Virtual Active Touch: Perception of Virtual Gratings Wavelength through Pointing-Stick Interface

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Abstract—Tactile feedback enhances the usability and enjoyment of human-computer interfaces. Many feedback techniques have been devised to present tactile stimuli corresponding to a user’s hand movements taking account of the concept of active touch. However, hand movements may not necessarily be required for achieving natural tactile feedback. Here, we propose a virtual-active-touch method that achieves haptic perception without actual/direct hand movements. In this method, a cursor manipulated by a force-input device is regarded as a virtual finger of the operator on the screen. Tactile feedback is provided to the operator in accordance with cursor movements. To validate the translation of virtual roughness gratings, we compare the virtual-active-touch interface with an interface that involves actual hand movements. By using the appropriate force-to-velocity gain for the pointing-stick interface, we show that the virtual-active-touch method presents the surface wavelengths of the gratings, which is a fundamental property for texture roughness, and that the gain significantly influences the textures experienced by the operators. Furthermore, we find that the perceived wavelengths of objects scaled and viewed on a small screen are skewed. We conclude that although some unique problems remain to be solved, we may be able to perceive the surface wavelengths solely with the intentions of active touch through virtual-active-touch interfaces.

Index Terms—Isometric interface, vibrotactile texture, handheld device, force-to-velocity gain.

1 INTRODUCTION

Currently, many human-computer interfaces such as mobile phones and portable game players are equipped with tactile interfaces. Tactile feedback is expected to enhance the usability and enjoyment of these interfaces. Given that the importance of active hand movements in haptic perception has been recognized [1], many tactile feedback technologies have thus far focused on the generation of stimuli in response to the active hand movements of their users. For example, for the presentation of virtual textures, tactile stimuli have been generated in synchronization with the position, velocity, and acceleration of a user’s finger or stylus (e.g., [2], [3], [4], [5]). In addition, for many tactile feedback techniques such as in [6] and [7], the presentation of tactile stimuli in accordance with the user’s active hand movements is considered to be a general method for augmenting the validity of a technique.

1.1 Virtual Active Touch

Despite the widespread use of tactile feedback techniques, our question is whether such hand movements are necessarily required for tactile interfaces. To address this question, we proposed the possibility of virtual active touch—the haptic perception when humans receive tactile feedback without actual hand movements but with the intentions of active touch [8]. Although it does not involve direct hand movements, virtual active touch may achieve haptic perception similar to that achieved by active touch. The present study is based on our previous study [8] in which we investigated human perception for virtual active touch. In the present study, we reached different conclusions with Experiment II in Section 5 as a result of involving a large number of participants.

Fig. 1 shows an example of a virtual-active-touch interface. The user of a mobile phone manipulates a cursor on the screen through a force-input device such as a pointing stick or isometric joystick. The tactile stimulator is actuated in response to cursor movement to provide tactile feedback. The user receives the feedback in accordance with his/her intentions of haptic exploration. As a result, she/he may perceive the haptic properties of virtual objects or her/his interaction with them just as well as when she/he explores them with direct hand movements.

1.2 General Benefits of Virtual-Active-Touch Interfaces

The drawbacks and advantages of the pointing stick compared with others have been discussed [9], [10], [11], [12]. In general, the pointing stick does not exhibit faster
positioning in a pointing task. It still has some benefits for computer interfaces lacking enough space for a touch pad or for business people or software engineers that prefer to maintain their wrist position for saving time. The pointing stick provides another option for designers or users of computer terminals. Furthermore, virtual-active-touch interfaces provide information terminals with some benefits as follows.

To install tactile feedback function on ATMs or information kiosks whose screens are larger than those of personal computers for the natural sense of virtual buttons or textures, actuators with large output forces are required for driving the entire touch screen in the case of vibrotactile stimulators. In general, these large actuators have slow responses and are unsuitable for generating complex tactile stimuli. The virtual-active-touch interface can be located in one place, and the mass that must be driven by the stimulator is relatively small. This allows the employment of an actuator with quick responsiveness.

For handheld devices with small screens, the ratio of the screen size to the finger is small. In the case of touch screens, the finger hides a large part of the display area when it scrolls across the screen. For virtual-active-touch interfaces, the sensor for capturing the user’s force inputs and the stimulator can be placed outside of the screen (Fig. 1). Hence, the user’s finger does not hide the display area.

1.3 Related Study
For natural tactile feedback, some researchers have already used an indirect mapping between human input motions and cursor movements on a computer. The devices proposed by Poupyrev et al. [13] and Oakley et al. [14] feedback vibrotactile signals to their users tilting the devices to select items in a menu. These devices may be included among the virtual-active-touch interfaces in the broader sense of indirect input motions for natural tactile feedback. This study adopts a pointing stick to capture the user’s virtual hand movements. There are few studies in the literature on pointing sticks with tactile feedback function. Campbell et al. introduced tactile feedbacks in a pointing-stick interface. They showed that providing tactile feedback could help navigation tasks [15] where a user of the pointing-stick draws a cursor on the screen along a circle as quickly and accurately as possible. However, their interests were in the effects of tactile information on navigation tasks rather than on perceptual properties. The combination of a joystick, which has some similarity with the pointing stick, and tactile feedbacks has been used for realizing a Braille map system by Parente and Bishop [16]. Although a number of studies related to virtual-active-touch interfaces, the perceptual properties of textures have yet to be studied for these interfaces.

Virtual active touch may be neither active nor passive touch. From the point of view that the user’s finger does not considerably move, it is similar to passive touch. On the other hand, the finger moves (albeit slightly) on the pointing stick, and the user voluntarily exerts forces. This is considered similar to active touch. Differences in perceptual properties between active and passive touch have been discussed from various views including roughness perception [17], [18], recognition of Braille letters or figures [19], [20], and sensitivity enhancement [21]. Virtual active touch may be a mixture of both modes or an entirely different mode.

1.4 Motivation
The interest of this study is in whether or not the virtual-active-touch interface can deliver tactile perception of textures. The perception of textures involves exploratory hand movements; hence it is a suitable topic for studying virtual active touch. In addition, texture presentation is practically valuable for many purposes such as the delivery of discrete icons or windows as different tactile textures, or the supplementary notification of the moving distances of the cursor while dragging. The presentation of texture sensations for unique materials in the virtual world naturally provides the users with enjoyment. For these purposes, the fundamental knowledge is how accurately the users of the virtual-active-touch interfaces perceive the virtual textures. As a first step, we investigate the perception of roughness textures, for which the literature is voluminous. We target the surface wavelengths of roughness textures, which is one of the major parameters that influence the perception of roughness textures such as gratings. Given that the wavelength determines temporal factors of vibrotactile stimuli depending on hand motions, the wavelength has drawn the interest of many researchers in order to examine relationships between roughness perception and the relative movements of a finger pad and textured surfaces [22], [23], [24], [25], [26], [27], [28].

1.5 Objective I (Experiment I)
In Experiment I, using a pointing-stick interface with a vibrotactile stimulator, we show that the virtual-active-touch interface can provide users with information on surface wavelengths. To this end, we compare the perceived wavelengths represented by the pointing stick and those represented by the linear-slider-type vibrotactile display that involves user’s hand movements. From informal preliminary studies, we know that the force-to-velocity gain of the input device is a crucial parameter. Therefore, we also investigate the effects of this gain on the perception of wavelengths.

1.6 Objective II (Experiment II)
One of the merits of force-input interfaces such as a pointing stick is the adaptability to variations in screen size. Cursor movements are adjusted to the screen size by changing the force-to-display gain. Objects on a screen are visually scaled or enlarged so that they fit with the screen size. It is expected that users naturally interact with scaled
objects on a small screen. However, no study has reported the tactile perception of these scaled objects. We examine the human perceptual properties of the wavelengths by varying the visual scales of roughness textures displayed on a screen.

2 VISUAL AND TACTILE STIMULI

2.1 Tactile Stimuli

2.1.1 Virtual Gratings

Virtual sinusoidal gratings are used as tactile textures. When a user’s finger traverses the virtual grating, sinusoidal displacements are applied to his/her finger pad. The profile of the displacements applied to the finger skin is expressed as

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

where \( x(t) \) and \( \lambda \) are the position of the finger or cursor along the virtual texture and the spatial surface wavelength of the texture, respectively. These sinusoidal displacements have been used by some researchers to investigate the perception of virtual gratings presented by haptic displays [29], [30], [31]. A vibratory actuator is used as the tactile stimulator; the voltage supply to the actuator is expressed by (1) where \( A \) is the amplitude of the voltage. We fix \( A \) and vary \( \lambda \). In association with hand movements, \( \lambda \) influences texture perception. When the instantaneous velocity of the finger is \( \dot{x}(t) \), the frequency of the vibratory stimuli presented to the user is given by \( f(t) = \dot{x}(t) / \lambda \); this affects the perception of the textures. On the other hand, \( A \) affects the perception independently on the hand movements. We fix \( A \) because the interest of this study is in the perception caused by virtual movements of the hand.

2.1.2 Stimulator

The vibratory actuators are piezo-stack actuators (AHB800C801FPOLF, NEC/TOKIN, Sendai, Japan). Their output displacement is approximately linear to the applied voltage. The output displacements are 34.7 and 63.0 \( \mu \)m for \( A \) values of 30 and 50 V, respectively (these voltages are used in the latter experiments). The amplitude-frequency response of the vibrator is almost flat in the range used for the experiments. The displacement reaches –3 dB at frequencies of 275 and 195 Hz for \( A \) values of 30 and 50 V, respectively. A bipolar amplifier (BA4825, NF, Yokohama, Japan) whose nominal frequency response is up to 2 MHz is used.

The control frequency for updating the supplied voltage is 5 kHz. It is controlled by a personal computer with ART-Linux through an IO board (LPC-361216, Interface corp., Hiroshima, Japan). The output displacement is not feedback controlled. This is because the force of a human finger, being much smaller than the output force of the stimulator (approximately 800 N) does not degrade the output displacement.

The output displacements are sufficient to allow participants to experience tactile sensations while exploring virtual textures. In informal introspective reports, the participants agreed that through the tactile display systems mentioned later, they experience sensations similar to those acquired when they explore rough textures such as sandpapers or gratings using a stylus with a blunt point.

2.2 Visual Stimuli

The image of the target texture used as the visual stimulus should be a familiar item such that every participant can imagine its actual dimensions. We use the image of a brown brick, as shown in Fig. 2. Its dimensions as observed on a computer screen are 120 \times 60 \text{mm}, which are close to those commonly used in Japan. The cursor that is manipulated by the interface is a 6-mm square. Even when this is scaled down in Experiment II, it is still sufficiently large for the participants to see without stress. Its movements are confined along the \( X \)-axis.

3 EXPERIMENTAL EQUIPMENT

Two types of tactile interfaces are prepared. One is a pointing-stick-type (PS-type) interface for virtual active touch. The other is a linear-slider-type (LS-type) interface for tactile exploration with hand movements. Participants compare the gratings presented through these two types of interfaces.

3.1 Pointing-Stick-Type (PS-Type) Tactile Interface

The PS-type tactile interface is shown in Fig. 3. When the user applied tangential forces with a finger along the \( X \)-axis, the cursor on a computer screen moved according to the applied force. When the cursor slid on the brick, vibratory stimuli
were presented to the participants through a tactile stimulator. A contact shoe was installed on top of the vibrator to secure an adequate contact area between the finger and the stimulator. The shoe was circular in shape with a diameter of 20 mm. A six-axis force sensor (MINI2/10, BL-AUTOTECH, Kobe, Japan) with the resolution of $1.96 \times 10^{-2}$ N and a 100-Hz-low-pass filter was installed beneath the stimulator to measure the tangential force applied to the stimulator along the X-axis. The IO board on the computer received the sensory information and output the voltage to the stimulator through the amplifier.

We employed a linear transformation between the applied force ($F(t)$) and the cursor velocity ($\dot{x}(t)$) to simplify the analysis. The equation to transform these two types of information is expressed as

$$\dot{x}(t) = \alpha F(t),$$

where $\alpha$ is the control gain. The control frequency of this system was 5 kHz, i.e., the latency between the motion input and vibrotactile output was less than 200 $\mu$s.

### 3.2 Linear-Slider-Type (LS-Type) Tactile Interface

The LS-type tactile interface is shown in Fig. 4. The vibratory stimulator was installed on top of the linear slider and was moved along the X-axis by the participant’s hand movement. When the operator placed a finger on the vibrator and moved his/her hand along with the linear slider, the cursor on the computer screen moved while tactile stimuli were presented to the participant’s finger. The movable length on the guide was approximately 200 mm. The position of the stimulator on the guide was measured by an optical encoder (SR-P1000, Canon, Tokyo, Japan) whose spatial resolution was 0.4 $\mu$m. The encoder pulses were counted by a counter board (LPC-632104, Interface corp., Hiroshima, Japan) installed on the computer. Its IO board then output the voltage to the stimulator. The velocity of the cursor controlled by the LS-type interface was equal to the actual hand velocity measured by the encoder, which means the control gain was 1.

### 4 EXPERIMENT I: CONVEYANCE OF SURFACE WAVELENGTHS BY VIRTUAL ACTIVE TOUCH

In this experiment, the participants compare the virtual gratings they perceive through both the PS-type and LS-type interfaces. The participants adjust the surface wavelength of the gratings ($\lambda$) presented by the PS-type interface so that it feels similar or identical to that presented by the LS-type interface, following the psychophysical method of adjustment. The control gain ($\alpha$ in (2)) is varied in order to examine its effect on texture sensations.

#### 4.1 Experimental Tasks, Stimuli, and Participants

##### 4.1.1 Tasks

The reference and test stimuli were presented by the LS- and PS-type tactile interfaces, respectively. The participants adjusted $\lambda$ of the test stimulus so that the gratings presented by the PS-type interface became close to those obtained by the LS-type interface. They could adjust $\lambda$ only for the PS-type interface by pressing keys on a keyboard. A single press of a key changed $\lambda$ by 0.05 mm. Random values were assigned to the initial values for the test $\lambda$. The participants could freely switch between the PS- and LS-type interfaces that were placed on a desk before them. The duration of a single trial was limited to 30 s in order to prevent unexpectedly long deliberation by the participants. If the participant did not complete a trial within 30 s, the trial was repeated after the completion of all remaining trials. These retrials happened at most a few times for individual participants.

##### 4.1.2 Stimuli

Eight reference stimuli whose $\lambda$ values varied from 0.4 to 1.8 mm in 0.2 mm steps were used in random order. The four $\alpha$ values employed were: $1.02 \times 10^2$, $2.04 \times 10^2$, $4.08 \times 10^2$, and $6.12 \times 10^2$ mm/sN. Four trials were conducted for each condition. In total, 128 (8 reference stimuli $\times$ 4 gains $\times$ 4 repetitions) trials were conducted for each participant.

As a result of a limitation in the voltage amplifiers used for the vibrators, the maximum applied voltage (defined by $A$ in (1)) was set to 30 and 50 V when the reference wavelengths were 0.4-0.8 mm and 1.0-1.8 mm, respectively. The same $A$ value was used for both the reference and test stimuli in a single trial.

##### 4.1.3 Participants

Five voluntary students from the authors’ laboratory (excluding the authors) in their 20s, given informed consent, performed the tasks. They wore earplugs and headphones through which pink noise was audible to prevent sounds generated by the vibrator from being heard. Before performing the experiment, the participants practiced manipulating the cursors using both the PS- and LS-type tactile interfaces. During the experiments, they were instructed to match the velocities and strokes of the cursor movements for the PS-type interface with those of the LS-type interface. None of them voluntarily reported feeling that their exploratory movements were unnatural and that this matching of velocity prevented them from conducting the tasks. No reference marker to instruct/teach the movements of the cursor to the participants was presented. Individuals could move the cursor at speeds and rhythms with which they felt comfortable. The participants could practice until they were comfortable with the tasks, which usually took a few minutes.

#### 4.2 Experimental Results

Fig. 5 shows the relationships between the adjusted $\lambda$ and the reference $\lambda$ for each $\alpha$ value. The error bars indicate
standard deviations across the participants. The dashed line denotes the relationship in which the adjusted and reference λ values are identical. It can be observed from the figure that the adjusted λ increased with the reference λ for all α values. Also, the adjusted λ differed for different α values. Analysis of covariance was applied to the experimental results, with the reference λ as the covariant and α as the group factor. The results of the analysis showed that there was a significant difference between the slopes of the regression lines at different values of α ($F(3, 152) = 14.09, p = 3.78 \times 10^{-8}$). At smaller values of α, the adjusted λ values tended to be smaller than those for larger gains. This trend was observed for all participants.

### 4.3 Optimal Gain

From the experimental data above, we estimate the optimal gain $\alpha'$, defined as the gain at which the adjusted λ is equal to the reference λ. The value of $\alpha'$ is estimated by performing a regression analysis of the experimental results. From this analysis, the adjusted wavelength ($\lambda_a$) is given by

$$\lambda_a = 5.41 \times 10^{-4} \alpha + 1.05 \lambda_r - 0.152,$$

where $\lambda_r$ is the reference wavelength. $\alpha'$ is defined as

$$\alpha' = \arg \min_{\alpha} \int_{0.4}^{1.8} (\lambda_a - \lambda_r)^2 d\lambda_r.$$

From this equation, we obtain $\alpha' = 174$ mm/sN. The task described in Section 4.1 was then performed by the same participants with this value of $\alpha'$. The results are shown in Fig. 6. The adjusted λ values were almost same as the reference λ values displayed by the LS-type tactile interface ($R^2 = 0.995$). It is concluded that the PS-type tactile interface with a tuned gain can display the surface wavelengths approximating those displayed by the LS-type tactile interface.

### 4.4 Discussion: Effects of Control Gain on Adjusted Wavelength

We analyzed the movements of the cursors and found that the cursor velocity varied with α. It should be noted that the participants were instructed to equalize the apparent movements of the cursors between the PS- and LS-type interfaces during the experiments.

Fig. 7 shows the relationship between α and the average cursor velocity for the two types of interfaces. The error bars indicate the standard deviations across the participants. The average velocities were calculated for values greater than 5 mm/s. A significant positive correlation between the cursor velocity and α was observed for the PS-type interface ($r = 0.58, t_0(18) = 3.84, p = 6.0 \times 10^{-4}$). On the other hand, no such correlation was observed for the LS-type interface ($r = 0.17, t_0(18) = 0.81, p = 0.22$). Although the participants were instructed to balance the cursor movements for both types of interface, the cursor velocities of the two types differed when α was large.

Based on the observed differences in cursor velocities between the two types of interfaces, we explain the influence of α on the judgment of λ as follows: the participants are supposed to have judged λ values based on the relationship between the cursor movement and the corresponding vibrotactile frequency. This relationship is given by $\lambda = f(t) \cdot \tilde{x}(t)$, which indicates that $\tilde{x}(t)$ affects the judgment of λ. When the cursor velocity for the PS-type interface was larger than that for the LS-type interface, participants felt the λ for the PS-type interface to be larger than that for the LS-type interface. Hence, differences in the cursor velocities between the two types of interfaces might have led to differences in the judgment of λ.
5 EXPERIMENT II: TEXTURE PRESENTATIONS FOR SCALED OBJECTS

Large-sized objects need to be scaled so that they are recognizable on small screens such as those of mobile terminals. In this section, the perception of $\lambda$ for scaled textures is experimentally investigated.

5.1 Method for Displaying Scaled Gratings

To present virtual gratings independent of their scaling on the screen, the velocity of the cursor and the spatial characteristics of the gratings are scaled at a scaling rate equal to that of the visual image. The participants are assumed to judge $\lambda$ from the relationship between the cursor velocity and the vibrotactile feedback presented. This relationship, which is expressed in the form of a definition of the vibrotactile frequency,

$$f(t) = \frac{\dot{x}(t)}{\lambda},$$

should be maintained before and after the objects are scaled. In order to maintain the vibratory frequencies, $\dot{x}(t)$ and $\lambda$ are scaled at the same rate as are the visual dimensions of the object on the screen. As long as $\dot{x}(t)$ and $\lambda$ are scaled at the same rate, $f(t)$ is unaffected.

5.2 Experimental Conditions and Tasks

Using only the PS-type interface, the participants compared the gratings of scaled and nonscaled objects and matched their $\lambda$ by the psychophysical method of adjustment. The reference stimulus was a nonscaled object. The test stimulus was an object whose visual dimensions, $\lambda$, and $\dot{x}(t)$ were scaled at the same rate as are the visual dimensions of the object on the screen. Three trials were conducted for each of the five reference wavelengths and three scaling values. In total, 45 (five reference wavelengths $\times$ 3 scaling values $\times$ 3 repetitions) trials were conducted for each participant. The order in which the stimuli were displayed was random.

5.2.2 Tasks

The participants explored the reference and test stimuli in alternation, switching freely between the two types of stimuli by pressing a key on a keyboard. They adjusted the $\lambda$ of the test stimuli by pressing other keys. The duration of a single trial was limited to 30 s. If the participants did not complete the trial within that time, the trial was repeated after the completion of the remaining trials. They practiced the abovementioned tasks before performing the experiments until they were comfortable with the tasks. Seventeen voluntary participants performed these tasks.

5.3 Experimental Results

Fig. 9 shows averages of the adjusted $\lambda$ for each scaling value. The error bars indicate the standard deviations across the participants. Analysis of covariance was applied to the results with the reference $\lambda$ as the covariant and the scaling size as the group factor. The analysis showed a significant effect of scaling size ($F(2, 251) = 3.84, P = 0.023$), indicating that the reported $\lambda$ values increased as the scaling size increased.

![Fig. 8. Visually scaled virtual object. Left: fundamental scale size (reference/test stimulus). Center: half-scale size (test stimulus). Right: Quarter-scale size (test stimulus).](image)

![Fig. 9. Adjusted wavelength versus reference wavelength at different scaling values.](image)
decreased. The participants perceived the \( \lambda \) of scaled objects as different from that of nonscaled objects.

From the perspective of psychophysics, the effect of the scaling size is nonnegligible. The reported values were larger than the reference values by 9.3 percent on average when the scale size was 0.25. The 75 percent limen of real gratings with a surface wavelength of 1.0 mm is approximately 5–8 percent \([24, 18]\). The limen for virtual gratings is possibly higher than those for real gratings \([30]\). Further, because the participants judged the wavelengths based on the vibrotactile frequencies, we compare the distortion of perceived wavelengths with the limen of the frequencies that are approximately 20–30 percent \([32, 33]\). However, this value is not also directly comparable with the experimental results because the participant’s judgment was based not only on the vibratory frequencies but also on the cursor velocities. If we take a conservative comparison in the absence of directly comparable data, the effect of the scaling value on the perceived wavelengths may be as large as the just noticeable difference.

It is concluded that even when the scaling ratios of visual objects, cursor movements, and surface wavelengths of gratings are identical and the relationships between the cursor movements and the corresponding tactile feedback stimuli are maintained, a scaling ratio of one-fourth skewed the perceived wavelengths by 9.3 percent on average. Thus, visually scaled textures do not provide the correct texture sensations. Of course, the skew of perceived wavelengths can be corrected by adjusting the force-to-velocity gain of the pointing stick device. Furthermore, a 10 percent distortion may not be that significant for many applications, especially for entertainment.

6 DISCUSSIONS

6.1 Can Virtual Active Touch Present Surface Wavelengths of Virtual Gratings?

As shown in Experiment I (Section 4.3), the participants perceived the \( \lambda \) of virtual gratings through the virtual-active-touch interface as well as they did through the LS-type interface. However, it was found that the force-to-velocity gain of the pointing stick significantly influences the perceived wavelengths. The proper gain may depend on the types of input devices. For example, gains need to be specifically tuned for touch pads or joysticks. Further, we need to elucidate related issues including the identification of factors that affect the optimal gain, or the perception under a nonlinear control gain.

As to the scaling effects of the gratings, when the gratings and cursor velocities were scaled at the same ratio, the participants reported \( \lambda \) values that were larger than expected. The difference between the reported and expected \( \lambda \) was approximately 10 percent on average at a scaling factor of 0.25. This difference may be as large as the discrimination threshold of the surface wavelengths. The virtual-active-touch interface cannot present surface wavelengths when they are scaled.

6.2 Why Was Perceived \( \lambda \) Skewed When Gratings Were Scaled?

In Experiment II, the perceived wavelength was investigated when the gratings were scaled while maintaining the relationship \( \dot{x}(t) = \lambda \cdot f(t) \) before and after scaling. However, the perceived wavelengths were skewed when they were scaled. One potential cause underlying the skewed perception is a nonlinear perception of velocity. When Stevens’ power law holds for the perception of visual velocity of a moving object, the perceived surface wavelength is described as

\[
\hat{\lambda}(t) = \frac{k\dot{x}(t)^m}{f(t)},
\]

where \( k \) and \( m \) are constants. Algom and Cohen-Raz summarized the power indices \( (m) \) reported by several research groups \([34]\). Although the reported \( m \) values depend on methods of investigation, the majority are less than 1. When \( m \) is smaller than 1, the decrease in the perceived velocity is smaller than the actual decrease. As a result, \( \hat{\lambda} \) becomes larger than the actual \( \lambda \). For example, when the texture is scaled by a factor of 0.25, the cursor velocity also becomes one-fourth. However, since the perceived velocity does not decrease as much, the perceived \( \lambda \) becomes larger than the actual \( \lambda \).

Another possible reason is that the optimal gain depends on the scaling factor. In Experiment II, the same optimal gain acquired in Experiment I was used without respect to scaling rates. This gain might not be optimal for the scaling rates of 0.5 and 0.25, and thus cause the distortion of perceived wavelengths. In addition, the visual shrinkage of the bricks might have influenced the perceived wavelengths. Investigating the reasons for this distortion is the next challenge.

7 CONCLUSIONS

Virtual active touch is the perception of touch and its underlying process when a person touches objects on a computer screen through an input interface that does not involve direct exploratory hand movements. The objective of this study was to validate the capabilities of virtual-active-touch interfaces to present users with the surface wavelength, which fundamentally specifies the gratings. Furthermore, the effects of force-to-velocity gains on the perceived wavelength and the presentation of visually scaled gratings were investigated.

For validation, we compared the perceived wavelengths by an isometric tactile interface (pointing-stick-type) for which the hand moved only slightly, and an isotonic interface (linear-slider-type) for which it moved as much as the cursor. The results of psychophysical experiments confirmed that the pointing-stick-type tactile interface presented wavelengths similar to those presented by the linear-slider-type tactile interface with a tuned force-to-velocity gain. Furthermore, it was found that this gain significantly affected the perceived wavelengths. For visually scaled gratings, the virtual-active-touch interface skewed the perceived wavelengths. When the scaling factor was one-fourth, a distortion of approximately 10 percent was observed in the wavelengths perceived by the participants.

Certain problems remain to be solved. These include the specification of factors that influence the optimal control gain, as well as the validation of virtual active touch for perceived roughness or other vibrotactile textures given
that the present study verified only the perception of wavelengths. Collectively, the findings of this study suggest that virtual-active-touch interfaces are capable of presenting the surface wavelengths of gratings at least when the gain is carefully tuned and scaling is not applied to the virtual gratings. With further investigations, virtual active touch is expected to enhance the usability and enjoyment of tactile feedback functions on mobile or portable game players.

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