Detectability and Perceptual Consequences of Delayed Feedback in a Vibrotactile Texture Display

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Abstract—This study estimated the maximum allowable system latency for haptic displays that produce tactile stimuli in response to the hand movements of users. In Experiment 1, two types of detection thresholds were estimated for the time delay of stimuli through psychophysical experiments involving 13 participants. One was a threshold for the users to notice the existence of a time delay. The other was a threshold for the users to experience changes in the perceived textures in comparison with stimuli with no time delay. The estimated thresholds were approximately 60 and 40 ms, respectively. In interviews, the participants reported that they experienced various types of subjective changes due to the time delay. In Experiment 2, the types of subjective sensations that might be altered by the time delay were investigated. The time delays were controlled based on the acceleration of the hand motions of the participants. The participants evaluated the differences in the perceived textures between the stimuli with a controlled time delay and ones with no delay. The results indicated that the participants associated the time-delayed stimuli with changes in mechanical parameters such as kinetic friction coefficient in addition to changes in the perceived roughness of the textures.

Index Terms—Detection threshold, tactile display, time delay.

1 Introduction

Tactile displays can be used to produce appropriate tactile stimuli according to the hand motions of users in order to induce a natural sense of touch. In such display methods, users experience the stimuli triggered by their motions just like those triggered when they touch real objects when engaging in haptic exploration.

Numbers of tactile display systems have been developed that present stimuli to users in response to their hand movements. For example, we have demonstrated a method that presents various types of textures by means of stimuli in synchronization with the position, velocity, and acceleration of user's hands [1]. Other researchers have also proposed systems that use hand motions as inputs and output the corresponding stimuli [2], [3], [4]. In tactile telepresence based on master-slave systems, system operators maneuver the master arms and then acquire corresponding tactile feedbacks from the tactile sensors installed on the slave arm and the tactile displays on the master arm [5], [6], [7], [8], [9].

In the above-mentioned display methods and systems, system latency or communication time delay is inevitably present between the detection of hand motions and the production of stimuli. When the delay is significant, users no longer consider the stimuli to be caused by their actions, or they feel that the presented objects move unnaturally. The determination of the maximum allowable system latency will be helpful for designing haptic devices.

The present study estimates tactile detection thresholds for the time delay for haptic displays that produce stimuli in synchronization with hand motions. Two types of thresholds are investigated. One is a threshold at which users notice the existence of a delay. If the delay exceeds this threshold, users will detect the delay in the feedback. The other is a threshold at which users experience changes in the perceived textures of presented objects, although they may not be aware of the delay. When the delay exceeds this threshold, the users perceive the time-delayed objects to be different from those with no delay. Haptic sensations arise from spatio-temporal information such as the physical properties of target objects, hand movements, and neural signals. The delay of the stimulus is a type of temporal information that can possibly alter the perceived textures of objects. Due to the time delay, users experience sensations that are different from those that the system designers intend to present.

Further, when the delay changes the perceived textures, knowledge about the types of changes is helpful. This is because this knowledge leads to the development of new displaying methods or an understanding of haptic information process in humans.

This study comprises two experiments. In the first experiment, two types of detection thresholds are estimated for the system latency of tactile displays. In the second

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experiment, the types of changes in perceived textures caused by the time delay are investigated.

This paper is organized as follows: Related work is summarized in Section 2. The tactile stimuli and apparatus for the experiments are described in Section 3. The estimation of the two types of thresholds is presented in Section 4. The investigation of the effects of time-delayed stimuli on perceived textures is described in Section 5. Finally, the discussions and conclusions are presented in Sections 6 and 7, respectively.

2 Related Work

Many studies have investigated human perception of temporal gaps or intervals of tactile stimuli. For example, the amount of time that must pass between the onsets of two successively mechanical stimuli applied to two index fingers in order to temporally separate those stimuli has been investigated [10]. The amount of time depends on the intensity levels of the first and second stimuli [11]. Such temporal order judgment tasks have also been compared between a single finger pad, two fingers on the same hand, and two fingers on opposite hands [12]. The tasks have also been investigated using electrotactile stimuli [13]. The amplitudes of vibrotactile stimuli required to separate two successive stimuli with a slight temporal gap have been investigated [14]. These studies have focused on the temporal factor between one tactile stimulus and another.

Several studies have addressed the temporal delay between human motions and the resulting stimuli caused by these motions. For haptic input and auditory response, the detection threshold of a delay between a hammer or wand strike and the resulting collision noise delivered through headphones is 24-40 ms [15], [16]. In another study where virtual sounds were presented through headphones in response to head movements of users, the detection threshold for the system latency between head motions and virtual sound sources is 45-80 ms [17], [18]. For virtual musical instruments, the allowable time delay between a playing action and sound generation by controlling a theremin is 70-80 ms (calculated from the report [19]). For graphical user interfaces of computers, the threshold of the delay of graphical responses to mouse or typing motions is 100-200 ms [20]. The threshold of the delay of image presentation in response to eye movements is 100 ms [21]. The tolerance of asynchrony between hand movement and force feedback in a virtual soft wall simulation using PHANToM device is 30-35 ms [22]. The values determined in these studies cannot be compared directly due to differences in experimental methods. To the best of our knowledge, the detection threshold for the delay between haptic exploratory motions and tactile sensations has yet to be reported.

In addition to the new thresholds reported, the present study also investigates the effects of the time-delayed stimuli on haptic perception. Although no study has focused specifically on the effects of the delay between exploratory motions and tactile stimuli on haptic sensations, a few studies have reported that time delays impair task performance. For example, for remote haptic teaching or training, the permissible communication delay has been investigated

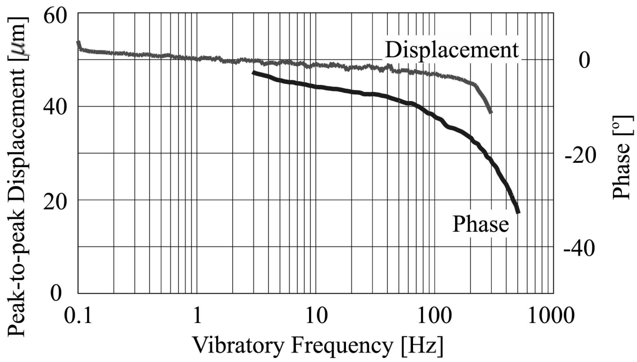

Fig. 1. Frequency responses of the vibrator when the peak-to-peak amplitude of voltage supply is 150 V.

[23], [24]. For collaboratively lifting or grasping objects in remote environments, the delay that decreases the quality of service has been reported [25]. In the presentation of soft objects, it has been reported that a delay in force generation alters the perceived softness or stiffness of the objects [26], [27]. The present study goes beyond threshold measurements by investigating the changes in haptic perception due to time delays.

3 Tactile Stimuli and Experimental Setup

3.1 Tactile Stimuli

The experimental task was the haptic exploration of virtual textures. The presentation of textures is an important feature of many vibrotactile displays. The experimental system required an apparatus to produce delayed tactile stimuli in response to the hand motions of the participants.

When using real textures such as sandpapers or grating scales, it is possible to simulate the time delay by moving the textures along the movement direction of the hand. The resultant stimuli resemble delayed haptic feedback in terms of the delayed change in the relative positions between the finger and the texture. However, variations in the relative velocities between the texture and finger also change the friction and contact conditions between them.

Better stimuli control can be achieved by generating virtual textures in response to measured finger movements using an experimental apparatus such as the one used in the present study. Participants explored virtual textures by moving a vertical rod along a linear track. The participant's middle finger was always in contact with the rod which transmitted vibrotactile stimuli in response to finger movements, with controlled time delay.

A vibrator was used as the tactile stimulator. The vibrator was a piezo-stack-type actuator (ASB510C801P0, NEC/TOKIN, Sendai, Japan). Fig. 1 shows its frequency responses with no load for input peak-to-peak voltage of 150 V. Fig. 2 shows the roughly linear relationship between vibratory displacements and input voltages. The maximum displacement was approximately $55\ \mu\text{m}$ when the frequency was 0.1 Hz. The frequency responses were measured using a frequency analyzer (FRA5014, NF, Yokohama, Japan), a voltage amplifier for the actuator (BA4825, NF, Yokohama, Japan) with a nominal maximum response frequency of

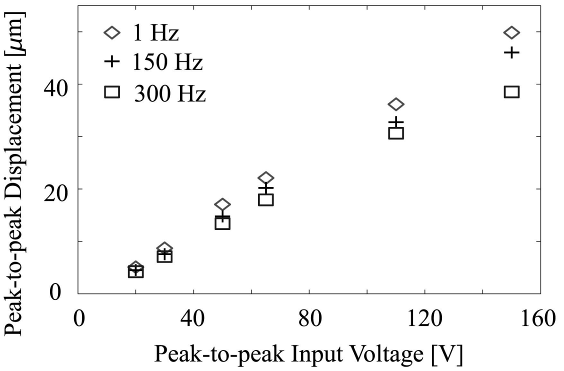

Fig. 2. Voltage-displacement plot of the vibrator.

2 MHz, a laser range finder (ZS-LD50, OMRON, Kyoto, Japan) for measuring magnitude responses, and a laser Doppler velocimeter (MLD-301AS, NEOARK, Tokyo, Japan) for measuring the phase characteristics.

The use of this vibrator was advantageous due to its high output force and roughly flat frequency response characteristics. Because the output force of the actuator was approximately 800 N, the force exerted by the finger was considered to be negligible and did not affect the commanded displacements. During the experiments, the finger force was measured and monitored such that it did not exceed 2 N. The amplitudes of the displacements depended on the frequency of the driven voltage; however, they were relatively flat in the range of up to 300 Hz that was used for the tactile stimuli. The displacement reached -3 dB when the frequency was approximately 310 Hz. The same voltage amplitude A was supplied to the vibrator throughout the entire frequency range up to approximately 300 Hz.

The virtual texture had a sinusoidal height profile along the finger-moving direction on its surface. The instantaneous position of the finger along the virtual texture was determined by the position of the vertical rod, $x(t)$. The electric voltage y supplied to the vibrator was

$$y = A\sin\left(2\pi\frac{x(t-D)}{\lambda}\right) + A, \tag{1}$$

where A was the peak amplitude (75 V), D was the simulated temporal delay between the hand movement and the corresponding vibratory stimulus, $x(t-D)$ was the delayed rod position along the hand movement direction, and λ (1 mm) was the spatial wavelength of the texture sample. Since the relation between the input voltage and the output displacement was mostly linear, (1) could also be viewed as the displacement stimuli delivered to the finger. The hand position data were buffered in a first-in-first-out queue for 200 ms such that the delay can be changed between 0 and 200 ms. When the stimuli included the time delay D, the stimuli presented to the finger were based on the hand position and the velocity recorded Ds ago. Equation (1) can be rewritten into

$$y = A\sin\left(2\pi\frac{\int_0^{t-D} v(\tau)d\tau}{\lambda}\right) + A, \tag{2}$$

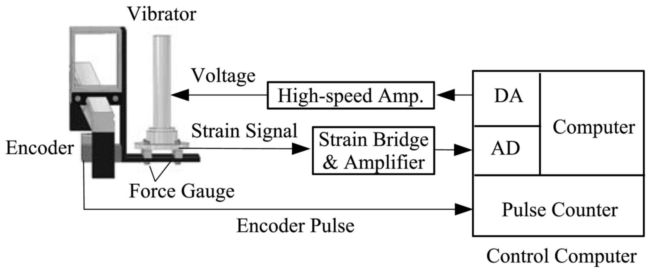

Fig. 3. Block diagram of the entire system.

where $v(t)$ is the finger velocity. The equation indicates that the vibratory frequency applied to the finger depended on the finger velocity, and was given by $v(t)/\lambda$. The hand velocity was calculated from the hand positions.

3.2 Experimental Setup

Fig. 3 shows a block diagram of the entire system. The vibrator was installed on a linear slider whose position on a linear guide was measured by an optical linear encoder (SR-P1000, Canon, Tokyo, Japan). The spatial resolution of the encoder is 1.6 μm. A linear guide was selected (SS series, NSK, Tokyo, Japan) for its low friction and low vibration during sliding. A control computer received the encoder pulses and supplied electric voltages to the vibrator through an amplifier. The interface board of the control computer was selected (Ritech Interface Board IF-0145-1, Okazakisangyo, Osaka, Japan). The update rate of the control computer was 5 kHz (RTLinux). The effective length of the guide was approximately 420 mm. The force applied by the finger along the z-axis was measured by a force gauge. Its output was transmitted to the control computer through a strain bridge and amplifier (MCD-8A, KYOWA, Tokyo, Japan) so that the force could be recoded and monitored.

Fig. 4 shows the apparatus from the participant's side. The participants moved their hands along the linear guide (x-axis in the figure). The vibrator generated a displacement along its longitudinal direction (z-axis in the figure). The vibrator had a circular contact surface having a diameter of 11.6 mm. The participants used an elbow rest during trials to avoid fatigue. As shown in Fig. 5, the participants placed their right middle fingers on the vibrator. They were instructed to avoid using any other part of their hand to

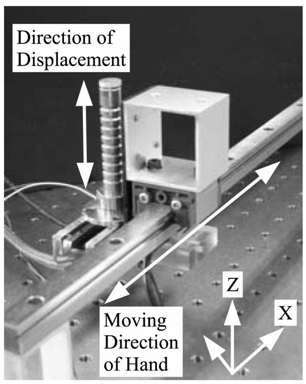

Fig. 4. Participant's view of the experimental apparatus.

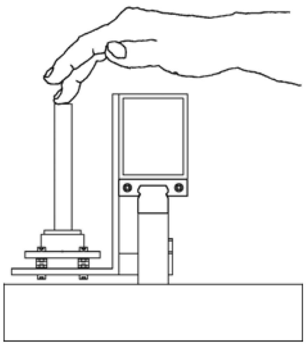

Fig. 5. Contact between the finger of the participant and the vibrator.

touch the apparatus. This ensured that the participants would not sense vibrations with any parts of their bodies other than the fingertips.

The participants commented that the vibrations transmitted by the equipment resembled the ones they perceived when they explored rough specimens such as grating scales through a stylus.

The inherent latency of the empirical system was measured 10 times. The inherent delay was defined as the time between the onset of the encoder pulse and the resultant voltage change to the vibrator. It was measured by an oscilloscope with a sampling frequency of 50 kHz and a resolution of 20 μs. The maximum and the median of the measured values were 160 μs and 140 μs, respectively, with a standard deviation of 43 μs. The inherent system latency was the minimum delay that was achieved by the system.

4 Experiment 1: Estimation of Two Types of Detection Thresholds

4.1 Procedures and Tasks

In Experiment 1, two types of detection thresholds were estimated in Experiments 1A and 1B. The participants compared a reference and test stimulus. The reference stimulus had no delay and the test stimulus had a simulated time delay.

The objective of Experiment 1A was to estimate the threshold at which the participants noticed the presence of a time delay in the stimulus. In this experiment, the participants were informed that the system might display a time-delayed stimulus, and the aim of the experiment was to estimate the detection thresholds for the time delay. The participants were required to answer whether the test stimulus was delayed or not.

The objective of Experiment 1B was to estimate the threshold at which the participants noticed a change in the perceived texture. In this experiment, the participants were informed that the test stimulus might differ slightly from the reference stimulus, and the aim of the experiment was to investigate whether the participants noticed a change. The experimenter did not inform them about the types of parameters being manipulated. The participants were required to answer whether the reference and test stimuli felt the same.

Thirteen males in their 20s and 30s participated in the experiments. None of the participants took part in both Experiments 1A and 1B on the same day. They did so within a period of 11 days. Six participants conducted Experiment 1A first followed by 1B on subsequent days. The other seven participants conducted the experiments in the reverse order.

The participants were provided with timing cues during the trials in the form of beep sounds through headphones. The participants explored the reference stimulus for 5 s between the first and second beeps. Then, after an interval of 3 s, the participants explored the test stimulus for another 5 s.

No true-false feedback was given to the participants during the experiment. The participants were informed not to change the contact conditions between the finger and the vibrator during the trial. The pressing force of the finger was measured during the trial. A trial was considered invalid if the force exceeded 2 N, and such trials were repeated after the completion of all trials. This was necessary because a higher pressing force of around 4 N or more affects roughness perception when exploring grating scales [28], [29]. The participants practiced exerting forces of 2 N or less for a few minutes before the experiments. The encoder values were recorded for the analyses. The participants were blindfolded with eye masks and heard pink noise over the headphones. The noise level was adjusted for each participant so that he did not hear the frictional sounds of the slider or the sounds generated by the vibrator.

Preliminary experiments were performed for each participant to estimate the maximum delay needed before it could be detected using the method of limits. Two ascending and descending series were repeated for each individual. The median of the values from the four series, D_{max}, ranged from 70-110 ms.

The main experiments were performed using the method of constant stimuli. The reference stimulus was $D = 0$ (not including the inherent latency of the experimental system). For the test stimuli, delays were presented in six levels between 0-D_{max} ms that varied from participants to participants. Each test stimulus was presented 10 times in a random order. One experiment comprised 60 trials and it lasted approximately 40 min, including the explanations and the preliminary experiments.

The reference stimuli were presented in Experiment 1A in order to equalize the experimental conditions of Experiments 1A and 1B for comparison. Early work has shown that by presenting reference stimuli before test stimuli, the participants become more sensitive to the delay than when the test stimulus was presented alone [18]. In our pilot study, the same trends were observed. Since our goal was to estimate the maximum allowable time delay in designing tactile displays, the experiments were designed such that the participants would remain sensitive to the delays.

4.2 Experimental Result

4.2.1 Calculation Method for Detection Thresholds

From the responses of the participants in Experiments 1A and 1B, the proportion of trials where a delay was detected (Experiment 1A) or a change in perception was noticed (Experiment 1B) were calculated for each delay. A logistic

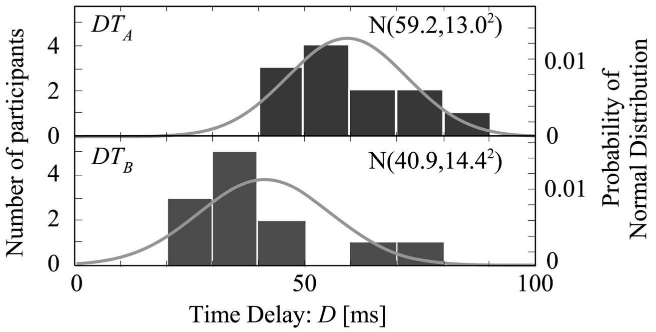

Fig. 6. Histograms of the detection thresholds in Experiments 1A and 1B and their expected normal distribution curves.

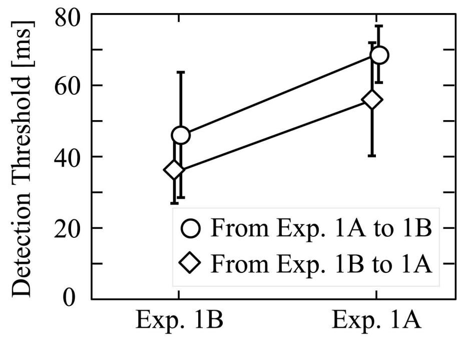

Fig. 7. Mean DT_A and DT_B values and their standard deviations by experimental order.

function was fitted to the data for the individual participants. The logistic function was

$$f(D) = \frac{1}{1 + \exp(-a - bD)}, \tag{3}$$

where a and b were characteristic parameters of the curve. We defined D, where $f(D) = 0.5$, as the detection threshold. We use DT_A and DT_B to denote the thresholds estimated in Experiments 1A and 1B, respectively.

4.2.2 Detection Thresholds

Fig. 6 shows the histograms of the estimated thresholds of 12 participants in Experiments 1A and 1B with expected curves of the normal distributions of the thresholds. All statistics were calculated based on 12 participants, excluding participant P11. This is because his DT_A was possibly an outlier (Grubb's test, $N = 13, p < 0.05$, one-tailed, $p = 0.037$), and his false alarm rates in both experiments were 0.3, which were much higher than those of the others. The mean DT_A (SD) was 59.2 (13.0) ms and the mean DT_B (SD) was 40.9 (14.4) ms. The mean DT_B was significantly less than the mean DT_A (paired $t\text{-test}, n = 12, p < 0.01$, one-tailed, $p = 0.0010$). Table 1 shows the thresholds, D_{max}, false alarm rates, and goodness of fit of the logistic functions (R^2), although 10 trials per stimulus was not adequate for calculating false alarm rates. In the case of all 13 participants, the outcome of the t-test was not affected by P11.

In order to examine the influence of the experimental order on the thresholds, a two-way ANOVA was applied to the thresholds with the factors being the type of experiments and the order in which the participants conducted Experiments 1A and 1B. Fig. 7 shows the mean DT_A and DT_B with their standard deviations. The circles indicate the mean thresholds of the six participants who performed Experiment 1A first. The diamonds indicate the mean thresholds of the other six participants who performed Experiment 1B first. The type of experiment was the main factor that contributed toward the observed difference between the thresholds ($F(1, 20) = 10.87, p < 0.01, p = 0.0036$). The experimental order did not significantly affect the thresholds ($F(1, 20) = 2.40, p = 0.14$). Also, the effect of interaction between the type of experiment and the experimental order was not significant ($F(1, 20) = 0.082, p = 0.78$). Although the number of trials per participant was small,

TABLE 1
Detection Thresholds, D_{max}, False Alarm Rates, and R^2 in Experiments 1A and 1B

Participant	Experiment 1A				Experiment 1B			
	Threshold [ms]	D_{max}	False alarm rate	R^2	Threshold [ms]	D_{max}	False alarm rate	R^2
P1	56	70	0	0.708	45	90	0.2	0.928
P2	40	80	0.1	0.993	38	80	0	0.972
P3	57	80	0	1.000	31	100	0	0.962
P4	61	80	0	0.908	28	100	0.3	0.877
P5	44	90	0	1.000	39	90	0.1	0.992
P6	70	90	0	0.997	65	90	0	0.713
P7	84	70	0	0.972	26	100	0.2	0.892
P8	44	90	0	0.881	25	90	0.3	0.875
P9	63	80	0	1.000	49	90	0.1	0.829
P10	57	100	0	0.999	37	100	0.1	0.990
P11	13	100	0.3	0.900	21	110	0.3	0.878
P12	59	90	0	0.993	38	90	0	1.000
P13	75	100	0	0.982	70	90	0.3	0.882

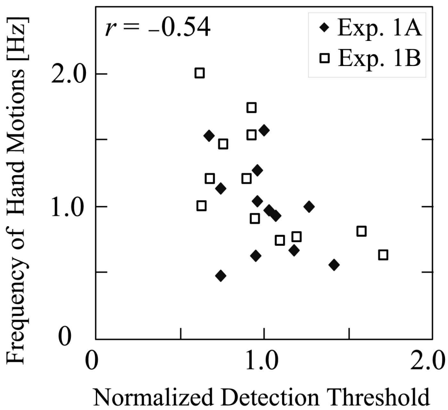

Fig. 8. Dominant frequency of the hand motions versus the detection thresholds.

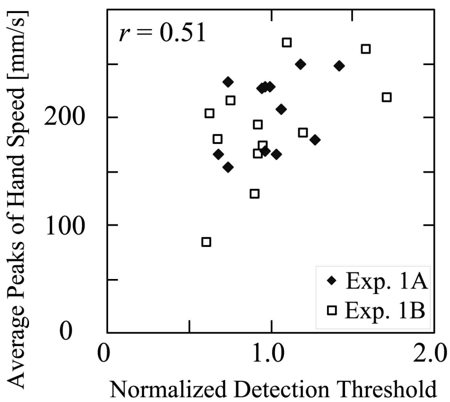

Fig. 9. Average peak speed of the reciprocating touch motions versus the detection thresholds.

the significance level is lower than 0.01 and the divergence between DT_A and DT_B appears clear.

Table 1 indicates that false alarm rates were different between Experiments 1A and 1B. We suggest two possibilities for this reason. One possibility is that the participants used different criteria for judgment in the two types of experiments. Another possibility is that the deviations of participants' internal responses to the time-delayed textures were different in the two experiments. The tasks of two experiments varied, which might have affected the internal process of participants. However, we do not pursue these possibilities in the present study.

From the above results and analyses, the detection thresholds for time delay were established. The threshold to detect the presence of a delay in tactile stimuli was approximately 60 ms. The threshold to detect the changes in the perceived textures was approximately 40 ms. These values were on the same order as the thresholds found with other sensory channels [15], [16], [17], [18], [19], [20], [21], [22].

4.2.3 Correlation between Detection Thresholds and Hand Motions

We have noticed the differences in the hand velocities and reciprocating frequencies among the individual participants. Furthermore, during the interviews after the experiments, some participants reported that they detected a delay in the tactile stimuli when they did not experience any tactile feedback at the onsets of their hand movements.

In order to investigate the relationship between the measured thresholds and the hand motions, the correlation coefficients between motion features and the thresholds were computed. Three types of motion features were computed. The first feature was the dominant frequency of hand motions. The power spectrum density of the hand velocity of each participant was computed, and the frequency at which the signal power was the maximum was considered as a representative frequency of the participant's hand motions. The second feature was the average of peak hand speed. The peak speed was measured, and their mean was computed as the second quantitative feature of the hand speed of each participant. The third feature was the average of peak accelerations. Maximum accelerations were observed around the onset of hand motion.

Fig. 8 is a scatter plot of the frequencies versus the thresholds. The thresholds in the figure are normalized by the mean DT_A or DT_B. There is a negative correlation between the thresholds and the frequencies ($r = -0.54, t\text{-test}, n = 24$, two-tailed, $p < 0.01, p = 0.0064$). When the thresholds are divided into those for Experiments 1A and 1B, DT_B values are found to be negatively correlated with the frequencies ($r = -0.66,\ t\text{-test}, n = 12,\ \text{two-tailed},\ p < 0.05, p = 0.019$) while DT_A values are not ($r = -0.36$).

Fig. 9 shows a plot of the average peaks of the hand velocity versus the normalized thresholds. There was a positive correlation between the thresholds and the peak velocities ($r = 0.51, t\text{-test}, n = 24$, two-tailed, $p < 0.05, p = 0.011$). Considering the DT_A and DT_B values separately, the latter ($r = 0.56$) are more strongly correlated with the hand velocity than the former ($r = 0.42$), though neither is significant.

Statistical analysis showed that the accelerations of hands were not significantly correlated with the detection thresholds ($r = -0.14, t\text{-test}, n = 24$, two-tailed, $p = 0.67$).

Collectively considering these relations, there was a tendency for smaller thresholds when the participants scanned the virtual textures with higher dominant frequencies and lower average velocities.

DT_B values were more strongly correlated with the features of hand movements than DT_A values were. This difference might suggest that the sensory information for delay detection and for the detection of changes in the perceived texture is processed in different ways. However, the coefficients show that the correlations are not very strong that we do not discuss this difference any further.

4.2.4 Subjective Impressions

After Experiment 1A, the participants were asked how they detected the presence of time delay. According to the interviews, the participants detected a time delay when they sensed no tactile feedback at the onset of hand motions, when they still perceived the vibratory stimuli even after they stopped hand motions, or when they felt that the virtual texture was moving unnaturally.

After Experiment 1B, the participants were interviewed about the changes in the perceived textures of the virtual objects. They reported that they felt the texture to be rougher or smoother as they perceived the magnitudes of the roughness to be increased or decreased. They also reported that the slider felt slippery or sticky and the frictional resistance of the slider varied. Some of them reported that they felt as if they had been moving their hands in water. Furthermore, some participants compared the changes they experienced to the changes in the mass of the slider. Among the obtained answers, some conflicting opinions were observed, such as rough versus smooth or slippery versus sticky. Even for the same delayed stimuli, some participants reported that the delayed stimuli were rougher while others judged them to be smoother, as compared to the nondelayed stimuli.

The participants' observations raised two questions and motivated us to conduct Experiment 2. First, we investigated the types of changes in haptic sensations when exploring delayed stimuli, such as changes in perceived roughness or friction. Second, we investigated the reason for why conflicting changes in haptic sensations were observed for delayed stimuli.

5 Experiment 2: Effect of Time Delay on Haptic Perception

One of the findings in Experiment 1 was that the participants experienced a variation in the perceived textures of the time-delayed stimuli as compared to the stimuli with no delay. Pursuing this observation may lead to new design methods for haptic displays. The participants reported changes not only in the perceived roughness of virtual textures but also changes that appeared to be associated with the mechanical properties of virtual textures. Tactile stimuli can be a substitute for a haptic display for presenting virtual textures. Contrasting cases have been reported where roughness can be displayed using haptic devices by exerting forces rather than applying geometric displacements to human fingers [30], [31].

There were two objectives in Experiment 2. First, the types of changes in haptic sensations while exploring the time-delayed stimuli were investigated. The participants were asked to indicate the perceived changes in a virtual texture using terms related to its mechanical parameters in order for us to clarify the types of perceptual changes induced by the time-delayed stimuli. The mechanical parameters are described in Section 5.2. Second, the reason for the conflicting descriptions of perceived changes induced by delayed stimuli was investigated. In order to investigate this, two types of delayed stimuli were used. These stimuli are described in Section 5.1.

5.1 Delay Control for Observing Changes in Haptic Sensations

In order to investigate the reason for the conflicting changes in haptic perception for delayed stimuli, two types of delayed stimuli were used. We focused on the acceleration of the hand motions while the participants explored the delayed stimuli. During the positive acceleration phase of the hand, tactile stimuli were produced based on a slower speed. Furthermore, the stimuli were not generated for a while at the onset of the hand motion. In contrast, during the deceleration phase of the hand, the stimuli were produced on the basis of a faster speed. Furthermore, the stimuli lasted for some duration even after the motion stopped. Therefore, it was conceivable that the delays in the acceleration and deceleration phases differentially affected the perceived quality of the textures.

Based on this hypothesis, two types of delayed stimuli based on the signs of acceleration were used. One was a stimulus that included a delay only in the acceleration phase. The other was a stimulus that included a delay only in the deceleration phase.

Under the condition that there was a delay only in the acceleration phase, the simulated delay D was given as

$$D = \begin{cases} T_a(\text{const}), & \text{if } \frac{d|v(t)|}{dt} \geq 0, \\ 0, & \text{otherwise}, \end{cases} \tag{4}$$

where $v(t)$ was the hand velocity of the participant. When there was a delay only in the deceleration phase, D was given as

$$D = \begin{cases} T_d(\text{const}), & \text{if } \frac{d|v(t)|}{dt} \leq 0, \\ 0, & \text{otherwise}. \end{cases} \tag{5}$$

The discrete-time equation of the voltage supplied to the vibrator was given by

$$Y_T = A \sin(\theta_T) + A, \tag{6}$$

$$\theta_T = 2\pi \frac{V_{T-D}}{\lambda} \Delta t + \theta_{T-1}, \tag{7}$$

where θ_T and V_T were the phase of stimulus and the hand velocity at time t, respectively, and $\Delta t = 0.2$ ms was the control period of the system. The vibratory frequency changed according to the hand velocity while maintaining the continuity of the phase at the transition of D as follows. When the sign of the acceleration switched, it took 10 ms to change D linearly between 0 and T_a or 0 and T_d. We avoided a step change in the value of D because the resultant change in the vibratory frequency was quite noticeable to the participants. For example, under the delay-in-acceleration-phase condition, D was determined by (4). When the acceleration of the hand became negative, D was gradually decreased to 0 in 10 ms. When the sign of acceleration changed from negative to positive, D was gradually increased to T_a in 10 ms.

T_a and T_d were the amount of delay required for the participants to detect a change in the perceived textures as compared to the nondelayed stimuli. They may be different from the 40 ms measured in Experiment 1B because the time-delayed stimuli used in Experiment 2 were different from the ones in Experiment 1B. Therefore, we estimated the values of T_a and T_b in a preliminary experiment using the method of limits for each individual participant. T_a and T_d were defined as the thresholds for the delay-in-acceleration-phase and the delay-in-deceleration-phase conditions, respectively. In the preliminary experiment, the ascending and descending series were repeated two times for each participant. A step size of 20 ms was used in both the ascending and descending series. During the ascending series, the participant explored time-delayed stimuli with increasing delays until a difference in the tactile perception of the nondelayed and delayed stimuli was detected. The threshold was estimated by subtracting 10 ms from the time delay at the time of detection. During the descending series,

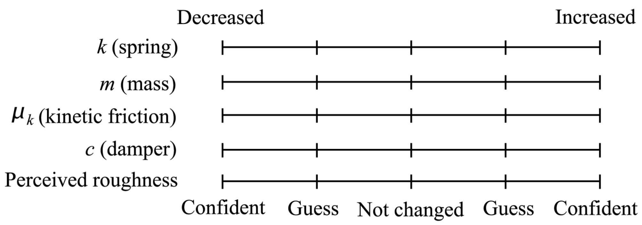

Fig. 10. Response sheet for the participants to describe the subjective changes in haptic sensations.

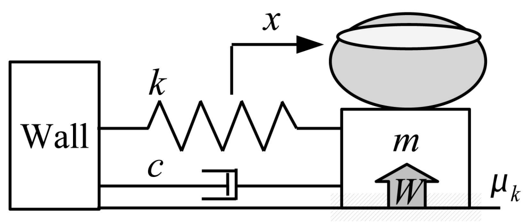

Fig. 11. Physical model for the participants to imagine and describe the subjective changes in haptic sensations.

the participant explored time-delayed stimuli with decreasing delays until the difference between the nondelayed and the delayed stimuli could no longer be perceived. The threshold was estimated by adding 10 ms to this time. T_a was the median of the four thresholds determined by two ascending and two descending series for the delay-in-acceleration-phase condition. T_d was the median for the delay-in-deceleration-phase condition. Among the 11 participants, T_a and T_d ranged from 60 to 120 ms.

5.2 Evaluation of Perceived Changes Using Mechanical Parameters

Mechanical parameters, such as mass or kinetic friction coefficients, were adopted as evaluation parameters. Fig. 10 shows the answer sheet used in Experiment 2. The participants rated changes in four mechanical parameters and the perceived roughness. The mechanical parameters were the spring stiffness, mass, viscosity, and kinetic friction coefficient of the model shown in Fig. 11. In the figure, the force applied to the finger is

$$-F = m\ddot{x} + c\dot{x} + kx + \mu_k W \operatorname{sign}(\dot{x}), \tag{8}$$

where m, c, k, and μ_k are the mass, viscosity, stiffness, and kinetic friction coefficient, respectively. The displacement of the mass from the equilibrium position of the spring is x. W is the reaction force in the normal direction exerted by the floor. On the response sheet, each item was marked with five levels ranging from "confidently decreased" to "confidently increased."

Before the experiments, the participants experienced the mechanical parameters shown in Fig. 11 simulated by the PHANToM Premium force display. At the same time, they could view a piece of paper as shown in Fig. 11 and (8). The participants were students and staff from an engineering school, and it was confirmed that they understood the general meanings of each parameter. Brief tests were conducted to check whether the participants recognized the effects of each parameter on their sensations. During the test, one parameter was changed when the others were set to zero. The participants indicated the parameter being changed and its direction of change. The ranges of the parameters were 0-0.13 kg for m, 0-15 N/m for k, 0-3 Ns/m for c, and 0-0.3 for μ_k. All participants passed the test. The participants were 11 males in their 20s and 30s who had participated in Experiment 1. The test took approximately 10 min for each participant.

5.3 Procedures and Tasks

During the experiment, the reference and test stimuli were arranged on the left and right sides, respectively, of the linear guide. The reference stimulus was a stimulus with no delay. The test stimulus was a stimulus whose delay was controlled by the method described earlier in Section 5.1. At the beginning of a trial, the slider was positioned at the center of the guide by the experimenter. The participants felt the two virtual textures on the left and right sides within 15 s and then marked the answer sheet.

When the slider crossed over the center of the guide, the control rules for the stimuli changed. The phases of the two stimuli were not continuous before and after the change of control rules. The participants were instructed to explore the two stimuli alternately so that this discontinuity did not affect their judgments.

Each experiment comprised of 25 trials. For 10 of the 25 trials, the test stimulus included a delay in the acceleration phase of hand movements. For another 10 trials, the test stimulus included a delay in the deceleration phase. For the remaining five trials, the test stimulus was the same as the reference stimulus. The order of the trials was randomized. For the first 12 trials, the reference stimuli were on the left side and the test stimuli were on the right side of the linear guide. For the last 13 trials, this arrangement was reversed. The participants were informed of the arrangement of the stimuli.

While the participants explored the textures, they were asked to close their eyes. After the exploration, they looked at the answer sheet and marked their responses. Similar to Experiment 1, the participants were required to maintain contact between their finger and the vibrator during each trial. The participants heard pink noise through a headphone. Trials during which the finger force exceeded 2 N were considered invalid and were presented again at the end of all trials. The experiment required approximately 1 h per participant, including instructions, practice, and the preliminary experiments for determining T_a and T_d.

5.4 Results

The proportions of trials in which the participants marked "increased" or "decreased" were calculated for the nondelayed, delay-in-acceleration-phase, and delay-in-deceleration-phase conditions. Fig. 12 shows the average of the proportions and the standard deviations among the participants. The "confident" and "guess" responses were categorized as one group. The suffixes + and − indicated that the parameter "increased" and "decreased," respectively. For example, $R+$ corresponds to "the perceived roughness increased."

The differences of proportions between each condition were tested for every signed parameter by Tukey's test

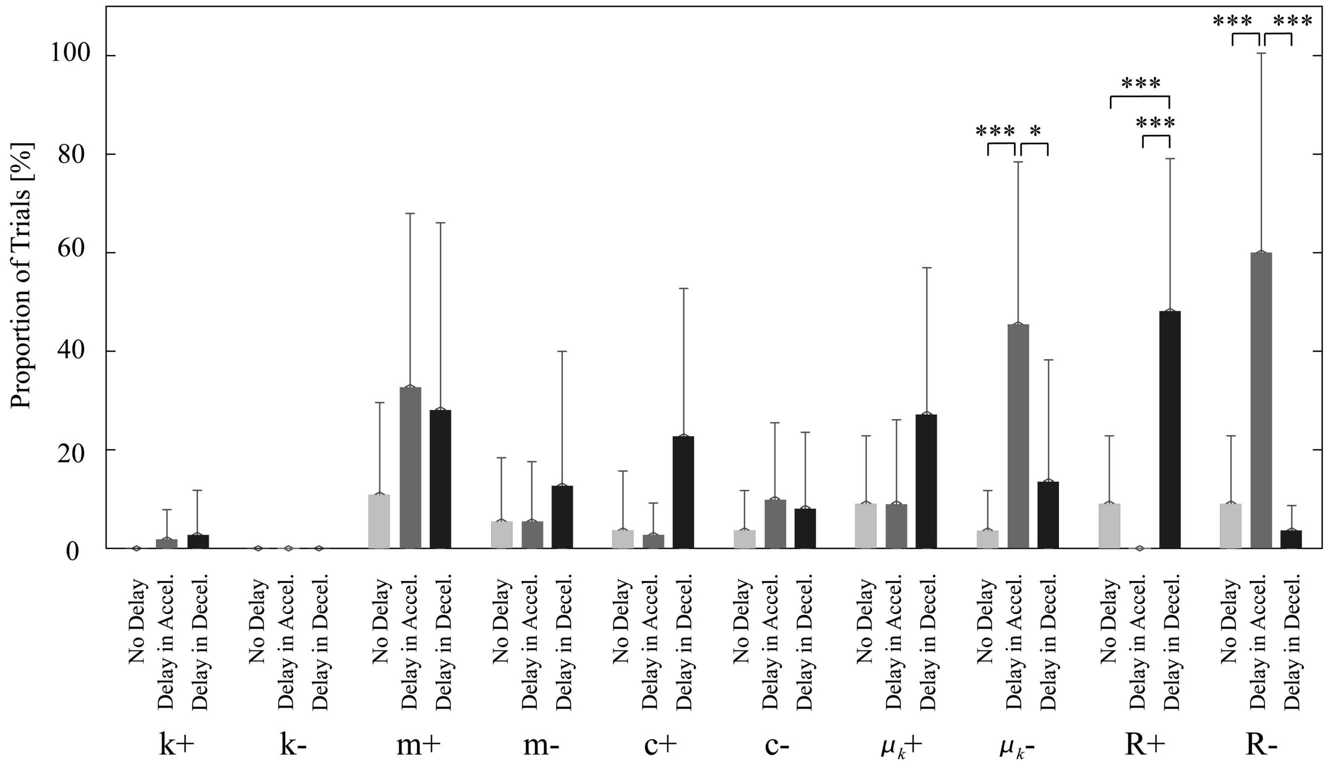

Fig. 12. Proportion of trials in which "confident" or "guess" were reported for every parameter by each delay condition. The asterisks $*$ and $***$ indicate the significance levels of $p < 0.05$ and 0.001, respectively. The error bars indicate the standard deviations among the participants.

(number of degrees of freedom: 30, number of groups: 3). For example, the proportions of $R+$ were compared with the nondelayed, delay-in-acceleration-phase, and delay-in-deceleration-phase conditions. Significant differences between the nondelayed and delayed conditions were observed for $\mu_k-, R+$, and $R-$. The proportion of μ_k- responses for the delay-in-acceleration-phase condition was significantly different from that of the nondelayed condition ($q(3,30) = 5.72, p < 0.001, p = 0.00094$). The $R+$ responses for the delay-in-deceleration-phase condition were significantly different from that for the nondelayed condition ($q(3,30) = 6.64, p < 0.001, p = 0.00016$). The $R-$ responses for the delay-in-acceleration-phase condition were significantly different from that for the nondelayed condition ($q(3,30) = 6.79, p < 0.001, p = 0.00012$).

When the delay existed only in the acceleration phase, the participants frequently selected "the perceived roughness decreased" and "the kinetic friction coefficients decreased" with regard to the textures they explored. When the delay existed only in the deceleration phase, the participants frequently selected "the perceived roughness increased" and "the viscosity increased" (although it was marginally significant with $p = 0.0503$). In general, they felt that it was easier to move the slider during the delay-in-the-acceleration-phase, and it was harder to move the slider during the delay-in-the-deceleration-phase.

The results are consistent with the conflicting subjective reports that we obtained at the end of Experiment 1. We now understood that the perceived textures of the time-delayed stimuli depended on the phase (acceleration versus deceleration) on which the participants based their judgments on during the exploration. In some trials, the participants felt that the perceived roughness decreased and the friction decreased because they were presumably paying more attention to the delay-in-the-acceleration phase. In other trials, they felt that the perceived roughness increased because they were presumably paying more attention to the delay-in-the-deceleration phase.

In case that the "guess" and "not changed" responses were categorized as one group, the significance test exhibited significant differences between the exact same pairs as the case where the "confident" and "guess" were categorized as one group. The way of categorizing the "confident," "guess," and "not changed" answers did not affect the results of significance tests.

6 Discussion

6.1 Design Guidelines for Tactile Displays in Terms of System Latency

The experimental results of the present study provide a design guideline for tactile displays in terms of system latency. For display systems that aim to present the textures of materials, the allowable latency should be smaller than 40 ms. This is because if the delay of the system is above this threshold, the users of the systems are likely to experience the perceived textures differently from the ones the designers intend to present. For display systems that aim to acknowledge the completion of an action, the allowable latency should be smaller than 60 ms. For example, the presentation of stimuli to inform the user that a button has been pressed need only be recognized as a causal effect of the pressing action by the user.

6.2 Why does Time Delay Affect Haptic Perception?

Two possibilities are suggested for the reason why participants experienced the changes in the perceived textures when the tactile stimuli included a time delay. First, the participants possibly perceived the variations in the spatial wavelength or the frequency of vibrations caused by the time delay. A time delay changes the effective wavelength of the displayed virtual textures, which can result in a sufficiently large change for the participants to perceive. The wavelength discrimination limen of a grating scale or a scale with raised dots with a spatial wavelength of 1 mm is approximately 2 percent - 8 percent of 1 mm [32], [33]. If we approximate hand velocity with a sinusoidal profile and use the average values from Experiment 1 for its amplitude and frequency, we obtain $v(t) = 196 \sin(2\pi 1.0t)$ mm/s for hand velocity. The ratio of wavelength change is equal to the ratio of $v(t)$ and $v(t-D)$, and is given by

$$c(t, D) = \left|\frac{v(t)}{v(t-D)}\right| = \left|\frac{\sin(2\pi t)}{\sin(2\pi(t-D))}\right|. \qquad (9)$$

When the delay is 40 ms ($D = 0.04$ s), for 80 percent of the exploration time period, $c(t, D)$ is less than 92 percent or greater than 108 percent, which is equivalent to wavelength changes of more than 8 percent. Therefore, for the majority of the exploration, the wavelength changes caused by the delay were large enough for the participants to notice.

The changes in haptic perceptions due to time delay can be further explained on the basis of the discrimination limen of vibrotactile frequency. The frequency discrimination limen of sinusoidal vibratory stimuli is approximately 20 percent of reference frequencies over a wide frequency range [34], [35]. The frequency change due to time delay can also be expressed by $c(t, D)$. When the delay is 40 ms, for 55 percent of the exploration time period, $c(t, D)$ is less than 80 percent or greater than 120 percent. Therefore, during roughly half of the exploration period, the frequency changes are sufficiently large for the participants to notice.

It now follows that the changes in the perceived texture caused by time delay can be explained by the discrimination limen of both the spatial wavelength and the vibrotactile frequency of roughness scales.

Second, changes in the relationships between the hand motions and the stimuli possibly led to subjective changes in the perceived textures. When a delay is simulated, the stimuli are based on $v(t-D)$, which is different from the current instantaneous velocity of the hand $v(t)$. Thus, the delay results in a variation in the relationship between hand motions and tactile stimuli. With regard to the perception of textures by haptic exploration, the contributions of temporal cues of the vibratory stimuli to texture perception have been well established. For example, perceived roughness of grating scales depends on the vibratory frequency which is determined by the spatial wavelength and stroking velocities [36]. Availability of temporal cues has improved the performance of roughness discrimination tasks [37]. For discriminating fine textures, the lack of lateral movements between texture and skin can degrade the performance of discrimination tasks [38]. A mechanism of roughness perception that takes into account stroking velocities has been proposed, where neural signals of hand speeds inhibit the magnitude of perceived roughness. Consequently, roughness perception was independent of stroking velocity [39]. These studies suggest that texture perception is influenced by the relationship between hand velocities and the corresponding vibrotactile stimuli. Temporal delay changes this relationship which in turn changes the perceived textures. However, there have also been some reports that dispute the contribution of hand velocities to texture perception. For example, only a slight effect of hand speed was observed on roughness perception when exploring grating scales [29]. When scanning roughness scales, temporal variation of mechanoreceptive afferents was not correlated with perceived roughness [40].

6.3 Do People Associate Subjective Changes Due to Time Delay with Mechanical Properties?

In Experiment 2, the delays in both the acceleration and deceleration phases affected the perceived roughness of virtual textures. This was expected because the temporal delay affected the output displacements of the vibrotactile stimulator. However, the proportion of trials during which the participants perceived a decrease in the kinetic friction coefficient in the delay-in-acceleration-phase condition was significantly greater than that in the nondelayed and the delay-in-deceleration-phase conditions. In the presentation of virtual textures using force displays, it has been reported that the velocity-dependent resistance (viscosity) increases the perceived roughness of virtual textures on which resistive and nonresistive fields are alternately arranged [30], [31]. The viscosity and the kinetic friction coefficient are velocity-dependent resistances in the model shown in Fig. 11. In Experiment 2, when there was a delay in the acceleration phase, the perceived roughness and kinetic friction coefficient decreased. When there was a delay in the deceleration phase, the perceived roughness, kinetic friction coefficient, and viscosity increased while the increase in friction and viscosity were not statistically significant. Thus, in Experiment 2, the velocity-dependent resistances increased and decreased with the changes in the perceived roughness. The participants presumably interpreted the changes in velocity-dependent resistance as changes in perceived roughness.

7 Conclusion

The present study estimated two types of tactile detection thresholds for time delay with a tactile display that produced tactile stimuli in response to the hand motions of users. One was a threshold for users to notice the existence of a delay, which was found to be approximately 60 ms. The other was a threshold for users to notice the change in the perceived textures of the displayed objects, which was found to be approximately 40 ms. The subjective changes due to time delay were described using mechanical parameters such as the kinetic friction coefficient as well as the perceived roughness of virtual textures.

Acknowledgments

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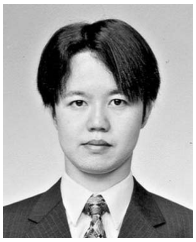

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