Edge Vibration Improves Ability to Discriminate Roughness Difference of Adjoining Areas

Yuki Ban, Yusuke Ujitoko, and Kouta Minamizawa,

***Abstract*—Researchers have studied the discrimination thresholds between different vibrotactile signals under various conditions. Humans cannot recognize slight differences in vibrotactile stimuli that are smaller than the perception threshold. This is a constraint in the vibrotactile design used in practical applications. This study focuses on the vibrational feedback at the "edge" between multiple areas, while previous studies have not considered this. We assume that the edge vibration not only emphasizes the presence of the edge itself, but also has an effect on the vibrotactile perception of the adjoining areas. Specifically, we hypothesize that the edge vibration would modify the user's ability to discriminate vibrotactile differences between adjoining areas. We conducted a user study to test this hypothesis. As a result, we found that presenting edge vibrations at the boundaries between adjacent textures makes it easier to discriminate the frequency and amplitude differences of the vibrations of those uneven textures. This work could increase the flexibility of vibrotactile design, and vibrotactile designers could use these results to design a wider variety of vibrations for adjacent areas.**

***Index Terms*—Texture Rendering, Vibrotactile**

I. INTRODUCTION

Owing to the popularity of mobile devices with vibrotactile actuators, surface tactile technology has gained significant attention in recent years [1]. Vibrotactile stimuli enable humans to perceive the texture of surface materials. Considering the development of practical vibrotactile applications, tactile designers need to design multiple vibrations to indicate different areas of material surfaces. A vibrotactile recorder [2] and vibrotactile designing toolkit [3] were developed recently, and now designers have the means to obtain whatever vibrations they want. Using such tools, designers can design a vibration for each surface area. However, this does not make sense if users cannot distinguish the differences between vibrations at different areas. Therefore, in such cases, designers have to consider whether users can distinguish between the different vibrotactile signals being provided. This capacity is quantified by the discrimination threshold. Generally, it is shown that a difference of at least 20-30% in amplitude or frequency is necessary for robust discrimination between vibrotactile stimuli for practical applications [4], [5]. Thus, it is difficult to enable users to recognize a slight difference in the vibration of different areas, and this is a constraint for vibrotactile design. For example, the user may not feel the texture as the designer intended, or the designer may not be able to express the difference between delicate textures.

The focus of this study is the design of vibrations at the edges between different areas. Few conventional implementations have focused on the edges between areas, but they did not set specific vibrations on the edges. However, Vardar et al. attempted to separate two textural regions in a haptic presentation on a touch screen by electrovibration, using the effect of tactile masking [6]. The tactile masking is a phenomenon by which presenting one stimulus might interfere with the perception of another stimulus. This phenomenon can cause certain deficits in perception, such as increase in detection thresholds and hindering of localization or identification [7], [8]. Vardar et al. revealed that the sharpness of the edge separating textural regions can be enhanced by producing the tactile masking effect by enhancing the local frequency contrast between the background and foreground stimuli. Besides, Dallmann et. al. showed that masking significantly reduces the precision of speed discrimination. This result suggests that slip-induced vibrations help with the discrimination of tactile speed [9]. On the other hand, tactile masking using voice coils [8], vibration motors [10], etc., has been studied; however, there has been no verification of the discrimination of multiple textural regions for touch-screen applications as in [11].

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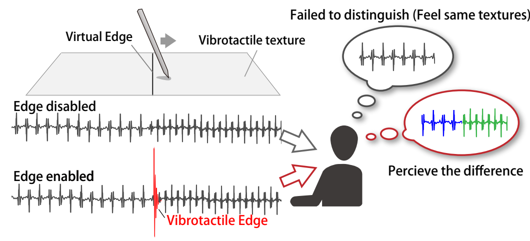

Fig. 1. Proposed method for improving the discrimination ability of vibrotactile stimuli on adjacent areas using edge vibration.

Considering these previous studies, this study focuses on attaching additional edge vibrations using a vibrator for interactions on touch screens with pen devices. We assumed that an edge vibration can not only emphasize the edge itself but also affect the ability to discriminate the vibrotactile ruggedness of areas divided by edges. Based on the analogy of an optical illusion in which a visual edge between two areas affects the perception of adjacent areas [12], [13], it is expected that there would be a similar effect for a vibrotactile edge. Specifically, we hypothesize that users can recognize a slight difference in vibrotactile texture with edge vibration, while they cannot recognize it without edge vibration (see Fig.1). In other words, the discrimination threshold with edge vibrations would be smaller than that without edge vibrations.

In the case of texture presentation using a touch screen, it is preferable that the vibration is less restricted from the viewpoint of practicability. In the previous approach [11], to produce the effect of tactile masking, it was necessary to adjust the frequency of the vibration stimulus in the region near the edge, due to the difference in the frequency of the neighboring texture. However, in our proposed method, it is only necessary to present the edge vibration at the boundary between textural areas. Thus, when the edges are superimposed on a content having multiple vibrational textures, there is the advantage that we do not have to redesign the vibrations of the original textural surfaces (such as decreasing or increasing the frequency of the textural vibration near the edges); we only have to attach a simple edge vibration.

We conducted a user study to test this hypothesis. Through the user study, we verified whether the vibration frequency and amplitude of two adjacent textures could be correctly discriminated by adding edge vibration. We chose the frequency and amplitude as the validation

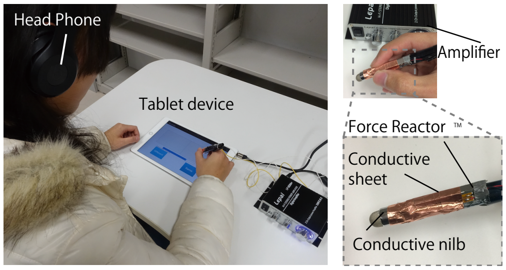

Fig. 2. Experimental system.

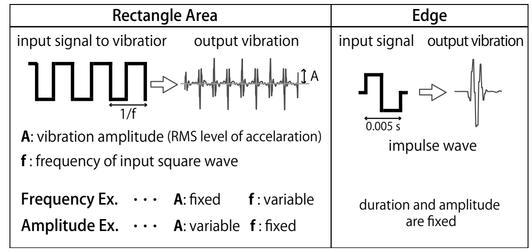

Fig. 3. Summary of parameters of vibration stimuli in this user study.

parameters because these two parameters significantly contribute to the presentation of various types of rugged textures. The contributions of this study are following two points.

- We focus on edge vibration and consider the problem of its effect on the ability to discriminate vibrotactile stimuli of the divided areas.
- A user study showed that the presenting edge vibrations between adjacent textures makes it easy to discriminate the frequency and amplitude differences of the vibrations of those textures.

II. Related Work

Researchers have conducted studies on vibrotactile perception that are useful for the design of effective vibrotactile applications. This knowledge can be particularly helpful to designers in choosing what vibrotactile signals to render.

Researchers have studied the absolute detection threshold of vibrotactile stimuli [14]. This threshold is the weakest intensity of a stimulus that allows a human to perceive with confidence, the presence of the stimulus. As is common with tactile perception, it depends on a number of factors such as the frequency, body site, or contact area [15]. For example, if the contact area or stimulus duration increases, all the thresholds of the PC channel decrease because of the summation effect. [16], [17] reviews on the absolute detection thresholds determined using tool-mediated stimulation conditions were used in the user study in this paper. Delhaye et al. revealed the presence of high-frequency vibrations in the wrists of users exploring rough surfaces, and showed that this vibration helps users detect the roughness of textural surfaces [18].

Once a stimulus is known to be perceptually recognizable, then tactile designers have to consider the ability of users to discriminate multiple vibrotactile stimuli. This is because there are multiple surfaces or content that exist simultaneously in a typical case. The capacity to detect a stimulus is quantified by the discrimination threshold. Because differential thresholds depend on the strength of the reference stimulus, discriminability is generally represented by a Weber fraction, which shows a linear relationship between differential threshold and stimulus intensity. Weber fractions mostly cluster around 10%–30% for vibration intensity and around 15%–30% for vibration frequency[5]. In general, it is known that a difference of at least 20%-30% in amplitude or frequency is necessary for robust discrimination between vibrotactile stimuli in practical applications [4], [5]. Thus, it is difficult for users to recognize a slight difference in roughness between multiple areas, and this is a constraint for vibrotactile design.

III. Experimental Design

A. Experimental system

The task in this study was to move a pen-type device on a tablet device while receiving vibrotactile feedback via the pen (Fig.2). The pen-device, which we handcrafted, was approximately 140 mm in length and weighed approximately 20 g. The diameter of the pen's grip was approximately 10 mm. We covered the pen tip with a conductive material because the shaft of the pen was plastic and did not conduct to the grip part. We wound a conductive sheet onto the grip to react with a capacitance type touch screen by electrically connecting a hand, grip, and a pen tips. We embedded a vibrator (ALPS Inc., Force Reactor) inside the pen-type device 20 mm from the tip of the pen, where the participants gripped. The operating frequency range from this vibrator was 0 - 500 Hz [19]. Its rated supply voltage was 3.3 - 5.0 V, and we measured the peak-to-peak voltage on the vibrator when f was 30 Hz (described below), and the voltage was 4.67 V. The vibrator was small (35.0 mm $\times$ 5.0 mm $\times$ 7.5 mm) and light (approximately 5 g), so the participants were not tired when moving the pen. When the participants moved the pen on the touchpad, the vibration signal was emitted from the earphone jack of the tablet device (Apple Inc., iPad Pro 9.7 inch). The amplifier (Lepai Inc., LP-2020A) amplified the signal, and the vibrator embedded in the pen presented the vibration to the fingers of the participants. This vibrator, which includes a voice coil and plate spring, can present the vibration in only one direction (along one axis), but it's no problem to present texture surfaces because Romano et al. constructed the method to reduce the three-dimensional acceleration signals to a perceptually equivalent one-dimensional signal [20].

The screen refresh rate was 60 Hz, and finger position acquisition was performed at 100 Hz. Although no formal data were obtained on the accuracy of the contact position acquisition, the resolution was 264 ppi and the contact position was acquired every 1 pixel; hence, it is assumed that the acquisition accuracy is about 0.1 mm.

The participants wore headphones with noise-cancellation and heard white noise to avoid background noise from the environment and to avoid hearing small sounds caused by the vibration of the pen-type devices. We confirmed in advance that the participants could hear no external noise or sounds emitted from the pen-device. A web browser rendered the experimental task screen presented to the participants on the tablet screen, and a JavaScript Web Audio API controlled the vibration signals. A signal was sent from the earphone jack of the tablet device, which was amplified by the amplifier and finally output as a vibration stimulus by the pen-device.

B. Vibrotactile texture stimuli

As the first step to investigate the effect of a vibrotactile edge on vibrotactile texture discrimination, we assumed a simple patterned virtual surface and edge. By moving the pen-type device, the participants felt vibrations of two adjacent virtual surfaces, and felt the vibration of the edge when the pen moves over the edge (Fig.1). Fig.3 shows a summary of the parameters of vibration stimuli for the rectangular area and for the edge.

1) Vibration on virtual surfaces: We focus on the rugged texture of rocks as the texture presented by the vibration and tactile stimulation. To present a rugged feeling texture, we used a square waveform, the frequency (f) and amplitude (A) of which are easily controllable. By controlling f, we can modify the interval length of the discrete vibration, which presents the spacing of ruggedness. By controlling

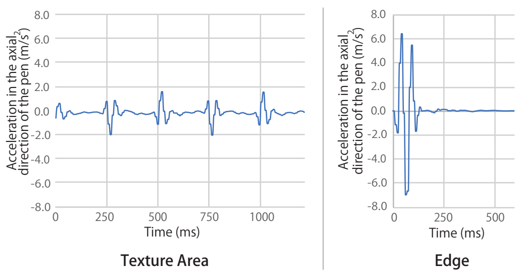

Fig. 4. Acceleration presented when the pen's tip moves on the texture area (Left), and that when the pen moves across the edge (Right). The left one is the vibration of the texture area when A is 4.90 $\mathrm{m/s^2}$ and f is 20 Hz

A, we can present the size of the ruggedness. We generated the stimulus difference between areas by changing the vibrotactile amplitude and frequency. These two parameters were controlled independently in separate experiments. Hereinafter, an experiment in which the amplitude of vibrotactile stimuli is changed is called "Amplitude Ex.", and an experiment in which the frequency of vibrotactile stimuli is changed is called "Frequency Ex.". The vibration frequency was selected by a pilot test to make it easier to recall the rugged texture of rocks. Specifically, we focused on the rock surface with a space period of several millimeter scale. As a pilot test, various vibrations with frequencies in the range of 10 to 200 Hz under the constant pen movement speed (78 mm/s) were tried by three participants. As a result, the spatial period was found to range from 2.6 mm to 7.8 mm, corresponding to vibrations from 30 Hz to 10 Hz; these were judged closer to the rugged feeling and were chosen as the experimental parameters.

For setting the vibration amplitude, we directly measured the acceleration output from the vibrator attached to the pen-device and set the scale of the parameters by calculating the RMS of the acceleration. We used this RMS of acceleration as the vibration amplitude (A). We hung a bare vibrator in air by using a string. At the flat side surface of the vibrator, a three-axis acceleration sensor (MPU-6050), working at 400 kHz, was tightly attached. We measured the acceleration data along the main axis of the vibrator at 2 kHz. The left part of Fig.4 shows the waveform of the textural area vibration. Through these pilot tests, we chose the variations of f and A (Table I, II). The gain was adjusted under each signal condition so that the RMS of acceleration could be adjusted even when the frequency of vibration stimulation was different. We call the vibrotactile signal variable "signal conditions" in this user study.

2) Vibration on the Edge: We generated an impulse waveform to present the sensation of exceeding the edge. An impulse waveform is usually used for presenting a key-click signal, and we consider that this waveform is the simplest vibrotactile stimulus, since it is the vibration that expresses the sensation of crossing edges. Through the pen-type device, the users felt the vibration of the virtual edge when the pen crossed over the edge line. The duration of the impulse waveform was set at 0.005 s. The RMS of the acceleration was heuristically determined through the pilot test. We chose the vibration duration and amplitude that were suitable for a small edge. The right part of Fig.4 shows the waveform of the edge vibration.

IV. Preliminary Study: Subjective evaluation of vibrotactile texture

In the main user study, we verified the effect of our method using the JND (just noticeable differences) methodology. Therefore, it was necessary to confirm that the vibrotactile signals' set is capable of covering a range of subjective ruggedness values. Besides, we also had to confirm that the frequency of vibration represents the fineness of the rugged textural surface, and that the amplitude of vibration

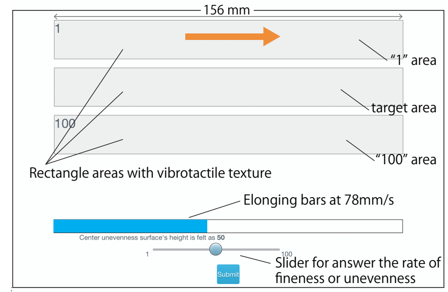

Fig. 5. Experimental window of the preliminary study

TABLE I
"Signal conditions" (f and A) of each textural area

Experiment	parameter	standard stimulus	comparison stimulus
Frequency Ex.	A	20 Hz	10, 14, 17, 19, 20, 21, 23, 26, 30 Hz
	f	4.90 $\mathrm{m/s^2}$	4.90 $\mathrm{m/s^2}$
Amplitude Ex.	A	20 Hz	20 Hz
	f	4.90 $\mathrm{m/s^2}$	0.98, 1.96, 2.94, 3.92, 4.90, 5.88, 6.86, 7.84, 8.82 $\mathrm{m/s^2}$

represents the unevenness of the textural surface. In other words, we had to confirm that as the frequency (amplitude) of vibration increases, the perceived texture surface becomes finer (more uneven). Therefore, we conducted a preliminary experiment to confirm a monotone increase in fineness and unevenness of the rugged surface with respect to the increase in frequency and amplitude of the presented vibrations within the parameters we set (Table 1).

A. Participants

There were twelve participants (nine males and three females) with ages ranging from 22 to 25 (23.5 ± 0.957). All of the participants were right-handed. None of them reported a history of neurological, psychiatric, or other diseases that could have interfered with tactile sensitivity. The University of Tokyo Ethics Committee approved the experiments presented in this paper (approbation number: 19-173), and written informed consent was obtained from all participants in the studies presented here and in the next section. The total time of the experiment was about thirty minutes, including the time for providing the explanation in advance and for the questions after the task. No reward was paid to the participants.

B. Task Design

This user study was conducted according to a within-participants design. The participants performed a task to evaluate the textural unevenness and fineness. Fig.5 shows the experimental screen on the tablet device during the preliminary study. Three vibrotactile textural areas were placed on the screen. The participants compared three signal conditions with extreme differences by moving the pen-device on the tablet. The participants moved the pen device over rectangle areas from left to right at a constant speed (78 mm/s) with their dominant hands. They were required to grip the pen with their fingers at the position where the vibrator was embedded so that they felt the vibration in their fingers. On the tablet screen, three vibrotactile areas, an elongating blue bar, and two buttons for providing the answer were displayed. This blue bar notified the participants of the speed and length (156 mm) of the pen-device movement. The target moving speed was heuristically determined through a pilot test such that it was not burdensome to the participants. We measured the speed of the touching point in the background, and confirmed that the tracing speed was within 77.2 ± 3.7 mm/s in the 78 mm section of the central zone, excluding the beginning and end of movement.

The experiment followed the magnitude estimation. For "Frequency Ex.", the participants recognized that the textural area for

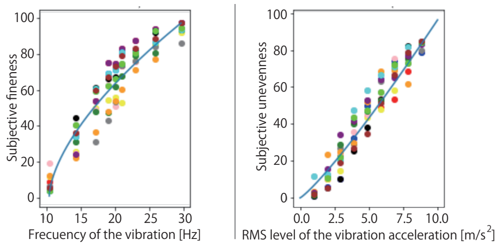

Fig. 6. Relationship between the subjective rating of fineness and the frequency of vibration for "Frequency Ex." (Left), and that of unevenness and the amplitude of vibration for "Amplitude Ex." (Right). The color difference of the dots shows the difference of the participants.

which f was 10 Hz was expressed as 1, and that the texture area for which f was 30 Hz was expressed as 100. The former was presented at the top textural area, and the latter was presented at the bottom textural area. The middle textural area presented nine types of f (shown in Table I) as the target area. The participants traced these three areas in order from top to bottom. The participants were asked to rate the fineness of the target area with the vibrotactile stimulus displayed on the pen-device. The speed and length of the pen-device movement was fixed as described, but the participants could trace the three areas any number of times. Each participant repeated the trial ten times for each signal condition; thus, overall there were 90 trials per participant ($= 9 \times 10$). The texture areas were presented in a random order and were counterbalanced across participants. The procedure of "Amplitude Ex." was almost the same as that of "Frequency Ex.". The experimental conditions are shown in Table I. The participants were asked to rate the unevenness of the target area. The participants used the slider and the button to indicate their ratings of fineness or unevenness. All the participants participated in both the preliminary studies. (i.e., in both "Frequency" and "Amplitude Ex."). The order of these two studies was counterbalanced among the participants.

Before these trials, we preliminarily confirmed the participants felt that the signal condition with f of 10 Hz was finer than that of 30 Hz, and that the signal condition with A of 8.82 $\mathrm{m/s^2}$ was more uneven than that of 0.98 $\mathrm{m/s^2}$.

C. Result and Discussion

The average data of each participant are shown in Fig.6. The perceived fineness of the texture area increased with increase in the frequency of vibrotactile stimulus (f) in "Frequency Ex.", And the unevenness of the texture area increased with increase in the amplitude of vibrotactile stimulus (A) in "Amplitude Ex." These results suggest that there was no problem with asking the participants about their perception of the difference in frequency/amplitude of the vibration as the degree of unevenness/fineness of a texture area. The data for each participant were fitted by Steven's power function $R(s) = k \cdot s^n$, where s represents f of the vibrotactile stimulus for "Frequency Ex.", and A of the vibrotactile stimulus for "Amplitude Ex.". $R(s)$ represents the subjective rate of fineness and unevenness. We applied Generalized linear mixed model (GLMM) to calculate this fitting curve. The fitted curve is shown in Fig.6. We confirmed that the subjective fineness/unevenness rate increased with increase in the vibrotactile stimulus frequency/amplitude. The obtained values for (k, n) were (15.5 0.622) in "Frequency Ex.", and (7.75, 1.16) in "Amplitude Ex.". These results indicate a monotone increase in the fineness and unevenness of the rugged surface with respect to the increase in frequency and amplitude of the presented vibrations within the parameters we set. Thus, we conducted the main user study with these "signal conditions."

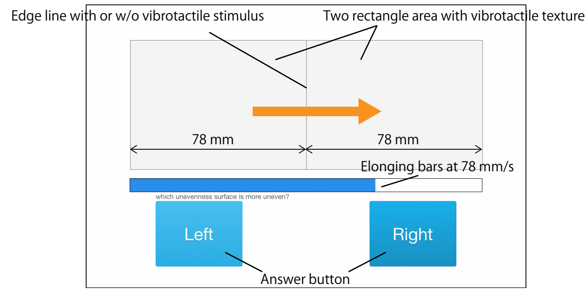

Fig. 7. Experimental window. The participants move the pen-type device from left to right on the two rectangular texture areas

V. Main User Study

By moving the pen-type device, the participants felt the vibrotactile textures of two adjacent areas (Fig.1). They compared the texture vibration feedback presented when moving the pen-type device over these two areas in succession. In terms of edge vibration, there were two conditions: with edge vibration and without edge vibration. There were twelve participants, and all of them participated in the preliminary study. The total time of the study was about one hour, including the time for the explanation in advance and the time for asking questions after the task. No reward was paid to participants.

A. Task Design

This user study was conducted according to a within-participants design. The design of the experiment followed a JND methodology [21]. We investigated whether the participants felt the unevenness of the "comparison stimulus" to be finer or more uneven than that of the "standard stimulus" with or without the edge vibration. The participants had to move the pen-type device once from left to right to cross two adjacent rectangle areas (Fig. 7). They received vibrational feedback from two textural areas through the pen device. The edge was visually placed at the boundary between these two areas. The width of this edge was 1 pixel, and it was just a line. The system determined whether the nib had passed the edge by comparing the current nib position with the preset edge position on the screen. In a touch screen vibrotactile application that presents multiple textures, we assume that visual information is also presented. In this situation, the boundary of the textural areas is clear from the visual difference of the texture. Thus, we also presented a visual edge in this study.

We describe the procedure of one trial in the task. The participants moved the pen over two rectangle areas from left to right at a constant speed (78 mm/s) with their dominant hands. The total distance over which the pen was moved was 156 mm. The system notified the participants of the speed using an elongating blue bar on the screen. We confirmed that the tracing speed was within 76.3 ± 3.4 mm/s in the 78 mm section of the central zone. Besides, since the average difference of moving speed in the left and right areas was less than 0.33 mm/s for a trial, the change of moving speed in a trial did not affect the perception of the difference of texture in the left and right areas. The participants were also instructed not to change the way of gripping a pen during the experiment. It is possible that the strength of gripping varied during the trials, even though the way of gripping was the same. However, even if the strength of the vibrator held by the participants had changed, the vibration of the voice coil inside the vibrator was not affected by the grasping pressure. Thus, we considered that there would be no effect on the experimental result even if the gripping strength was not controlled.

Under the condition with edge vibration, the participants felt the vibration from the edge when they went over it with the pen-device. After the participants finished the movement from left to

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TABLE II
"SIGNAL CONDITIONS" (f AND A) OF STANDARD AND COMPARISON STIMULI

Experiment	parameter	standard stimulus	comparison stimulus
Frequency Ex.	A	20 Hz	10, 14, 17, 19, 20, 21, 23, 26, 30 Hz
	f	4.90 m/s^2	4.90 m/s^2
Amplitude Ex.	A	20 Hz	20 Hz
	f	4.90 m/s^2	0.98, 1.96, 2.94, 3.92, 4.90, 5.88, 6.86, 7.84, 8.82 m/s^2

right with the pen-type device, they answered "which texture surface did they feel was finer?" in "Frequency Ex.", or "which texture surface did they feel was more uneven?" in "Amplitude Ex." We thought that these questions could correctly measure the effect of the edge, because we confirmed the correspondence of the frequency and amplitude of the vibration with the perception of textural fineness and unevenness through the preliminary study. The participants tapped one of the two answer buttons visualized on the screen. The following additional instructions were given to the participants. We told the participants that they could move the pen under each condition on only one round trip. We also asked them to select one of the two buttons randomly if they thought that it was difficult to judge. This 2AFC (2 Alternative Forced Choice Task) method is "criterion-free" in contrast to the alternative method such as "criterion-dependent" task such as "yes/no" question [22]. Thus, 2AFC method is commonly used to evaluate various discrimination thresholds of haptic sensation [23].

Here, we describe the details of the experimental conditions. The participants performed "Frequency Ex." and "Amplitude Ex.", and order of them was counterbalanced among the participants. In one trial, the participants compared two vibrotactile areas: a standard stimulus and a comparison stimulus. These two surfaces were presented under the same condition except the "signal conditions" (see Table II).

In this trial, the texture area on the right side following the edge vibration might be affected by tactile masking. To investigate this effect, the correspondence between the type of stimulus and the position of the texture area was fixed so that the left side was the "standard stimulus" and the right side was the "comparison stimulus." Moreover, there were two conditions of the edge at the boundary between these two areas. The "Edge condition" presented a vibration stimulus as described above when the pen-device crossed the edge, and the "None condition" did not present any edge vibration. The participants performed the experiments ten times for each combination of the edge conditions and the signal conditions of the comparison stimulus. Thus, each participant performed 180 trails ($= 10 \times 2$ (edge conditions) $\times$ 9 (the signal conditions of the comparison stimulus)) for both the tasks, namely "Frequency Ex." and "Amplitude Ex." The presentation order of these factors was randomly assigned and counterbalanced across participants. After all the trials were completed, the participants answered whether there was a difference in the feeling of the two textures due to the presentation of an edge vibration at the boundary, and if there was a difference, what kind of difference there was for each experiment.

B. Results

Fig.8 shows the response of one participant as an example of the results. These figures show the rate at which the participant answered that the comparison stimulus was finer or more uneven than that of the standard stimulus. These figures indicate that the participants felt the comparison stimulus to be finer when its vibration frequency f was higher than that of the standard stimulus, and felt the comparison stimulus to be more uneven when its vibration amplitude was larger than that of the standard stimulus.

Then, we calculated the psychometric function for each experimental condition to analyze which was the minimum noticeable difference that could be perceived by each participant. The JND results gave us an insight into the minimum difference of the frequency or amplitude coefficient that could be efficiently discriminated. The perceived probability curve was obtained by fitting the psychometric curve to the data ($f(x) = \frac{1}{1+\exp(-A\cdot(x-B))}$). The value of vibration frequency or amplitude at the 50% point on the perceived probability curve indicates the PSE (Point of Subjective Equality) of the perceived fineness or unevenness. The half of the difference in vibration frequency or amplitude between the 75% point and the 25% point on this curve indicates the JND. We obtained the PSE and JND for each participant (Table III), and applied Student's paired t-test for each experimental condition. This test revealed a significant difference in JND between "Edge condition" and "None condition" in "Frequency Ex." and "Amplitude Ex."($p < 0.01$). It also revealed that there was a marginally significant difference in the PSE between the two conditions in "Amplitude Ex." ($p < 0.10$).

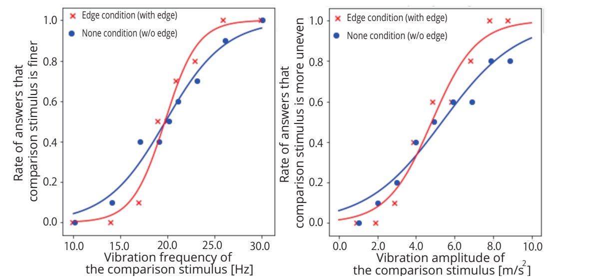

Fig. 8. Answer rate of one participant in "Frequency Ex."(Left) and in "Amplitude Ex."(Right).

TABLE III
JND AND PSE FOR EACH EXPERIMENTAL CONDITION.

Experiment	Condition	JND		PSE	
		AVE ± SE	p	AVE ± SE	p
Frequency Ex.	Edge	1.96 ± 0.187	4.11E-05	20.1 ± 0.163	0.142
	None	4.14 ± 0.363		20.5 ± 0.387	
Amplitude Ex.	Edge	0.547 ± 0.0912	3.23E-05	4.81 ± 0.0433	0.0712
	None	1.09 ± 0.0447		5.03 ± 0.0991	

C. Discussion

The results of "Frequency Ex." and "Amplitude Ex." shows that the JND of the "Edge condition" was significantly smaller than that of the "None condition." This means that presenting an edge vibration at the boundary of the two vibrotactile textures helped the participants discriminate the difference in vibration frequency and amplitude between the two adjacent textures correctly. Because there was no significant difference in the PSE between the two conditions of "Frequency Ex.", the addition of the edge vibration did not affect the feeling of vibration frequency within the texture area itself. This result appeared in the answer to the question after the task, and 10 (6) out of 12 participants answered that it was easier to discriminate the difference in the fineness (unevenness) of the left and right textures when the vibration was presented at the edge. These results show that crossing over the vibrotactile edge evoked a sensation that the textures on the left and right sides of an edge were different in fineness or amplitude. Furthermore, in both experiments, 4 out of 12 participants told that when the difference between the right and left vibrations was small, they felt that the texture vibrations were gradually switched without the edge vibration, and were abruptly switched with the edge vibration. Thus, it is considered that the change in vibration at the boundary of the texture areas can be felt sharply with the edge vibration.

However, the PSE of the "Edge condition" was marginally smaller than that of the "None condition" in "Amplitude Ex." This result indicates that the presentation of the vibration stimulus of the edge affected the perception of the amplitude of vibration of the textural areas. These results also appeared in the answers to a question after the task, and 5 out of 12 participants said that the texture on the right side, that is, the texture traced after crossing the edge, felt more uneven when the edge vibration was presented.

We considered that these results might be caused by the masking effect of the vibration stimulation. When a small stimulus is presented after a large stimulus in time series, the former may mask the latter, and only a large stimulus presented previously is perceived. This is called a temporal masking, and it can be occured with the tactile stimulation [10]. Moreover, in the case of simultaneous masking in which the masking effect is generated by presenting two kinds of stimuli simultaneously, it has been confirmed that the masking effect becomes remarkable when the target and the masking stimulus frequencies are the same [24]. These findings indicate the possibility that the vibration of the edge caused the tactile masking effect on the amplitude of the texture vibration of the right-side texture area traced after passing the edge. This effect might be caused by the amplitude of edge vibration being larger than that of the texture area's vibration, and the masking effect may have been more likely to occur because all the texture areas have the same f in "Amplitude Ex."

In summary, it was clarified that presenting edge vibrations between adjacent textures makes it easier for users to discriminate the frequency and amplitude differences of those vibrations.

D. Limitation and Future Work

In this study, as the first step towards verification of the proposed method, we investigated the effect on the discrimination of uneven texture with a simple pattern vibration in a limited low-frequency band. In future work, we should verify the effect of edge vibration on the vibration texture of various frequencies, amplitudes, and patterns.

Moreover, in this experiment, we heuristically used a single type of vibration on the edge. However, there is a possibility that the effect of edge vibration would change according to the various parameters of a vibrotactile signal. Thus, it is necessary to clarify which parameters of the edge vibration (e.g., waveform, amplitude) have the strongest effect on the result. We expect that controlling the intensity of the edge vibration according to the balance of the intensity of vibration in the texture areas may cancel the tactile masking effect. This may improve the discrimination ability in terms of the vibration amplitude.

VI. Conclusions

In this paper, we proposed a method for improving the ability to discriminate the vibrotactile stimuli for different areas using edge vibration. The user study yielded the following findings:

- Edge vibrations on the borders between adjacent textures makes it easier for users to discriminate the differences in frequency and amplitude of the vibrations assigned to those textures.
- Edge vibration may cause the tactile masking effect, which makes the users feel that the vibration amplitude of the texture traced after passing the edge is larger than it actually is.

In addition to the contributions from a scientific point of view, the findings in this study also contribute to vibrotactile design. In the real world, there are many objects composed of multiple materials, and to realize the experience of touching them virtually, it is necessary to make the user correctly recognize the difference between multiple textures distributed on the object surface. There are various applications such as industrial design, e-commerce, and telepresence that require the experience of touching a virtual texture. Therefore, it is essential to have a vibrotactile design by which the user can accurately perceive the difference between the vibration textures adjacent to the virtual object surface.

Due to the human detection thresholds of vibrotactile signals, it is difficult for users to recognize slight differences between multiple vibrotactile textures. This has been a constraint in vibration design. Therefore, if tactile designers adopt the use of edge vibration, the differential detection threshold would be decreased, and designers could design a wider range of vibrations for adjacent areas. Our proposed method can be applied not only to haptic experience through a tablet as verified this time, but also to a virtual environment experience using a Head Mounted Display (HMD) and a controller with vibrator; hence, it is expected to be widely used in vibrotactile design. Although the edge effect depends on each specific case according to the content or application, we provide promising new options for designers.

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