27) = 42.0, p < .001$), no significant difference was found in the interaction. The average equivalent amplitude that was calculated from the different shapes for each duration and participant is shown in Fig. 5 as a box plot. Multiple

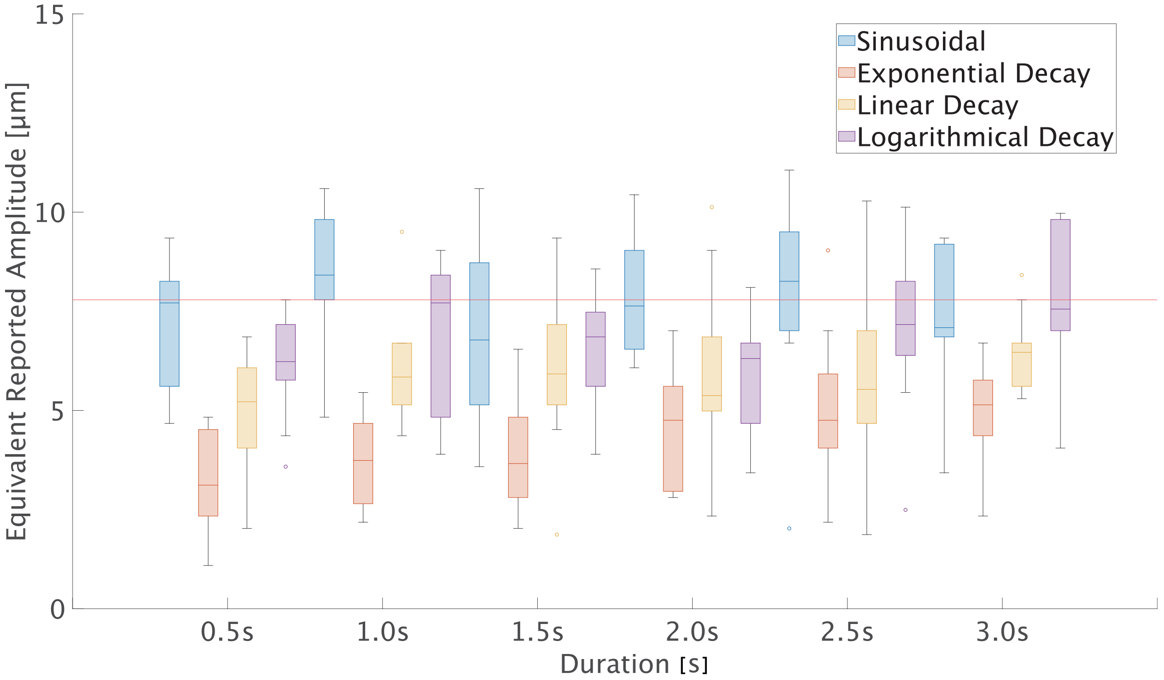


Fig. 4. Results for the experiment; the horizontal axis shows the difference in duration and the vertical axis shows the equivalent reported amplitude. The color difference of the box plot shows the difference of the waveforms

comparisons for the duration factor indicated a significant difference between the reported amplitudes for 0.5 s and 1.0 s ($p = 0.029$), as well as a significant tendency between the answered amplitudes of 0.5 s and 3.0 s ($p = 0.059$). For the waveform factor, the multiple comparisons indicated that there was a significant difference between each waveform shape, except for that between constant sinusoidal waves and logarithmical decaying waves. The adjusted p-values are listed in Table. I. This indicates that not only the damping of the waveform but the damping shape can affect the perceived intensity at different levels. From the results of the experiment, the constant sinusoidal wave yielded the strongest perceived intensity, followed by logarithmic decay and linear decay, with exponential decay being perceived as the weakest.

To determine how strongly the participants perceived the intensity, we conducted a Wilcoxon signed-rank test with a Bonferroni correction between the output amplitude of the reference stimulus (50: 7.79 µm) and reported amplitude for each waveform shape. Significant differences were reported for all shapes except the constant sinusoidal waveform. The adjusted p-values for the other three damping waveforms were all $p < .001$. These results indicate that damping the waveform may result in the perception of a lower intensity irrespective of shape.

Fig. 6 shows the calculated energy of each waveform shape for each duration. From the results, we can see that the constant sinusoidal wave had the strongest energy, followed by the logarithmic decaying-shaped waves, the third was the linear decaying shaped waves, and the exponential decaying shaped wave had the lowest energy for each duration. Fig. 7 shows a scatter plot of the average reported amplitude for each waveform along with its calculated energy, where the waveform is denoted by color and duration is represented by differences in transparency. Although a longer duration was associated with increased calculated energy, the perceived intensity did not change much over 35.7 $\mu\mathrm{m}^2$.

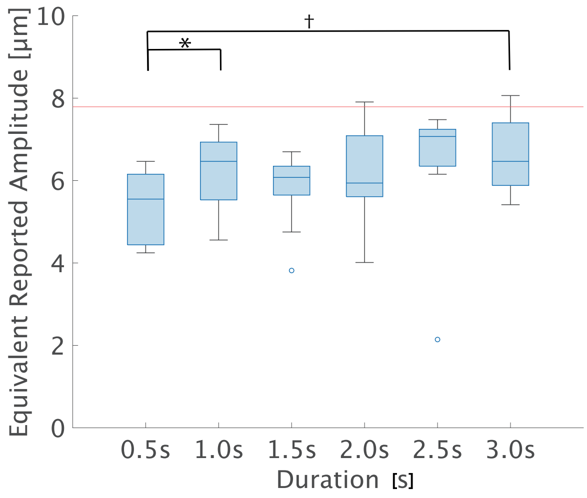


Fig. 5. Results for the difference of durations ($*p < 0.05, \dagger < 0.1$); the results are shown in a box plot that uses the participant's equivalent reported amplitude for each duration

V. DISCUSSION

The results from our experiment reveal significant differences between durations, indicating a significant tendency between the perceived intensity of the waveforms with a duration of 0.5 s and 3.0 s, which supports the results of prior

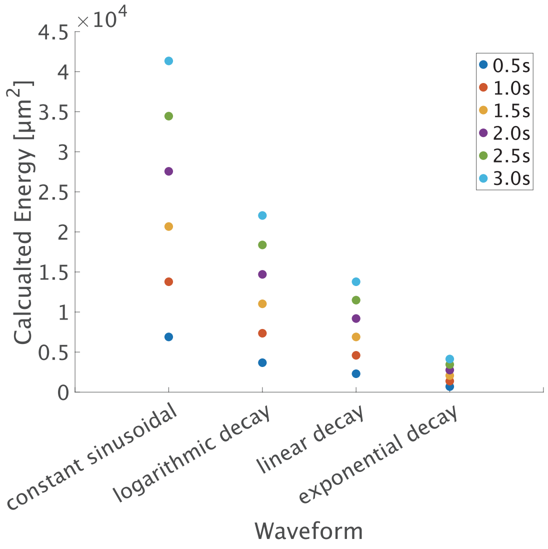


Fig. 6. Calculated energy for each waveform; the horizontal axis represents the difference of the waveforms and the vertical axis represents the calculated energy. The difference in the colors represents the difference in duration.

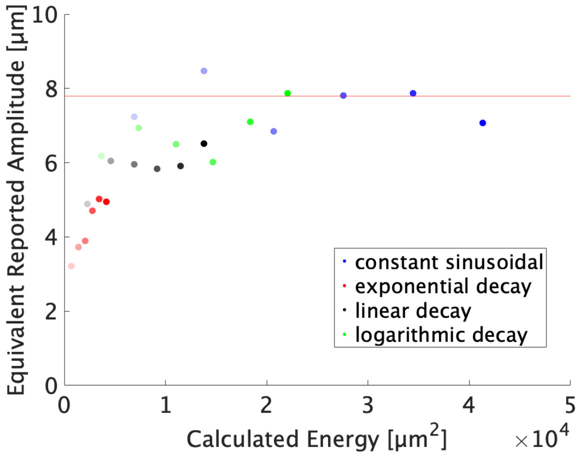


Fig. 7. Relationship between the calculated energy and the average answer for each waveform; the colors represent the difference of waveforms, and the transparency represents the difference in duration.

studies [12][13][14][21]. However, the reported duration had a slight difference between the results of the prior studies and our experiment, which the presented body part may have caused, as we presented the vibration to the whole hand, whereas prior studies presented the vibration to the fingertip or the entire body. It is also possible that the amplitude employed for the vibrotactile stimulus affects change in the perceived intensity since the amplitude employed in our experiment was stronger than that presented to the fingertips [14] and weaker than that presented to the whole body [21]. Furthermore, our experiments were conducted using different procedures that presented multiple waveforms, including decaying waveforms. In contrast, the aforementioned studies presented a specific constant waveform with a smaller amplitude than that used in our experiment. These possibilities may have influenced the evaluation of the equivalent amplitude.

In addition, the results of our experiment revealed a significant difference between waveforms, with the constant sinusoidal wave perceived as the strongest, followed by the logarithmic decaying wave, linear decaying wave, and exponential decaying wave. Although both the effect of duration and the difference in waveform exhibited significant differences, the former was subtle compared to the latter. Whereas the effect of duration showed a significant difference between the duration of 0.5 s and 1.0 s, as well as a significant tendency between 0.5 s and 3.0 s, the effect of waveforms showed a significant difference between each waveform except for the constant sinusoidal and logarithmic decaying shaped waves. The perceived order of intensity was also the same as that of calculated energy, indicating that the current results are consistent with those of previous studies [14] [21]. We can recognize from Fig. 6 that lengthening duration will increase the calculated energy proportionally. However, the equivalent amplitude of the constant sinusoidal wave was close to the input amplitude of 50, irrespective of duration. This indicates that time-averaged energy is a highly influential contributor to the perception of intensity.

From the scatter plot between the reported average equivalent amplitude and the calculated energy for each waveform, we can also recognize the possibility that the time-averaged energy affects the equivalent amplitude with higher energy corresponding to stronger perceived intensity. However, the equivalent amplitude appears to converge around the output amplitude when the energy exceeds 35.7 µm^2. This may be the limit of the relationship between perceived intensity and calculated energy owing to the averaged duration and non-linear characteristics of people's tactile perception. Another possible reason is the balance between the increase in perceived intensity caused by the energy and the decrease caused by adaptation. Prolonging the duration of vibrotactile stimuli can increase the calculated energy and cause adaptation. This indicates that when the calculated energy exceeds a certain threshold and is accompanied by a long duration, the perceived intensity can converge.

From a different perspective, there is a possibility that the perception mechanism differs due to the length of duration. Many prior studies focus on duration for a short term, often under 1.0 s, and many studies don't discuss a duration longer than 1.0 s. From Fig. 5, the results showed a significant difference between the answers for 0.5 s and 1.0 s and a significant tendency between the answers of 0.5 s and 3.0 s. This indicates the possibility that the perception mechanism for vibrotactile stimulus may differ between short and long durations.

VI. CONCLUSION

In this study, we investigated the effects of different decaying-shaped waveforms and durations on the perceived intensity of a vibrotactile simulation. Because prior studies have shown that short-term durations and waveform shapes both affect perceived intensity, we conducted an experiment to determine the specific effects of long-term durations and decaying-shaped waveforms on our perceived intensity. The results indicate that both changes in decaying-shaped waveforms and duration affect perceived intensity. Furthermore, the effect of duration is subtle compared to that of decaying-shaped waveforms, with significant differences between each pair of decaying-shaped waveforms.

ACKNOWLEDGMENT

This work was supported by JST SPRING, Grant Number JPMJSP2112, JSPS Grant in Aid for Early Career Scientists Grant Number 24K20816, Inamori Research Institute for Science, and JST Moonshot R&D Program under Grant JPMJMS2013.

REFERENCES

[1] Shirota, K., Uemura, M., Pore, R., & Minamizawa, K. “Liquid-VR: Wetness Sensations for Immersive Virtual Reality Experiences.” International Conference on Haptic Interaction - Science, Engineering and Design, 2018.

[2] Achibet, M., Girard, A., Talvas, A., Marchal, M., & Lécuyer, A. ”Elastic-Arm: Human-Scale Passive Haptic Feedback for Augmenting Interaction and Perception in Virtual Environments.” 2015 IEEE Virtual Reality (VR): 63-68, 2015.

[3] Jeon, W., Li, Y., Bahn, S., & Nam, C.S. “Assessing the Effectiveness of Vibrotactile Feedback on a 2D Navigation Task.” In M. (eds) Human-Computer Interaction. HCI 2013.

[4] Cancar, L., Díaz, A., Barrientos, A., Travieso, D., & Jacobs, D.M. ”Tactile-Sight: A Sensory Substitution Device Based on Distance-Related Vibrotactile Flow.” International Journal of Advanced Robotic Systems, 10, 2013.

[5] Culbertson, H., & Kuchenbecker, K.J. “Importance of Matching Physical Friction, Hardness, and Texture in Creating Realistic Haptic Virtual Surfaces.” IEEE Transactions on Haptics, 10, 63-74, 2017.

[6] Yamazaki, Y., Mitake, H., & Hasegawa, S. ”Tension-Based Wearable Vibroacoustic Device for Music Appreciation.” EuroHaptics 2016.

[7] Lylykangas, J., Surakka, V., Rantala, J., & Raisamo, R. “Intuitiveness of Vibrotactile Speed Regulation Cues.” ACM Transactions on Applied Perception (TAP), 10, 1-15, 2013.

[8] Cipriani, C., D’ Alonzo, M., & Carrozza, M. ”A Miniature Vibrotactile Sensory Substitution Device for Multifingered Hand Prosthetics.” IEEE Transactions on Biomedical Engineering, 59, 400-408, 2012.

[9] Nakada, N., Yukawa, H., & Tanaka, Y. ”Force Information Presentation by Vibrotactile Stimulation Combining Amplitude and Frequency Modulation.” 2023 IEEE International Conference on Systems, Man, and Cybernetics (SMC), Honolulu, Oahu, HI, USA, 2023, 4826-4831.

[10] Yukawa, H., Tsuruoka, M., Kodama, T., Odagiri, M., Sato, M., Takeda, M., Kurachi, M., & Tanaka, Y. ”Tactile Feedback Involving Actual Operation for Motor Skill Learning.” 2023 IEEE World Haptics Conference (WHC), 203-209, 2023.

[11] Steinbach, E., et al. ”Haptic Communications.” Proceedings of the IEEE, 100(4), 937-956, April 2012.

[12] Verrillo, R.T. ”Vibration Sensation in Humans.” Music Perception, 9(3), 281-302, 1992.

[13] Gescheider, G.A., Bolanowski, S.J., & Verrillo, R.T. ”Some Characteristics of Tactile Channels.” Behavioural Brain Research, 148(1-2), 35-40, 2004.

[14] Bochereau, S., Terekhov, A., & Hayward, V. ”Amplitude and Duration Interdependence in the Perceived Intensity of Complex Tactile Signals.” Proceedings of EuroHaptics, 93-100, 2014.

[15] Bensmaïa, S.J., Hollins, M., & Yau, J.M. “Vibrotactile Intensity and Frequency Information in the Pacinian System: A Psychophysical Model.” Perception & Psychophysics, 67, 828-841, 2005.

[16] Francisco, E. M., Holden, J. K., Nguyen, R. H., Favorov, O. V., & Tommerdahl, M. (2015). Percept of the duration of a vibrotactile stimulus is altered by changing its amplitude. Frontiers in systems neuroscience, 9, 77.

[17] M. Natsume, Y. Tanaka, W. M. Bergmann Tiest and A. M. L. Kappers, ”Skin vibration and contact force in active perception for roughness ratings,” 2017 26th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), Lisbon, Portugal, 2017, pp. 1479-1484

[18] Lamore, P., Muijser, H., & Keemink, C. ”Envelope Detection of Amplitude-Modulated High-Frequency Sinusoidal Signals by Skin Mechanoreceptors.” The Journal of the Acoustical Society of America, 79(4), 1082-1085, 1986.

[19] Coren, S. ”The Left-Hander Syndrome: The Causes & Consequences of Left-Handedness”. 1993.

[20] Wobbrock, J.O., Findlater, L., Gergle, D., & Higgins, J.J. ”The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only ANOVA Procedures.” Proceedings of the International Conference on Human Factors in Computing Systems (CHI 2011), 2011.

[21] Miwa, T. ”Evaluation Methods for Vibration Effect.” Industrial Health, 5, 183-205, 1968.