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Modifying Texture Perception with Pseudo-Haptic Feedback for a Projected Virtual Hand Interface

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ABSTRACT Human body augmentation makes it possible to obtain new abilities that we cannot achieve with our actual bodies. A projected virtual hand interface is a promising approach for body augmentation because it can extend a user's reach in daily life without the need to wear a device. Although users can manipulate a projected virtual hand as if it were their own hand and can interact with distant objects through it, they cannot feel the sensation of touch when the projected virtual hand is overlaid on a real object. In this paper, we propose a novel pseudo-haptic feedback framework to provide users with the tactile texture of objects without the use of haptic devices. We designed three types of visual effects that produce unevenness, slipperiness, and softness. The experimental results indicate that the proposed visual effects can lead users to feel the intended tactile sensation. Furthermore, the visual effects provide users with tactile sensations with three to five levels of intensity without producing a strange feeling.

INDEX TERMS Body augmentation, projected virtual hand, pseudo-haptic feedback, tactile sensation.

I. INTRODUCTION

Human augmentation technology has the potential to enable us to perform tasks efficiently and provide us with abilities that our bodies cannot attain. Prattichizzo *et al.* [1] proposed a robot finger attached to the wrist as a sixth finger to help increase a user's grasping ability. MetaArms [2] are wearable robotic arms that allow a user to perform complex tasks that are not possible with the user's body alone. By using robotic bodies for human augmentation, a user can work efficiently and physically interact with real objects. However, the physical size of robot bodies limits the range of user operation, and changing the structure and function of robot bodies is not simple.

To tackle these problems, promising methods include interfaces that virtually augment the body using virtual reality (VR) and mixed reality (MR). The Go-Go interaction technique [3] was developed based on the notion of being able to change arm length at will. Users can intuitively extend their arms and interact with virtual objects in a virtual world. There are also studies in which users can experience body augmentation in a real environment, not only in an immersive virtual world. ExtendedHand [4] is an interface that can virtually extend the reach of a user's hand in the real world by projecting a virtual hand with a video projector. Asai *et al.* [5] and Ueda *et al.* [6] proposed applications of ExtendedHand to facilitate communication between people and to interact with real objects in combination with Internet of Things technology. Although ExtendedHand allows users to intuitively manipulate a projected virtual hand as if it were their own hand, users cannot feel the touch sensation of objects when the projected virtual hand is overlaid on a real object. By providing the touch sensation, users would be able to experience virtual body augmentation more intuitively and immersively.

Several studies [7]–[9] have reported that providing haptic stimuli to a user using a haptic device when a virtual hand touches an object enhances the reality of the virtual hand. However, haptic devices limit the usage environment and interface opportunities because they must be prepared

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and worn when using the interfaces. A method that creates virtual touch sensations through visual effects is an approach that addresses this limitation. Studies have reported that it is possible for pseudo-haptic information to be produced by visual information alone. Lecuyér *et al.* [10] showed that in a mouse/display system, users felt frictional force by changing the control/display (C/D) ratio of a virtual object manipulated by the users when the virtual object crossed an area. Touchy [11] provided users with tactile textures for images displayed on a touch panel by changing the shape and movement of a white ring drawn on the panel. These studies suggest that users can feel tactile sensations of objects from virtual hand interfaces with pseudo-haptic feedback, which has not yet been thoroughly studied.

In this paper, following our previous research [12], we propose a novel pseudo-haptic method to lead a user to feel tactile perceptions of objects when a projected virtual hand touches an object. Our system provides the user with a tactile sensation by adding visual effects to the projected image of the virtual hand when the virtual hand touches an object. Fig. 1 presents an overview of our proposed method. Although we introduced the basic design and qualitative evaluation of visual effects in a previous study [12], in the present study, we developed three sophisticated visual effect designs that provide sensations of unevenness, slipperiness, and softness. In addition, we performed an evaluation of the proposed visual effects and confirmed that they can effectively provide their intended tactile sensations. This paper also provides guidelines for incorporating visual effects into existing projected virtual hand interfaces. We investigated the intensity ranges of visual effects that are appropriate according to the characteristics of a target object. We also evaluated the influence of the intensity change of the visual effects on tactile perception. Our results allow a user to perceive several levels of difference in the tactile texture of an object without producing a strange feeling. The proposed method thus allows a user to feel various tactile sensations without the use of haptic devices.

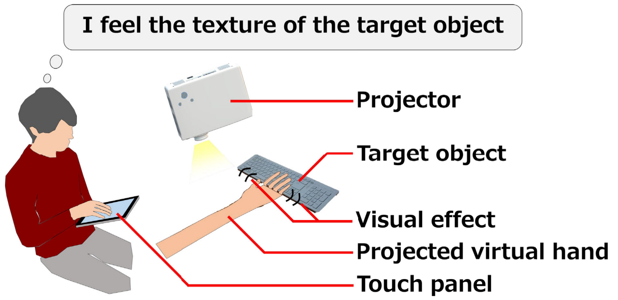

FIGURE 1. **Proposed system. Users can feel and move a projected virtual hand as if it were their hand by operating a touch panel while gazing at projected virtual hand. When the projected virtual hand is overlaid on an object, a visual effect (e.g., vibration) is added to the projected hand, and the user can feel the tactile sensation of the object.**

The main contributions of this study are as follows.

- We designed three visual effects that allow a user to feel unevenness, slipperiness, and softness, and demonstrated their effectiveness through subjective experiments.
- We clarified how to determine the intensities of the visual effects for the physical properties of touched objects.
- We investigated the influence of changing the intensity of the visual effects on the tactile sensations felt by the users, and clarified the appropriate range of visual effects.

II. RELATED WORK

In this section, we review existing research on projected virtual hand interfaces and work in which pseudo-haptic feedback effect are used.

A. PROJECTED VIRTUAL HAND

User interfaces for human body augmentation have been proposed in the research fields of VR and MR. One of these interfaces is the projected virtual hand interface, which allows a user to move a virtual hand in conjunction with his/her hand using a projection-based system. Projected virtual hand interfaces are suitable for use in everyday life because they allow users and others to see the virtual hand without wearing devices such as a head-mounted display. Ogawa *et al.* [4] proposed a projected virtual hand interface called ExtendedHand, which measures the posture and movement of a user's hand using a camera and reflects its movement to the virtual hand. The user can thus interact intuitively with various unreachable objects present in daily life. Ueda *et al.* [6] improved ExtendedHand to create a system in which a widely used touch panel performs hand-sensing. These studies confirmed that a sense of ownership, the impression that the optically projected virtual hand is actually the user's own hand, occurs, such as the rubber hand illusion [13] and virtual hand illusion [14]. As an application of the projected virtual hand interface in daily life, Asai *et al.* [5] proposed a system that mounts the ExtendedHand interface on a wheelchair to help the wheelchair user communicate with others.

From the perspective of tactile sensations, the projected virtual hand interfaces mentioned above do not consider providing the sensations. Many studies on rubber hand illusion and virtual hand illusion have reported that the provision of tactile stimulation synchronized with visual information improves body ownership [13]–[15]. It has also been reported that in virtual hand interfaces, providing haptic sensations with a haptic feedback device enhances the sense of ownership and the immersion of the VR experience [7], [16]. In projected virtual hand interfaces, the users would be able to experience virtual body augmentation more intuitively and immersively by providing the haptic sensation [9], [17]. However, most of the existing research methods required an additional haptic feedback device to provide a haptic sensation.

Pseudo-haptic feedback, which can provide tactile sensations without additional devices, is an alternative to using devices.

B. PSEUDO-HAPTIC FEEDBACK

A number of studies have focused on providing various haptic sensations using pseudo-haptic feedback [10], [18]–[20]. A study by Lécuyer *et al.* [10] was the first to report that adding a visual effect to an image on a display can change the perception of the stiffness of the virtual spring while the user grasps an isometric device. Lécuyer *et al.* [18] also reported that a user can feel resistance, bump, and hole sensations by changing the C/D ratio of a mouse cursor on a display. Mensvoort [19] proposed an active cursor that provides bump/hole and wind flow sensations by only slightly changing the position of the mouse cursor. Argelaguet *et al.* [20] proposed an algorithm to deform a graphed image into an image that appears concave when a user clicks on it. They reported that this changed the user's softness perception. These studies all involved a system using a display and mouse.

Several studies have applied pseudo-haptic feedback techniques in scenarios other than those involving a display and a mouse. Achibet *et al.* [21], [22] proposed a method to allow users to enhance haptic perception without interaction limitations by combining simple and cost-effective haptic devices with pseudo-haptic effects. Ban *et al.* [23], [24] changed the size and shape of a real object as perceived by users by deforming the image of the user's hand and the object when the user touches the real object in the MR environment. Issartel *et al.* [25] changed the weight of a virtual object using a virtual effector in the MR system. Ho *et al.* [26] and Punpongsanon *et al.* [27] changed warmth and softness perception, respectively, using projection-based MR systems. Although pseudo-haptic feedback has been utilized in various interfaces, including VR and MR systems, there have been no studies that aim to produce haptic sensations using pseudo-haptic feedback for projected virtual hand interfaces. We aim to provide users with tactile sensations of objects without physical haptic devices by using pseudo-haptic feedback techniques for a projected virtual hand interface.

III. METHOD AND IMPLEMENTATION

We propose a pseudo-haptic method for making a user feel tactile sensations in a projected virtual hand interface by adding a visual effect to the projected virtual hand. For the projected virtual hand interface, we used the touch-panel-based ExtendedHand proposed by Ueda *et al.* [6]. A user can manipulate the virtual hand projected from a video projector by moving his/her hand on the touch panel (see Fig. 1). Several studies on rubber hand illusion and virtual hand illusion have reported that it is important for the virtual hand to move synchronized with the user's hand movements [15], [28]. In light of this finding, an important design guideline for the visual effects is to change the movement and structure of the projected virtual hand to match the movement of the user's hand to the extent that the user can imagine it. A sudden change in the virtual hand may make the user unable to resolve why the virtual hand change and the user would find the virtual hand strange, and the reality of the user's body augmentation experience would be degraded. In the following subsections, we introduce the design and implementation of visual effects for providing tactile sensations of objects.

A. DESIGN OF VISUAL EFFECTS

We propose three visual effects that can provide three tactile sensations: unevenness, slipperiness, and softness. These are the basic sensations that constitute tactile sensations [29]. We refer to the visual effect for unevenness as Shaking-finger, the effect for slipperiness as Increasing-speed, and the effect for softness as Deforming-object.

1) SHAKING-FINGER

We applied vibration to produce the tactile sensation of unevenness. Touchy [11] suggested that vibrating a white cursor on a display made users feel the sensation of unevenness. In our Shaking-finger effect, only the fingertip of the pointing finger shakes. Fig. 2 illustrates the Shaking-finger effect applied to a virtual hand. We implemented the Shaking-finger effect by oscillating the rotation angle of the metacarpophalangeal joint (third joint) of the touching finger using the fundamental frequency of wave function that is the most straightforward periodicity representation, as shown in the following equation:

$$Rot_Y = A_v \sin(2\pi t v/\lambda), \quad (1)$$

$$Rot_Z = A_v \cos(2\pi t v/\lambda), \quad (2)$$

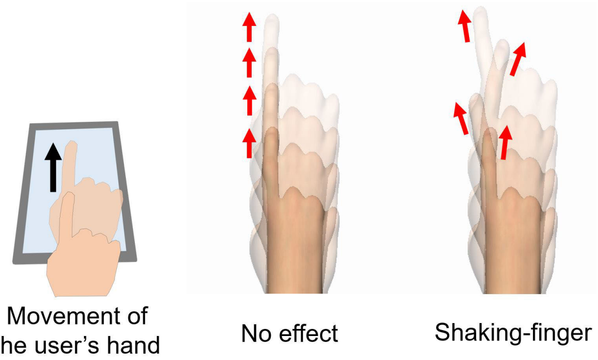

FIGURE 2. Projected virtual hand image applying the Shaking-finger effect. When the virtual hand moves, the touching finger of the virtual hand shakes.

where Rot_Y, Rot_Z are the rotation angles about the Y-axis and Z-axis in Fig. 3, respectively. In addition, t is the elapsed time after the virtual hand touches the object, and v is the speed of the virtual hand. λ is the average distance from the center of a bump to the center of the next bump in an uneven object with many bumps, which is the reciprocal of spatial frequency. A_v [rad] is a variable that determines the amplitude

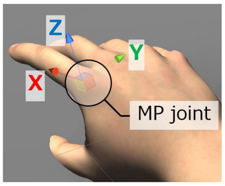

FIGURE 3. Coordinate system of the metacarpophalangeal (MP) joint (third joint).

of the shaking, and it is calculated by the following equation:

$$A_v = \begin{cases} G_A A_{real} (v/\lambda)^2 & (v/\lambda < th) \\ G_A A_{real} & (v/\lambda \geq th), \end{cases} \tag{3}$$

where A_{real} [mm] is a value representing the maximum movement width of the fingertip in a real environment. G_A [rad/mm] is a conversion factor that corresponds A_{real} [mm] to angle [rad], which is the reciprocal of the physical length of the index finger of a virtual hand projected in a real environment. We thought that the amount of physical movement of the fingertips is the essence, so we describe A_{real} and λ in length rather than angle. th [Hz] is a threshold for changing the behavior of A_v. We found that when the virtual hand's speed is slow, a large amount of fingertip movement made us feel a sense of strangeness. Therefore, we made sure that the shaking amplitude is set to be small when $v/\lambda < th$ is satisfied. In this paper, we set the parameter th to 1 Hz. This correction was applied to give the user a consistent experience, and we chose values that we subjectively felt were good. Note that our Shaking-finger effect shakes the fingertips of the virtual hand not only in the direction that corresponds to the virtual hand's movement but also in the direction perpendicular to it. We adopted this model because to shake the fingertips in various directions on the projection surface was rated better than only shake it in the direction that matches the direction of the virtual hand's movement in preliminary tests of this effect. The adjustable parameters are A_{real}, which determines the shaking amplitude of the fingertip, and λ, which represents the unevenness of objects.

2) INCREASING-SPEED

For producing a slippery sensation, we proposed the Increasing-speed effect, which increases the moving speed of the virtual hand when it traces an object (see Fig. 4). This effect was proposed based on the fact that when a person moves his/her finger with a certain force while touching an object, the moving distance of his/her finger increases as the touched object becomes more slippery. We focused on modulating the C/D ratio, which is frequently used in pseudo-haptic feedback studies. We implemented the Increasing-speed effect by changing the C/D ratio to a value obtained by multiplying the reference C/D ratio by the increasing rate γ. The adjustable parameter is γ, and a larger γ leads to an increased sensation of slipperiness.

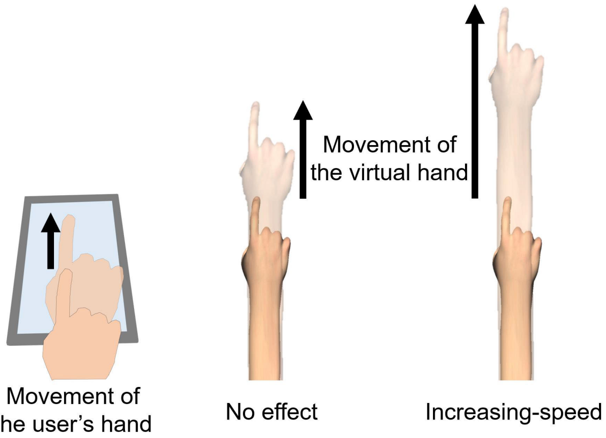

FIGURE 4. Increasing-speed effect. The moving speed of the projected virtual hand is increased when the projected virtual hand touches an object.

3) DEFORMING-OBJECT

For producing the softness sensation, we proposed the Deforming-object effect to deform an object to make it appear concave. We focused on studies in which softness perception can be controlled by changing the appearance and shape of object surfaces [20], [27]. We implemented this visual effect using the Deformation Lamps technique [30]. Our system can generate the effect in real time using the following procedure: 1) prepare a reference image of a target object, 2) generate a pseudo-concave image from the reference image using the method proposed by Argelaguet *et al.* [20], and 3) create a luminance motion image from the reference image and pseudo-concave image. Fig. 5 displays an image of the projected virtual hand with the Deforming-object effect.

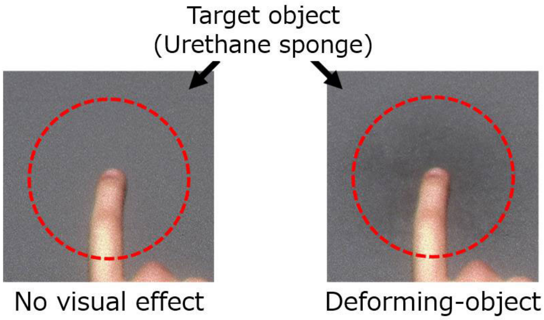

FIGURE 5. Deforming-object effect. An object touched by the projected virtual hand is deformed so that it appears concave.

There are four adjustable parameters for this visual effect. Parameter r [mm] is the radius of the deformation influence range, t [s] is the animation time to reach the maximum amount of deformation, and d [mm] is the maximum amount of texture deformation. These parameters are defined by the method of Argelaguet *et al.* [20]. The parameter d_{shade} is the darkness of shade. According to the Shadows and Creases proposed by Argelaguet *et al.* [20], we also added the shade effect to the pseudo-concave image (we fixed the parameter K at 10, which is the number of creases). We determined that the shade created by this method was dark under the projection environment; thus, we adjusted the darkness of shade by multiplying $d_{shade} \in [0, 1]$ by the term of shade $l(t, r)$ proposed by Argelaguet *et al.* [20]. This adjustment signifies that the deformation image is identical to the image generated by the method if $d_{shade} = 1$. In contrast, the image has no shade if $d_{shade} = 0$.

B. PROTOTYPE SYSTEM

We implemented a prototype system of the projected virtual hand interface with pseudo-haptic feedback. We used a hand model created by SuperDasil as the virtual hand[1], and controlled the virtual hand and visual effects using Unity 2019. We used a PC with a touch panel (Microsoft Surface Pro 4, CPU: Core i7-6650 2.2 GHz, Memory: 16 GB) and projector (NEC, NP-L51WJD). The resolution of projected images was 1920 × 1080 px.

We set the C/D ratio of the virtual hand to 1:5. This signifies that the projected virtual hand moves 50 mm when the user's hand moves 10 mm on a touch panel. We measured the delay time from the touch panel input to the projected virtual hand movement, and the result was 150 ms. Shimada *et al.* [31] reported that participants were not aware of the delay when the time was less than 200 ms. The delay time of our system satisfies this requirement, and none of the participants reported problems with delay of the movement of the projected virtual hand during the experiments.

IV. EXPERIMENTS

We conducted three experiments to evaluate the proposed system. In the first experiment, we investigated whether our proposed visual effects led users to experience the intended tactile sensations. In the second experiment, we explored guidelines for determining the parameters of the visual effects according to the characteristics of the touched objects. In the third experiment, we clarified the resolution of tactile sensations perceived by users.

A. SUFFICIENCY OF VISUAL EFFECTS (EXPERIMENT A)

We investigated whether our proposed visual effects led users to feel our intended tactile sensations under the unique condition of the projected virtual hand interface in which a real object below was also visible through. We also explored whether the users' perception changed by modifying the intensity of the visual effects.

1) VISUAL EFFECTS AND HYPOTHESES

We created two intensity levels, high and low, for each of the three visual effects (Shaking-finger, Increasing-speed, and Deforming-object described in Section III-A). Table 1 presents the parameter values for each visual effect.

TABLE 1. Parameter values of visual effects. We set low and high levels so that participants could descriminate the differences between the two.

Shaking-finger	A_{real} [mm]	λ [mm]		
Low level	0.53	10		
High level	0.84	10		
Increasing-speed	γ			
Low level	1.8			
High level	2.5			
Deforming-object	r [mm]	$time$ [ms]	d [mm]	d_{shade}
Low level	10	500	0.6	0.1
High level	30	250	6.0	0.3

We selected low and high values so that participants could clearly descriminate the differences between the two levels. In addition, we added the "no visual effect" condition as the reference. The no visual effect condition signifies that no proposed visual effects were added to the projected virtual hand when it touched a target object. Therefore, a total of seven visual effects were used in this experiment.

Our hypotheses are as follows.

- H1-1: Shaking-finger leads users to feel that they are touching an uneven object.
- H1-2: Increasing-speed leads users to feel that they are touching a slippery object.
- H1-3: Deforming-object leads users to feel that they are touching a soft object.

- H2-1: Shaking-finger with higher A_{real} leads users to feel a more uneven sensation.
- H2-2: Increasing-speed with higher γ leads users to feel a more slippery sensation.
- H2-3: Deforming-object with higher r, d, d_{shade}, and lower $time$ leads users to feel a softer sensation.

2) EXPERIMENTAL SETUP AND PROCEDURE

We conducted this experiment based on a study [32] that confirmed the strength of the pseudo-haptic effect using Scheffé's pairwise comparison method [33]. That is, a participant repeated a task in which he/she touched two target objects (A and B, each providing a different visual effect) with a virtual hand and answered questions comparing them. Fig. 6 presents the experimental setup. For the material of the object to be touched by the projected virtual hand, we selected a commercially available polystyrene-board sandwiched between white waterproof paper (Koyo Sangyo, goo panel). The size of the objects was 300 mm in length, 200 mm in width, and 5 mm in height. We placed the two objects 550 mm from the edge onto a white desk. The virtual hand was projected of this desk. The entire projected area was 910 mm in length and 540 mm in width.

Before starting the trials, we provided each participant with time to become accustomed to operating the projected virtual hand. In this experiment, the participants were required to manipulate the virtual hand with only their index fingers. Each trial was as follows. The participants touched target

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[1] DeviantArt, https://www.deviantart.com/superdasil/art/3D-hand-560775971 (accessed on 29 June 2020)

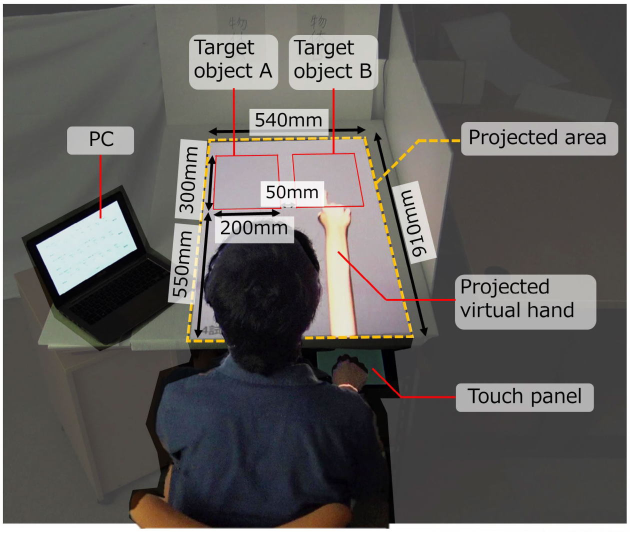


FIGURE 6. **Experimental setup. A video projector mounted on the ceiling projects a virtual hand onto a white table. A participant manipulates the projected virtual hand by moving his/her right hand on a touch panel. When the projected virtual hand touches one of the objects, a visual effect is applied to the projected virtual hand.**

objects A and B on the desk with the virtual hand. At that time, they moved the virtual hand in the direction of its arm stretching and contracting and touched each target object at a speed that traced the object plate for approximately 1 s. Then, they answered the following three questions displayed on a different PC with a seven-point Likert scale:

- Comparing object A and object B, which one do you feel is more uneven?
- Comparing object A and object B, which one do you feel is more slippery?
- Comparing object A and object B, which one do you feel is softer?

We recruited 14 participants whose dominant hand was right and whose age ranged 19 to 25 (12 males and two females). The participants were naive to the purpose of the experiment. We performed ${}_7C_2 = 21$ trials for seven visual effects, and each participant repeated these trials three times. Therefore, each participant responded to the questions in the 63 trials ($= 21 \times 3$). We balanced the order and location in which each visual effect was provided among the participants. Each trial was 20–40 s, and it took approximately 30 min to conduct all trials. We conducted an interview with each participant after the experiment. In total, it took 40 min for each participant to complete the procedures.

3) RESULTS

We used Scheffé's method of paired comparison (Ura's version [33]) as the verification method. Fig. 7 presents the experimental results for each questionnaire. The graphs displays the perceived strength of each pseudo-tactile effect, and higher positive values indicate a more significant perceptual effect.

a: UNEVENNESS

In the unevenness perception results, an ANOVA revealed that the main effect was significant (F = 743.62, $p < 0.001$). We calculated the confidence intervals (CIs) of the difference between each condition using a yardstick Y. There were significant differences (99.9% CI, ±0.1820) between Shaking-finger with high/low levels and other visual effects, Deforming-object with a high level and Increasing-speed with high/low levels, and Deforming-object with a low level and Increasing-speed with a high level. In addition, there were significant differences between Shaking-finger with a high level and Shaking-finger with a low level.

b: SLIPPERINESS

In the perception of slipperiness, an ANOVA revealed that the main effect was significant (F = 634.82, $p < 0.001$). There were significant differences (99.9% CI, ±0.2522) between all combinations except for the combination of Shaking-finger with a low level and Shaking-finger with a high level.

c: SOFTNESS

In the perception of softness, an ANOVA revealed that the main effect was significant (F = 525.17, $p < 0.001$). Participants felt a significantly softer sensation (99.9% CI, ±0.2053) in Deforming-object with high/low levels than in other visual effects. The participants also felt a significantly softer sensation in Deforming-object with a high level than in Deforming-object with a low level.

4) DISCUSSION

The results indicate that each visual effect produced its intended tactile sensation on participants. The Shaking-finger, Increasing-speed, and Deforming-object effects led participants to feel sensations that were more uneven, more slippery, and softer than the other visual effects, respectively. In addition, the pseudo-tactile effects were enhanced by increasing the intensity of the visual effects. As a result, all of our hypotheses were supported.

Several significant unexpected differences appeared are evident in Fig. 7(a), (b). For example, Shaking-finger produced significantly less slipperiness than other visual effects. The possible reason is that the three tactile dimensions are not psychologically independent. For example in the Increasing-speed, the fingertips of the virtual hand went straight forward with momentum, which may have led the participants to associate the object with no bumps on its surface. Therefore, the Increasing-speed effect for producing slipperiness may have recorded a low score in unevenness.

B. DETERMINING APPROPRIATE PARAMETERS (Experiment B)

In Experiment A, we confirmed that the tactile sensations experienced by users were affected by the magnitude of the intensity of the visual effects. However, since the proposed

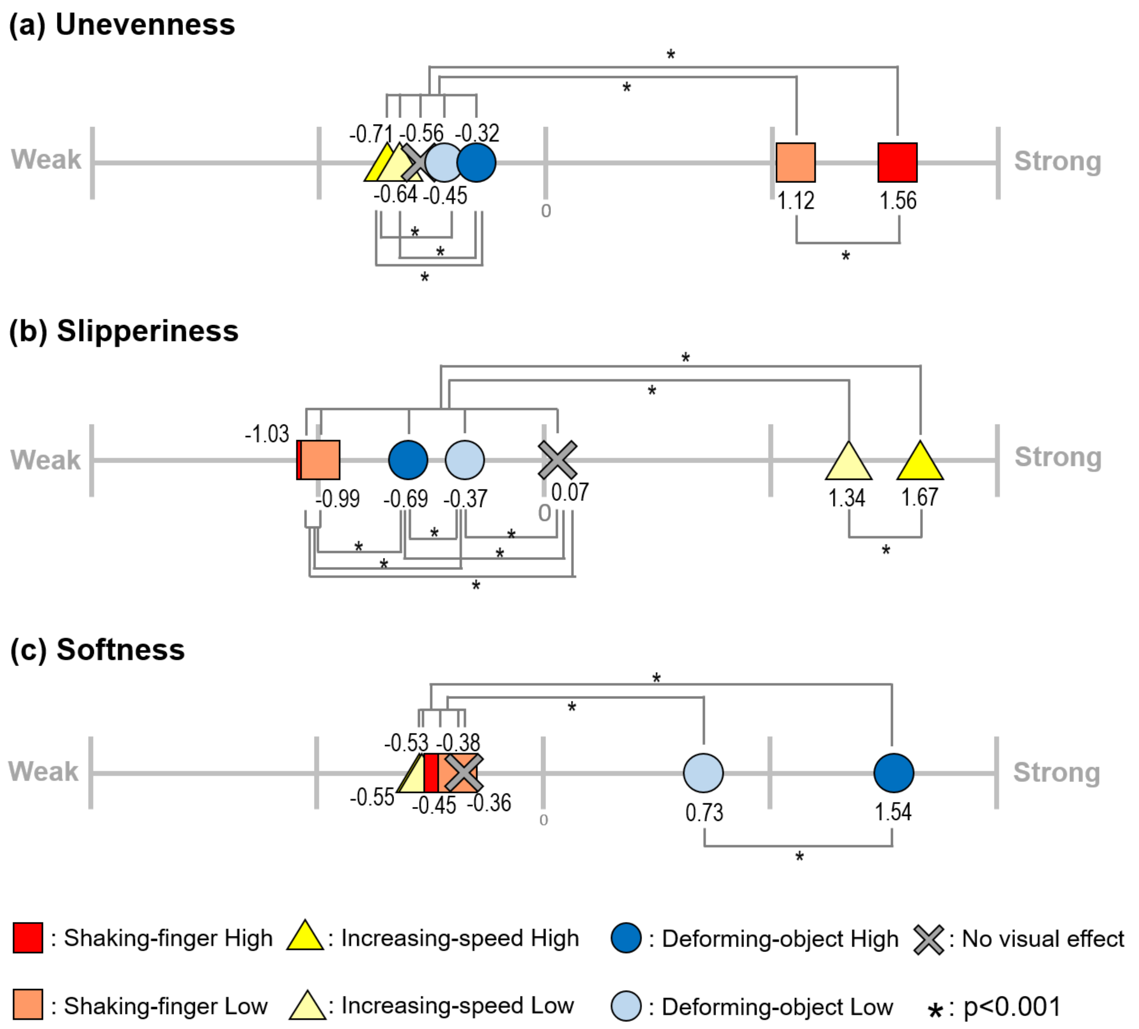


FIGURE 7. Perceived strength of the pseudo-tactile effects caused by visual effects (*: $p < 0.001$). Higher positive values indicate that participants felt the tactile texture more strongly.

method is applied when the projected virtual hand is overlaid on a real object, it is important to prepare a visual effect that takes into account the object's characteristics. For example, if the intensity of the Shaking-finger is too high for an object without bumps, the user would not understand why fingertips were shaking so much, and the reality of the user's body augmentation experience would be degraded. We considered that there are the intensity ranges of the visual effects that allow users to feel tactile sensations without a strange feeling according to the physical characteristics of objects. In this experiment, we examined the suitable intensity ranges on various objects to provide guidelines for the projected virtual hand to interact with the objects.

1) VISUAL EFFECTS

We prepared eight intensities for each visual effect. First, we set the maximum and minimum values of each parameter of the visual effects (Table 2). We selected the maximum value at which almost all users feel a sense of strangeness, while the minimum was equivalent to no visual effects. We obtained eight different intensities by substituting $\alpha = 0$, 1/7, 2/7, 3/7, 4/7, 5/7, 6/7, and 1 into the following equation:

$$X(\alpha) = \alpha X_{max} + (1 - \alpha) X_{min}. \tag{4}$$

where X is the calculated value of each parameter, X_{max} and X_{min} are the maximum and minimum values of each parameter, and α is the parameter of an intensity level. Therefore, the larger the value of α, the larger the intensity of the visual effect.

2) TARGET OBJECTS

For the target objects touched by the virtual hand, we selected three flat plates with different characteristics for each sensation of unevenness, slipperiness, and softness. Fig. 8 displays the appearances of the target objects. The size of all objects was 300 mm in length and 200 mm in width, and the thickness

TABLE 2. **Parameter values of the visual effects. The minimum values are equivalent to no visual effect. The maximum values were set based on the high value from Experiment A in Section IV-A except A_{real} of Shaking-finger, γ of Increasing-speed, and r, d_{shade} of Deforming-object. We set these values based on comments from the participants. The value of λ of Shaking-finger was fixed to the bump width of the target object (6 mm, 12 mm, 24 mm).**

Shaking-finger	A_{real} [mm]	λ [mm]		
Minimum	0.00	6, 12, 24		
Maximum	2.14	6, 12, 24		
Increasing-speed	γ			
Minimum	1.0			
Maximum	3.5			
Deforming-object	r [mm]	$time$ [ms]	d [mm]	d_{shade}
Minimum	0	1000	0.6	0.0
Maximum	80	250	6.0	0.15

was 10 mm for uneven objects and soft objects, and 5 mm for slippery objects.

a: UNEVEN OBJECTS (Fig. 8a)

We used three types of medium-density fiberboard (MDF) plates with uneven surfaces of different bump widths as uneven objects. The bump widths were 6 mm, 12 mm, and 24 mm, respectively, and the depth of a bump was 3mm. In this experiment, the participants manipulated the virtual hand only in the direction of arm extension and contraction, as in Experiment A. Therefore, we selected the plates with bumps only in the direction that matched the direction of movement of the virtual hand.

b: SLIPPERY OBJECTS (Fig. 8b)

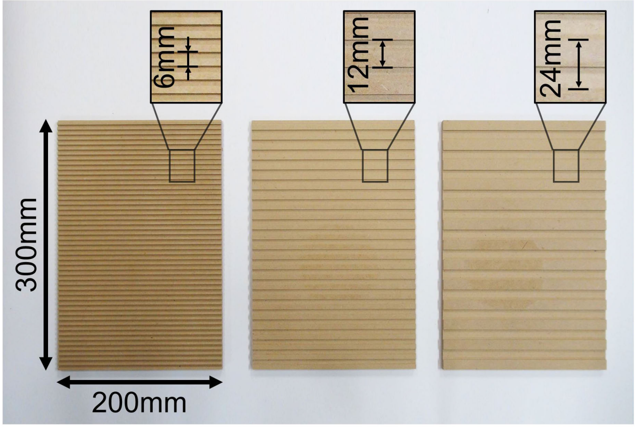
We used Washi (traditional Japanese paper), Bristol paper, and a Naflon sheet with different degrees of slipperiness as the slippery objects. The static friction coefficient between each target object and the paper plate (used in Section IV-A) was 0.63 for Japanese paper, 0.50 for Bristol paper, and 0.17 for the Naflon sheet.

c: SOFT OBJECTS (Fig. 8c)

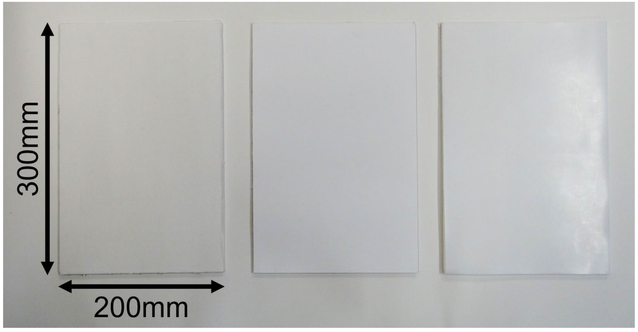
We used a Melamine-faced MDF plate, polyethylene sponge, and urethane sponge as soft objects. To ensure that each object had different softness levels, we measured the forces required to produce a 7-mm dent in each object. We used a force gauge (IMADA, ZTS-50N) to mesure the forces. The measured forces were greater than 50 N (exact level could not be measured due to the upper limit of the gauge) for the Melamine-faced MDF plate, 19.0 N for the polyethylene sponge, and 1.5 N for the urethane sponge.

3) EXPERIMENTAL SETUP AND PROCEDURE

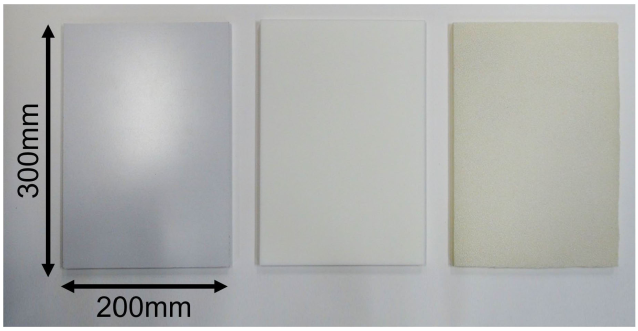
The experimental setup was the same as in Experiment A in Section IV-A, except that there was only one target object on the desk. The experiment consisted of "an object impression survey" to evaluate the participants' perceptions of the objects, and a "main experiment" to investigate the participants' perceptions when they touched an object with the virtual hand. In the following paragraphs, we describe the procedure of the two experiments.



(a) Uneven objects.
The bump widths are (left) 6 mm, (middle) 12 mm, and (right) 24 mm.



(b) Slippery objects:
(left) Washi (Japanese paper), (middle) Bristol paper, and (right) Naflon sheet.



(c) Soft objects: (left) Melamine-faced MDF plate, (middle) polyethylene sponge, and (right) urethane sponge.

FIGURE 8. **Target objects used in the experiment. The size of each object was 300 mm in length and 200 mm in width. The thickness was 10 mm for uneven objects and soft objects, and 5 mm for slippery objects.**

a: OBJECT IMPRESSION SURVEY

First, we investigated the participants' perceptions of an object under each of the two conditions. The first condition was the looking-only condition. We placed one of the target objects 550 mm away from the edge of the desk. First, a participant looked at the target object and the background object. The background object was vinyl chloride resin wallpaper (Sangetsu, SP9536, see Fig. 9) affixed to the top surface of the desk. The participant then answered one of the following

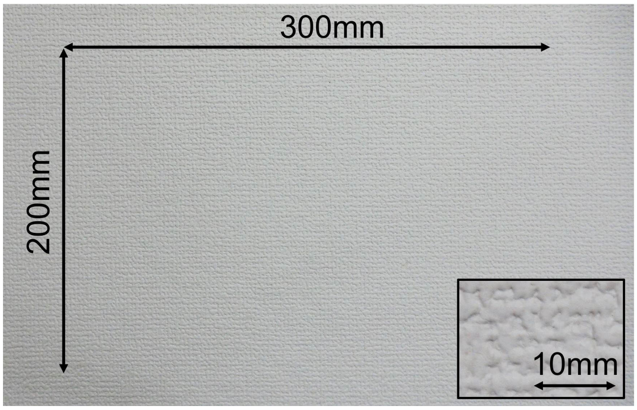


FIGURE 9. **Background object. We used vinyl chloride resin wallpaper (Sangetsu, SP9536) as the background object.**

three questions that corresponded to the tactile texture of the target object.

- For uneven objects (Fig. 8a)
  Comparing the target object and background object, which one do you feel is more uneven?
- For slippery objects (Fig. 8b)
  Comparing the target object and background object, which one do you feel is more slippery?
- For soft objects (Fig. 8c)
  Comparing the target object and background object, which one do you feel is softer?

These questions had a 7-point scales (from −3: "I feel that the background is very much uneven, slippery, soft" to +3: "I feel that the target object is very much uneven, slippery, soft"). Each participant answered the question for every target object.

After the looking-only condition was completed for all target objects, we executed the second condition (touching-with-looking condition). In this condition, a participant actually touched the target object and background object with his/her hand while looking at the objects and answered the same question. Each participant performed this comparison for every target object.

b: MAIN EXPERIMENT

After the object impression surveys, we conducted the main experiment in which participants touched the target object with a projected virtual hand. We conducted this experiment based on the method of constant stimuli, which is used in the field of psychophysics [34]. In each trial, the participants touched the target object by manipulating the projected virtual hand. At that time, the participants manipulated the virtual hand with only their index fingers in the direction of the virtual hand's arm stretching and contracting as in Experiment A. When the projected virtual hand touched the target object, our system produced a visual effect on the projected virtual hand corresponding to the object. After observing the effect, the participant answered yes or no to the following question: "Do you feel that you are touching the object without a sense of strangeness?" If the participant answered no, he/she also answered either "Do you feel a sense of strangeness due to small changes in visual effects?" or "Do you feel a sense of strangeness due to large changes in visual effects?" Since the constant stimuli method requires repeating a huge number of trials, we considered the burden on the participants and adopted this questionnaire that they could easily answer.

We set each of the eight intensities of the visual effects to repeat eight times; therefore, each participant performed 64 trials for each object. We shuffled the order in which each intensity was provided. Because there were nine target objects, a participant performed this trial set nine times (576 trials in total). At the beginning of a trial set, the participant looked at and touched a target object. We balanced the order in which each object was used across participants. We recruited nine participants whose dominant hand was right and whose age ranged from 18 to 23 (seven males and two females). The participants were naive to the purpose of the experiment. Each trial was approximately 4 s, and it took 60 min to conduct all the trials for a participant. We interviewed each participant after all the trials. In total, it took 80 min to perform all of the procedures for each participant.

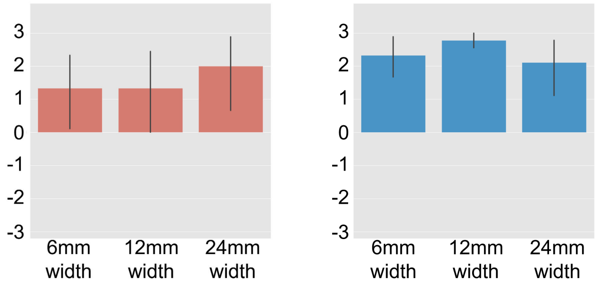
4) RESULTS

a: OBJECT IMPRESSION SURVEY

Fig. 10 presents the results of the questionnaire according to the tactile texture of the objects. The graphs indicate that the larger the value on the vertical axis, the more strongly the participants perceived the corresponding tactile sensation of the target object than that of the background object. We performed Friedman's test for both the looking-only condition and touching-with-looking condition, using the type of objects as factors. For the uneven objects, there was no significant difference in either of these conditions. For the slippery objects, there was a significant difference only in the touching-with-looking condition ($\chi^2(2) = 12.3, p < 0.01$). There was also a significant difference ($p < 0.05$) between the Washi and Bristol paper with the multiple comparisons test (Wilcoxon signed-rank test with Bonferroni correction). For the soft objects, there were significant differences in both conditions (looking-only condition: $\chi^2(2) = 14.0$, $p < 0.01$, touching-with-looking condition: $\chi^2(2) = 17.2$, $p < 0.01$). The multiple comparisons test revealed significant differences between the Melamine-faced MDF plate and the polyethylene sponge, and between the Melamine-faced MDF plate and urethane sponge in the looking-only condition ($p < 0.05$). There were also significant differences between all objects in the touching-with-looking condition ($p < 0.05$).

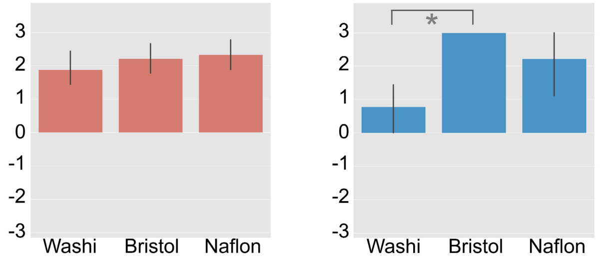
b: MAIN EXPERIMENT

For each participant, we calculated the rate at which the participant said that he/she touched the object without feeling a sense of strangeness for each visual effect intensity. We refer to this rate as the perception rate. Fig. 11 presents the average values of the perception rate for all intensities.



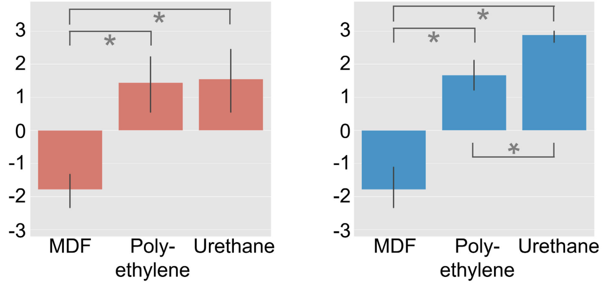
(a) Uneven objects (looking-only)

(b) Uneven objects (touching with looking)



(c) Slippery objects (looking-only)

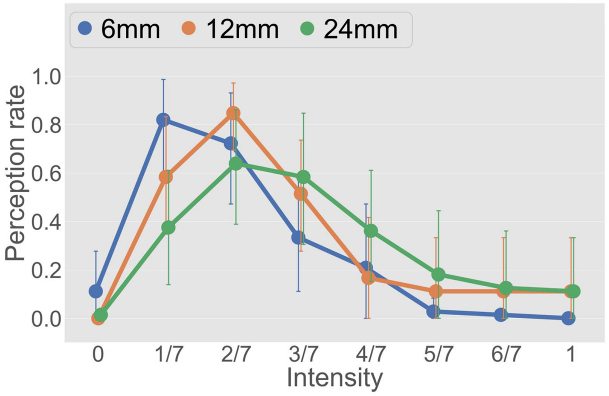
(d) Slippery objects (touching with looking)



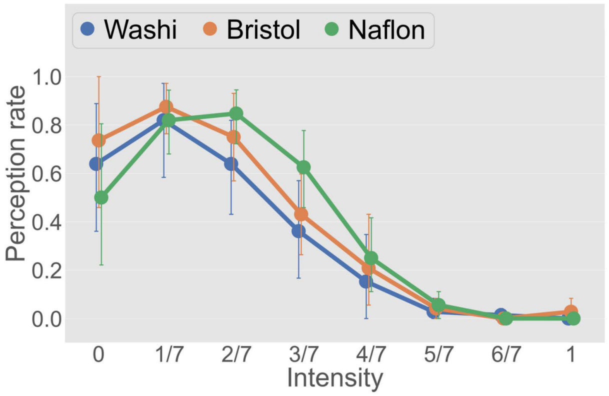
(e) Soft objects (looking-only)

(f) Soft objects (touching with looking)

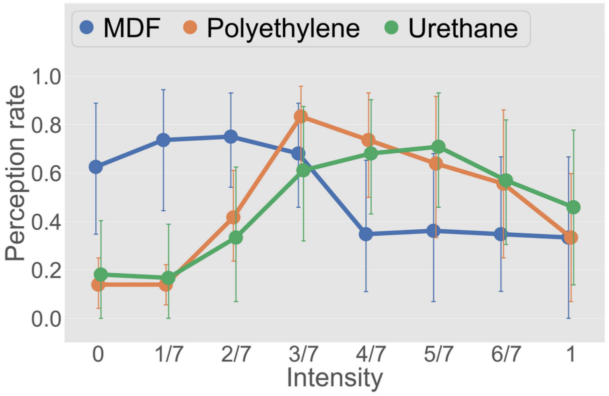
FIGURE 10. Results of the object impression survey. Higher positive values indicate that participants perceived the corresponding tactile sensation more strongly with the target object than with the background object.



(a) Uneven objects



(b) Slippery objects



(c) Soft objects

FIGURE 11. Average values of the perception rate of the intensity of the visual effects. The perception rate is the rate at which participants reported that they touched an object without feeling a sense of strangeness. Bars represent 95% confidence intervals.

Next, we calculated the appropriate intensity ranges for the visual effects by the following procedure (see Fig. 12). First, for each participant's data, we calculated the rate at which the participant answered "feel a sense of strangeness due to small changes in visual effects" and the rate at which the participant answered "feel a sense of strangeness due to large changes in visual effects". We call each rate $rate_{small}$ and $rate_{large}$. Then, we fitted both $rate_{small}$ and $rate_{large}$ to the psychometric curves of the following equations:

$$f_{small}(x) = \frac{1}{1 + exp(\frac{x-A}{B})}, \tag{5}$$

$$f_{large}(x) = 1 - f_{small}(x). \tag{6}$$

We calculated x, where the fitted $f_{small}(x)$ equals 0.5. We call this x the lower end. Similarly, we calculated x where the fitted $f_{large}(x)$ equals 0.5, and call this x the upper end. We also refer to the range from the lower end to the upper end as the effective area. Within the effective area, the participant was expected to touch the object without experiencing a strange feeling at the rate of more than 50%. We determined the effective area for each participant. In Fig. 13, the top part

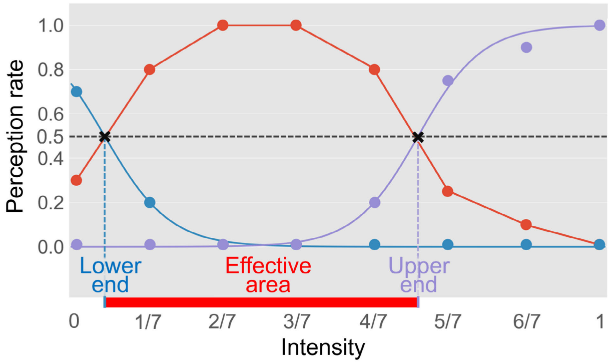


FIGURE 12. **Procedure for determining the appropriate intensity range. Red points represent the perception rate of a participant, while blue and purple points represent the rates at which the participant did not say "feel a sense of strangeness due to small changes in visual effects" and "feel a sense of strangeness due to large changes in visual effects," respectively. Blue and purple curves are psychometric curves that fit those rates, respectively. We call the crossover point at which each psychometric curve is a chance rate (0.5) the lower end and upper end, and call the range between them the effective area. Within the effective area, the participant would touch the target object without experiencing a strange feeling at the rate of more than 50%.**

displays the distribution of the lower end and upper end of the participants, while the bottom part displays the average of the effective area. For each of the upper and lower ends, we performed an ANOVA with the type of objects as a factor. We also performed the multiple comparisons test with Bonferroni correction if there was a significant difference.

Uneven Objects: For uneven objects, the ANOVA revealed significant main effects at both upper and lower ends (upper end: $F(2, 16) = 3.99$, $p < 0.05$, lower end: $F(2, 16) = 8.18$, $p < 0.01$). In a post-hoc analysis with Bonferroni correction, there was a significant difference between bump widths of 6 mm and 24 mm for both the upper and lower ends ($p < 0.05$).

Slippery Objects: For slippery objects, the ANOVA demonstrated a significant trend at both upper and lower ends (upper end: $F(2, 16) = 3.04$, $p < 0.1$, lower end: $F(2, 16) = 2.83$, $p < 0.1$). In a post-hoc analysis, there was no significant difference between any objects.

Soft Objects: For soft objects, the ANOVA revealed significant main effects at both upper and lower ends (upper end: $F(2, 16) = 7.21$, $p < 0.01$, lower end: $F(2, 16) = 7.40$, $p < 0.01$). In a post-hoc analysis, there were significant differences between the Melamine-faced MDF plate and polyethylene sponge at the lower end, between the Melamine-faced MDF plate and urethane sponge at the lower end, and between the Melamine-faced MDF plate and the urethane sponge at the upper end ($p < 0.05$).

5) DISCUSSION

a: OBJECT IMPRESSION SURVEY

For all uneven objects, the participants felt that the target object was more uneven than the background object, as illustrated in Fig. 10a and 10b. On the other hand, the results of multiple comparisons did not reveal which objects participants felt were more uneven under either condition. We prepared the target objects according to our assumption that a larger bump width would lead to a more uneven sensation; however, the results suggested that the bump width that created the most uneven sensation was judged differently by participants.

For slippery objects, the participants felt that all of the objects were slippery simply by looking at them, as displayed in Fig. 10c. In addition, participants recognized how slippery the objects were by touching them, as displayed in Fig. 10d.

For soft objects, the participants felt that the objects were soft, with the exception of the Melamine-faced MDF plate, as illustrated in Fig. 10e. In addition, the degree of softness was recognized by touching, as illustrated in Fig. 10f.

b: SHAKING-FINGER AND UNEVEN OBJECTS

The results indicate that the lower and upper ends change as the bump width of the object changes. Fig. 13a suggests that the larger the bump width is, the larger the lower and upper ends of the effective area are. In other words, it is preferable to increase the intensity of the Shaking-finger effect as the bump width increases for uneven objects.

c: INCREASING-SPEED AND SLIPPERY OBJECTS

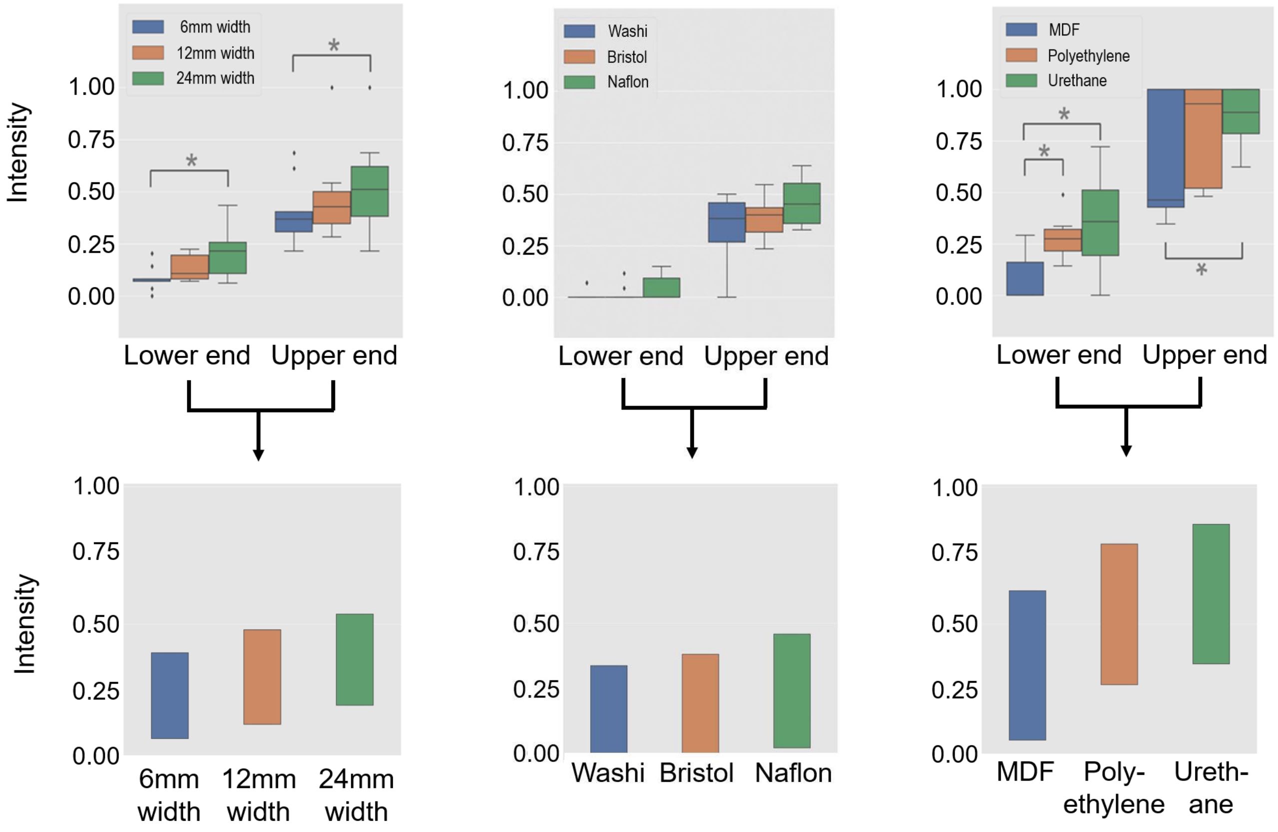
The results indicate that the lower and upper ends tend to change as the slipperiness of the object changes. Fig. 13b suggests that the more slippery the object is, the higher the lower and upper ends of the effective area are. On the other hand, Fig. 13b demonstrates that the upper end of the effective area is approximately 0.46 (rate of increase $\gamma = 2.15$), even though the Naflon sheet is physically very slippery. This result suggests that the maximum intensity should be limited to $\gamma = 2.15$ for the Increasing-speed effect.

d: DEFORMING-OBJECT AND SOFT OBJECTS

The results presented in Fig. 13c suggest that the lower and upper ends change as the softness of the object changes. In other words, it is preferable to increase the intensity of the Deforming-object effect as the softness of the object increases. Interestingly, applying the Deforming-object effect did not lead to a strange feeling even with the Melamine-faced MDF plate that the participants recognized as a hard object. In addition, three participants did not feel a sense of strangeness even at the maximum intensity for all soft objects. It is possible that the participants recognized that the visual information provided by the Deforming-object was natural without considering the original softness of the objects. Thus, the Deforming-object effect can alter a user's impression of an object when the user touches it with a projected virtual hand.

e: GENERAL DISCUSSION

An interesting finding throughout the experiment is that the common effective areas of all combinations of visual effects and objects are wide. For example, the mean value



(a) Uneven objects (b) Slippery objects (c) Soft objects

FIGURE 13. **(Top) Box plots indicating the lower and upper ends of the effective areas (*$p < 0.05$). (Bottom) Average effective areas. We drew the effective areas using the average of the lower end and the average of the upper end. Within the effective area, more than 50% of participants are likely to touch objects without experiencing a strange feeling.**

of the effective areas for the participants was a minimum of 0.31 for each object, and this width covered three of the eight intensities. In addition, the participants reported that although they perceived that their intensities were different from each other, they did not feel a sense of strangeness from those intensities. This indicates that the intensity of the visual effects can be set within a certain range when an object is touched with a projected virtual hand. Furthermore, the common effective area for all objects in each target sensation also existed (Shaking-finger: 0.205–0.396, Increasing-speed: 0.045–0.345, Deforming-object: 0.355–0.621, calculated in the condition of the average effective area). This suggests that by applying an intensity in the common effective area, users can feel that they are touching an object without a sense of strangeness.

C. RESOLUTION OF TACTILE SENSATION (Experiment C)

In this experiment, we measured the just noticeable differences (JNDs) of the visual effects to examine how many levels of tactile sensation a user was able to perceive within the effective area determined in Experiment B in Section IV-B when the projected virtual hand interact with objects presented in the real scene.

TABLE 3. **Parameter values of visual effects. We set the lower/upper end of the effective areas of the corresponding object as the minimum/maximum values. We used an MDF plate whose bump width was 12 mm as an uneven object; thus, we fixed the λ of the Shaking-finger at 12 mm..**

Shaking-finger	A_{real} [mm]	λ [mm]		
Minimum	0.182	12		
Maximum	1.026	12		
Increasing-speed	γ			
Minimum	1.04			
Maximum	1.97			
Deforming-object	r [mm]	$time$ [ms]	d [mm]	d_{shade}
Minimum	22.2	844	2.10	0.042
Maximum	63.4	459	4.88	0.119

1) VISUAL EFFECTS

We set one reference intensity and six comparison intensities for each visual effect by the following procedure. First, we set maximum and minimum values for each parameter of the visual effects. Table 3 presents these values. We set the reference intensity to $\alpha = 0.5$ in (4). In addition, we set six comparison intensities that varied by ±15%, ±30%, ±45% of the reference intensity; these values correspond the intensities at $\alpha = 0.275, 0.35, 0.425, 0.575, 0.65,$ and 0.725 in (4).

2) TARGET OBJECTS

For target objects touched by the virtual hand, we selected one of the objects used in Section IV-B as follows.

- Unevenness: MDF plate with a bump width of 12 mm (Fig. 8a (middle))
- Slipperiness: Bristol paper (Fig. 8b (middle))
- Softness: Polyethylene sponge (Fig. 8c (middle))

We prepared two objects for each sensation because each trial of the experiment required two identical objects.

3) EXPERIMENTAL SETUP AND PROCEDURE

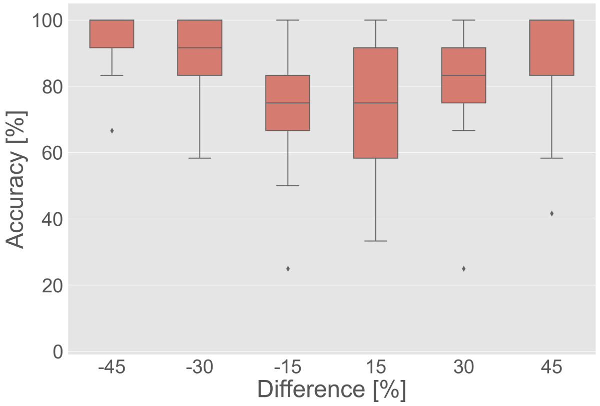
We used the JND methodology [34]. Each participant touched each of two objects (object A and object B) with a virtual hand, which produced visual effects of different intensities. Each participant then reported the object whose tactile texture he/she perceived more strongly. The experimental setup was the same as that of Experiment A described in Section IV-A.

Before starting the trials, we provided time for each participant to become accustomed to the operation of the projected virtual hand. In each trial, the participant touched objects A and B twice by manipulating the projected virtual hand. At that time, the participants manipulated the virtual hand with only their index fingers in the direction of the virtual hand's arm stretching and contracting as in Experiment A. The participant then answered "object A" or "object B" to the following questionnaire items corresponding to the tactile texture of the target objects:

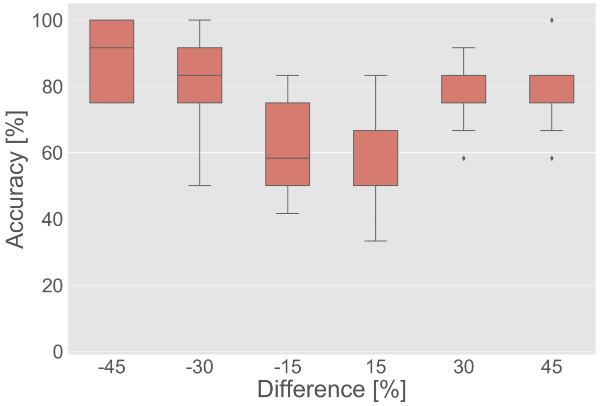
- For uneven object (Fig. 8a (middle))
  Comparing object A and object B, which one do you feel is more uneven?
- For slippery object (Fig. 8b (middle))
  Comparing object A and object B, which one do you feel is more slippery?
- For soft object (Fig. 8c (middle))
  Comparing object A and object B, which one do you feel is softer?

There were six comparison intensities for one reference intensity, and we set each of these combinations to be repeated 12 times. Thus, each participant performed 72 trials for each object. Because there were three target objects, the participant repeated this trial set three times (216 trials in total). We balanced the order and position in which each comparison intensity was provided. We also balanced the order in which each object was provided among participants.

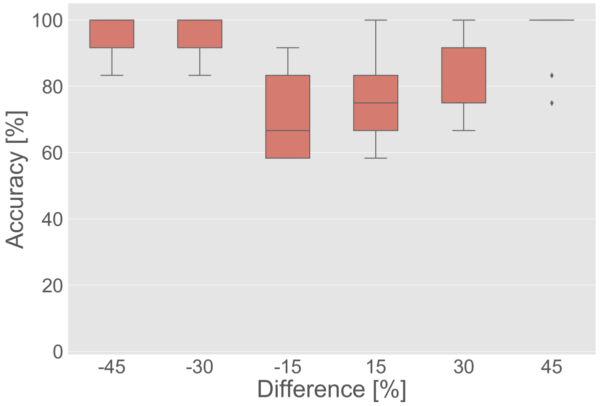
We recruited nine participants whose dominant hand was right and whose age ranged from 18 to 22 (eight males and one female). Each trial was approximately 10 s, and it took approximately 40 min to conduct all trials. We conducted an interview with each participant after the experiment. In total, it took 55 min for each participant to complete the procedures.



(a) Unevenness



(b) Slipperiness



(c) Softness

FIGURE 14. **Distribution of accuracy for each comparison intensity.**

4) RESULTS

When the intensity of the visual effect in object A is stronger than that in object B, the case in which a participant selects object A is considered the correct choice, and vice versa. We calculated the ratio of the number of correct choices to the number of iterations. Fig. 14 illustrates the distribution of the accuracy of the participants for each comparison intensity. For each sensation of unevenness, slipperiness, and softness, we performed an ANOVA with the comparison intensity as a factor. The ANOVA revealed significant differences for all three tactile sensations (unevenness: $F(5, 40) = 4.58$, $p < 0.01$, slipperiness: $F(5, 40) = 8.50$, $p < 0.01$, softness: $F(5, 40) = 13.49$, $p < 0.01$). A post-hoc analysis with

Bonferroni correction demonstrated the following significant differences ($p < 0.05$).

a: SHAKING-FINGER

A difference of -45% is significantly more accurate than that of $\pm 15\%$. A difference of -30% is also significantly more accurate than that of -15%.

b: INCREASING-SPEED

A difference of $\pm 45\%$ and -30% is significantly more accurate than that of $\pm 15\%$. A difference of $+30\%$ is significantly more accurate than that of $+15\%$.

c: DEFORMING-OBJECT

A difference of $\pm 45\%$ and -30% is significantly more accurate than that of $\pm 15\%$, and a difference of $+30\%$ is significantly more accurate than that of -15%.

We analyzed the JNDs that could be perceived by the participants. Instead of considering the accuracy value, we considered the rate at which the participants judged the comparison intensity created a stronger sensation than the reference intensity (see Fig. 15). We obtained the Weber fraction by fitting the psychometric curve (5) to the data. The A and B values for each factor were: $A = 1.47$ and $B = 18.0$ (Shaking-finger), $A = 2.36$ and $B = 26.1$ (Increasing-speed), and $A = 0.15$ and $B = 14.3$ (Deforming-object). We set the threshold for calculating the Weber fraction to 84%, and the Weber fraction for each tactile sensation was 0.299 (Shaking-finger), 0.433 (Increasing-speed), and 0.237 (Deforming-object).

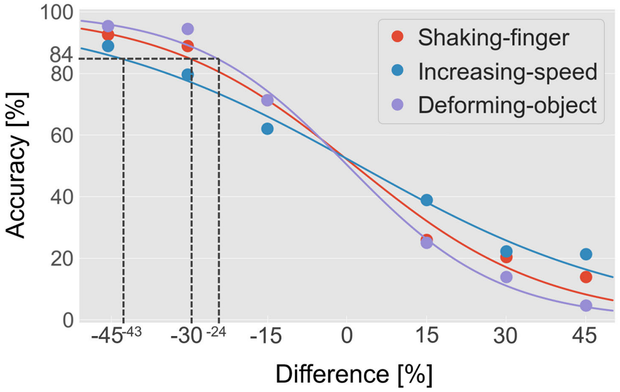


FIGURE 15. **Plot of the psychometric curve fitted to the data. The PSE for all curves matches the condition in which the difference between the reference intensity and comparison intensity is zero.**

Assuming that we can determine the resolution of tactile sensation using the Weber fraction, it can be concluded that the participants are able to perceive the Shaking-finger effect in four stages (0, 0.299, 0.598, 0.897), the Increasing-speed effect in three stages (0, 0.433, 0.866), and the Deforming-object effect in five stages (0, 0.237, 0.474, 0.71, 0.947) without feeling a sense of strangeness.

5) DISCUSSION

The higher the intensity of the visual effects was, the more strongly the participants perceived the corresponding tactile texture of the object. This result is consistent with the results of Experiment A. In addition, the larger the difference between the reference and comparison intensities was, the more accurately the participants recognized the difference.

A post-hoc analysis determined that differences of $+45\%$ and $+30\%$ were not significantly more accurate than $\pm 15\%$ in the unevenness sensation. We believe that this is due to individual differences in perceiving the Shaking-finger effect. For example, one participant reported that he selected a lower intensity as the intensity that made him feel that the object was more uneven because he felt a sense of strangeness when the intensity of the Shaking-finger effect was high.

The Weber fractions indicated that the proposed visual effects can express detailed tactile differences in order of 1: Deforming-object, 2: Shaking-finger, 3: Increasing-speed. The participants' comments supported this result. Many participants perceived the unevenness sensation by the movement width of the virtual hand's fingertip, the smoothness by the moving speed of the virtual hand, and the softness by the size, darkness, and time of the deformation effect. For the softness sensation, the Weber fraction decreased because there were many factors to judge. In contrast, for the slipperiness sensation, the Weber fraction became higher than other effects because the moving speed of the virtual hand depended on the operating speed of the participant.

V. GENERAL DISCUSSION

Although various types of visual effects can be designed for tactile sensations, we focused on three types of tactile sensations in this paper: unevenness, slipperiness, and softness. Okamoto *et al.* [29] reported that fine roughness and warmth are also the basic tactile sensations in addition to the three types of sensations discussed in this paper.

In this study, we designed and presented visual effects for three types of tactile sensations individually and confirmed their effectiveness. However, combining different visual effects has the potential to produce tactile sensations more efficiently.

Objects in the real world have various characteristics such as bump depth, glossiness, etc., besides bump width, static frictional force, and softness, which were handled in Experiment B. We focused on these characteristics in Experiment B, because we wanted to provide one of the guidelines underlying the setting of the intensity of the visual effects when the projected virtual hand touches an object. As a next step, we should create a model that sets up appropriate visual effects and their intensities, including the various objects' characteristics that we did not focus on in Experiment B.

In the experiments described in Section IV, the participants were allowed only limited manipulation of the projected virtual hand. In other words, they manipulated the virtual hand with only their index fingers in the direction of stretching and contraction and touched an object placed at a certain distance. On the other hand, in the actual use of the projected virtual hand interface, the user is assumed to move the virtual hand in various directions with various numbers of fingers and to touch an object in various locations. Therefore, we should investigate the effectiveness of our proposed method in a more varied condition and environment in future work. For reasons of the feedback comments of the participants in a conference exhibition of the system [12], we expected that the visual effects will work in a variety of conditions and environments.

We focused on the ability to provide tactile sensations of the visual effects and the provision of guidelines on how to incorporate the visual effects into projected virtual hand interfaces in this paper. However, we did not investigate in terms of either a sense of ownership or agency (that is, a sense that the user is manipulating the projected virtual hand). A future work should also investigate the influence of visual effects on the ownership and agency for a projected virtual hand. In the exhibition of the system [12], some participants commented that ownership and agency were improved by adding visual effects.

VI. CONCLUSION

In this study, we proposed a novel pseudo-haptic feedback method for providing users with tactile sensation of objects in a projected virtual hand interface without the use of haptic devices. We focused on the textures of objects and designed three visual effects: Shaking-finger for unevenness, Increasing-speed for slipperiness, and Deforming-object for softness. In Experiment A (Section IV-A), we demonstrated that visual effects make users feel each intended tactile sensation. In Experiment B (Section IV-B), we explored the intensity range in which users feel tactile sensations without experiencing a sense of strangeness. The results suggested that although the intensity range is affected by the object's characteristics, we found a common intensity range according to the property of the target object used in Experiment B. We also investigated the resolution of tactile sensations in the appropriate intensity ranges in Experiment C (Section IV-C). The results suggested that users can perceive tactile sensations at a maximum of five stages without a feeling of strangeness using only visual information. In summary, our proposed method achieves various tactile sensations without haptic devices in the projected virtual hand interface.

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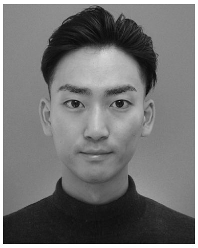

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