Pseudo Tactile Feedback for Extended Hand Users

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September 2024

Pseudo Tactile Feedback for Extended Hand Users

A dissertation submitted to
GRADUATE SCHOOL OF ENGINEERING SCIENCE
OSAKA UNIVERSITY
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY IN ENGINEERING

by
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September 2024

Abstract

Human hands can interact with external objects and perceive their properties. However, physical distance fundamentally limits these functions and cannot be used for objects out of reach. The ExtendedHand interface partially overcomes this limitation by projecting a computer graphics (CG) hand into real space, which users can intuitively control. This enables users to point at or gesture toward objects beyond their physical reach using the projected CG hand (extended hand). On the other hand, users cannot perceive the tactile sensations of the objects touched by the extended hand.

This dissertation aims to realize a solution that allows users to feel the tactile sensations of objects touched by the extended hand by utilizing pseudo-haptic feedback that allows users to perceive pseudo-tactile sensations from visual and auditory stimuli. This approach enables users to experience the tactile sensations of various objects that are typically out of their reach without the need for haptic devices.

To demonstrate this concept, I undertook three initiatives: First, I proposed a method to add a visual effect to the extended hand when it touches an object and to make the user perceive the object's tactile sensation from the visual feedback. I designed three visual effects that provide the sensations of unevenness, slipperiness, and softness, respectively. Through user studies, I demonstrated that these visual effects can effectively convey tactile sensations.

Second, I focused on a method to playback a sound texture (a sound produced when an object is traced) from speakers or headphones to make the user feel the tactile sensations of objects. I explored appropriate sound texture feedback design in situations where users touch a distant object with the extended hand, which users have never experienced. Through user studies, I established design guidelines for sound textures that make users naturally feel the tactile sensations of objects.

Lastly, I developed a system that automatically estimates suitable visual effects for touched objects using an RGB-D camera and deep learning to broaden the applicability of this tactile feedback method. Through a user evaluation, I showed that the proposed system effectively allows users to perceive tactile sensations of the touched objects without prior information about objects in the scene.

These efforts overcame the physical limitations of the human hand in not being able to feel the tactile sensations of unreachable objects.

Preface

The publications arising from the studies presented in this thesis are enumerated below:

Pseudo-Haptic Feedback in a Projected Virtual Hand for Tactile Perception of Textures (Yushi Sato, Naruki Tanabe, Takefumi Hiraki, Parinya Punpongsanon, Haruka Matsukura, Daisuke Iwai, Kosuke Sato, *IEEE WHC*, 2019)
This work is related to Chapter 2. I submitted this work to the poster and demo sessions of *IEEE WHC 2019* [1]. I wrote the manuscript, produced the supplementary media, and submitted this work, under the supervision of Dr. Hiraki, Dr. Ponpongsanon, Dr. Matsukura, Dr. Iwai, and Dr. Sato.

Modifying Texture Perception with Pseudo-Haptic Feedback for a Projected Virtual Hand Interface: (Yushi Sato, Naruki Tanabe, Takefumi Hiraki, Haruka Matsukura, Daisuke Iwai, Kosuke Sato, *IEEE Access*, 2020)
The Chapter 2 of this thesis is published as [2]. This work is the updated version of the paper published in the poster and demo sessions of IEEE WHC 2019. I have conceived the initial idea of the project under the guidance of Dr. Sato. I also implemented and conducted experiments, and wrote the manuscript under the supervision of Dr. Hiraki, Dr. Matsukura, Dr. Iwai, and Dr. Sato.

Sound Texture Feedback for a Projected Extended Hand Interface: (Yushi Sato, Daisuke Iwai, Kosuke Sato, *IEEE Access*, 2024)
The Chapter 3 of this thesis is published as [3]. I have conceived the idea and designed and conducted experiments, and wrote the manuscript under the supervision of Dr. Iwai, and Dr. Sato.

Responsive-ExtendedHand: Adaptive Visuo-Haptic Feedback Recognizing Object Property with RGB-D Camera for Projected Extended Hand: (Yushi Sato, Daisuke Iwai, Kosuke Sato, *IEEE Access*, 2024)
The Chapter 4 of this thesis is published as [4]. I have conceived the idea and implemented and conducted experiments, and wrote the manuscript under the supervision of Dr. Iwai, and Dr. Sato.

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List of Abbreviations

ANOVA	Analysis of Variance
B-F	Bending-finger
C/D	Control-Display
CG	Computer Graphics
CI	Confidence Interval
D-O	Deforming-object
GT	Ground Truth
I-S	Increasing-speed
MAE	Mean Absolute Error
MP	MetacarPophalangea
MR	Mixed Reality
S-F	Shaking-finger
RGB-D	RGB-Depth
VR	Virtual Reality

Chapter 1

Introduction

Human hands can interact with external objects and perceive their properties. However, these functions are fundamentally limited by physical distance and cannot be used for objects that are out of reach. ExtendedHand [5] is a human augmentation technology that partially overcomes this constraint by projecting a computer graphics (CG) hand into real space, which users can intuitively control. This allows users to point at or gesture toward objects beyond their physical reach using the projected CG hand (extended hand). On the other hand, users cannot perceive the tactile sensations of the objects touched by the extended hand.

In this dissertation, I aim to realize a novel solution that allows users to feel the tactile sensations of objects touched by the extended hand by utilizing pseudo-haptic feedback [6]. This approach enables users to experience the tactile sensations of various objects that they would not otherwise be able to touch, without wearing specialized devices.

This chapter outlines the research background, objectives, essential challenges, contributions, and the structure of this doctoral dissertation.

1.1 Projection-Based Arm Extension Interface: ExtendedHand

The body and sensory organs act as interfaces that connect the individual with the external environment. We interact with the world and gather information through our bodies and sensory organs. Our bodies and sense organs are physical entities from birth and, therefore, have physical limitations. For example, we humans cannot see infrared light, hear ultrasonic waves, or feel the touch of distant objects that are out of our reach.

Human augmentation is a technology that enhances the human body's and sensory organs' capabilities [7, 8, 9]. This field goes beyond simply using technology to increase convenience; it emphasizes the seamless integration of humans and technology to form a unified entity. Industrially, it is expected to not only increase productivity at work but also to transform traditional human behavioral patterns and support the realization of each individual's ideal lifestyle [10]. Human augmentation is still in its early stages, with various technologies being developed to extend different human capabilities. These enhancements include devices that allow us to perceive normally invisible phenomena, such as infrared [11] and the underside of obstacles [12, 13], as well as technologies that enhance physical abilites, such as powered suits [14], or provide additional body part like a third arm [15, 16, 17]. One of the technologies is ExtendedHand, which employs projection-based augmented reality technology to visually extend the user's hand in everyday indoor situations [5, 18, 19].

The ExtendedHand interface senses the user's hand movements through a camera [5, 18] or a touch panel [19], amplifies these movements and reflects them in the movements of a computer graphics (CG) hand, which is then projected into real space using a projector. I refer to this projected CG hand as the "extended hand". Due to the nature of projection, the extended hand can be displayed over a wide area in real space, allowing the user and others to view it without wearing a device such as a head-mounted display [20, 21]. This allows the user to perform actions such as pointing at or gesturing towards objects that are beyond their physical reach with the extended hand. Psychological studies have indicated that users experience a sense of body ownership towards the extended hand, similar to the rubber hand illusion [22] or virtual hand illusion [23], where users feel the extended hand as their own.

To date, ExtendedHand applications have been developed to facilitate communication among users and others in various situations. Examples include ExtendedHand-equipped wheelchairs for users with mobility difficulties [24, 25], ExtendedHand for tremor patients to point at objects accurately [26]. Furthermore, an application has been proposed to intuitively operate home appliances by integrating the Internet of Things into ExtendedHand [19].

As introduced, ExtendedHand naturally extends the range of actions that humans can perform with their hands toward objects, excluding actions that physically move physical objects. Here, human hands also have a sensory role in recognizing the properties of objects in addition to performing actions. In ExtendedHand, the extended hand is superimposed over physical objects (in this thesis, it is described as "the extended hand touches objects"). However, during this interaction, users only receive visual information and cannot feel the tactile sensation of the objects.

1.2 Tactile Feedback for Surrogate Hands

Providing tactile feedback to users when a surrogate hand touches or is touched by an object is beneficial from various perspectives. In the context of the rubber hand and virtual hand illusions, presenting tactile feedback synchronized with visual information is crucial for users to experience a sense of body ownership toward the surrogate hands [22, 23, 27]. Additionally, presenting tactile information to users with a surrogate hand has improved task performance [28, 29] and enhanced the immersion and realism of experiences [30, 31]. Furthermore, tactile feedback allows users to experience normally unattainable sensations, such as feeling the texture of virtual objects [21, 32, 33] or objects located remotely [34, 35, 36].

In ExtendedHand, allowing users to feel the tactile sensations of objects touched by the extended hand would enhance the realism of the extended hand experience and improve task performance. Furthermore, it enables users to experience touching objects such as stuffed animals placed in high places, animals in zoos, or exhibits in museums that are typically out of reach or where touching is prohibited.

The most common method for enabling users to feel the tactile sensations of objects touched by a surrogate hand is using haptic feedback devices [21, 31, 32, 33, 34, 35, 36]. Typically, users either wear specialized haptic feedback devices on their hands or place their hands in a designated location. These devices then provide appropriate tactile stimuli synchronized with the surrogate hand's interaction with the objects. In ExtendedHand, several studies have used specialized haptic feedback devices to provide the tactile sensations of objects touched by the extended hand, enhancing the sense of body ownership and the realism of object interactions [37, 38].

These methods, which utilize haptic feedback devices, can accurately replicate the physical sensations experienced when an actual hand touches an object, offering realistic and precise tactile feedback. However, users may feel inconvenienced as they must continuously wear these devices or have a limited range of hand movements in order to receive tactile feedback. Particularly in everyday life scenarios that ExtendedHand primarily targets, where precise tactile accuracy is less critical, the practicality of continuously constraining users' hands with these devices may be challenging.

1.3 Vision of This Thesis

I believe that for human augmentation technology to become widely adopted and consistently experienced in everyday life, it is crucial that it does not impose any physical burden on users. Therefore, this doctoral thesis aims to establish a solution that allows users to feel the tactile sensations of various objects touched by the extended hand without needing to wear any specialized devices. The key idea for achieving this is based on *pseudo-haptic feedback* [6, 39]. Pseudo-haptics refers to the phenomenon where visual information is prioritized when it conflicts with tactile information, leading the user to perceive consistent pseudo-tactile information. Pseudo-haptic feedback is a technique that modulates visual feedback to create a contradiction with tactile information, thus enabling the user to perceive the desired tactile information through pseudo-haptics. Moreover, pseudo-haptic feedback based on auditory feedback has also been reported [40, 41]. I apply pseudo-haptic feedback to the ExtendedHand, enabling users to perceive the tactile sensations of objects without direct tactile stimulation. Figure 1.1 illustrates the difference between the conventional approach to providing the tactile sensation of objects and the approach used in this study.

Specifically, in the application scenarios for ExtendedHand, images of the extended hand generated by a computer are projected as the extended hand from a projector. These images can be easily modified. Additionally, sound can be readily provided to the user using commonly available audio devices such as headphones or speakers. This research focuses on adding visual effects to the projected extended hand and utilizing texture sounds, which trace objects, to allow users to perceive the tactile sensations of objects touched by the projected hand through visual and auditory stimuli.

Furthermore, in order to provide appropriate visual and auditory feedback for the objects touched by the extended hand, it is crucial to recognize these objects and estimate the appropriate feedback. In this study, I propose a system to generate the appropriate feedback using an RGB-D camera and deep learning.

Through these efforts, I overcome the limitation that we cannot feel the tactile sensations of unreachable objects without the need for specialized devices. Figure 1.2 provides an overview of this doctoral thesis, while Fig. 1.3 shows the content of each chapter.

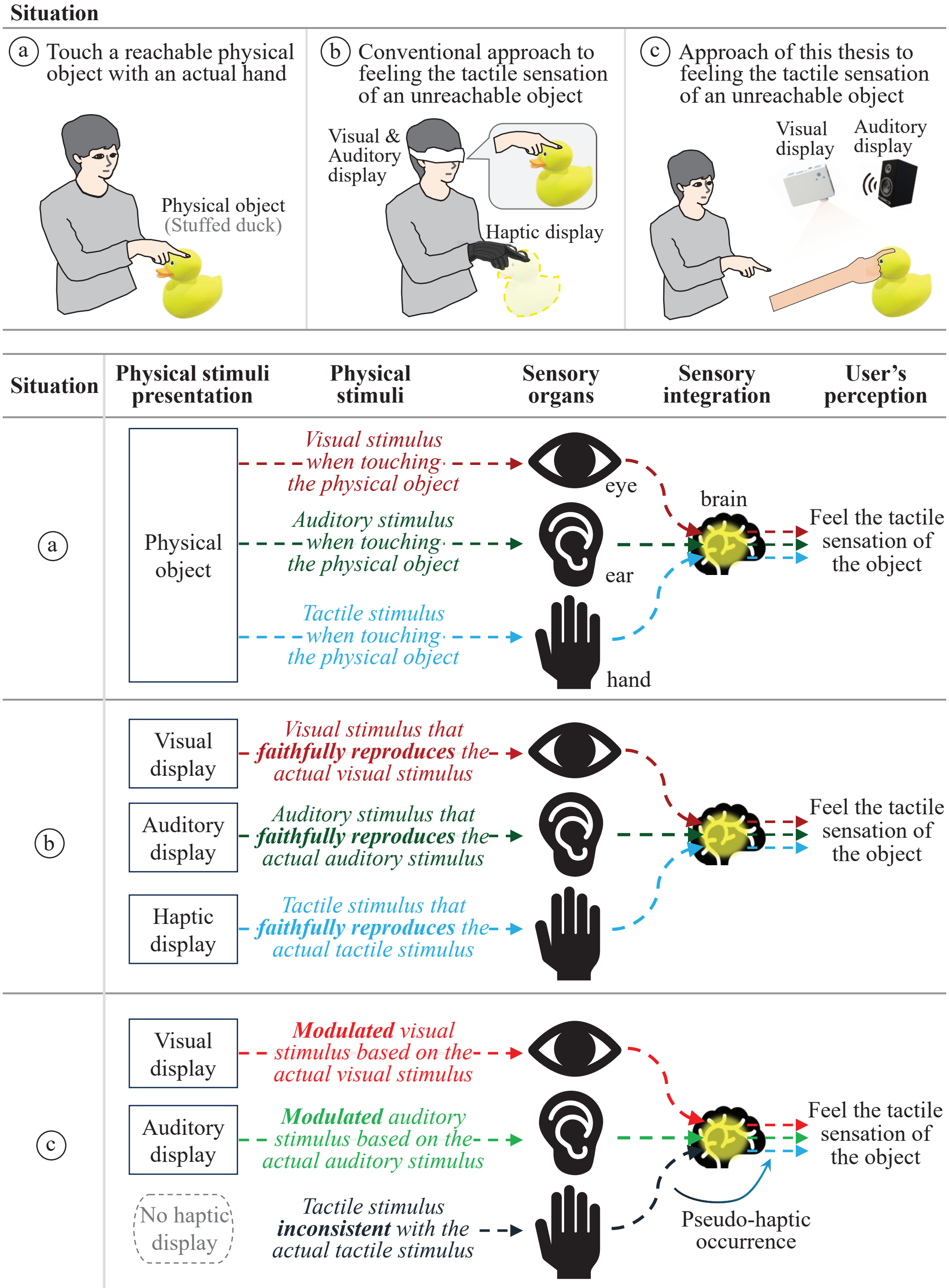


Figure 1.1: Tactile feedback approach of this thesis. The conventional approach emphasizes matching the stimuli feedback to the user with the actual stimuli. In contrast, this study's approach does not emphasize matching the feedback stimuli with the actual stimuli. Instead, it aims to generate pseudo-haptic sensations through sensory integration in the user's brain, ultimately aligning the user's final perception with the intended tactile experience.

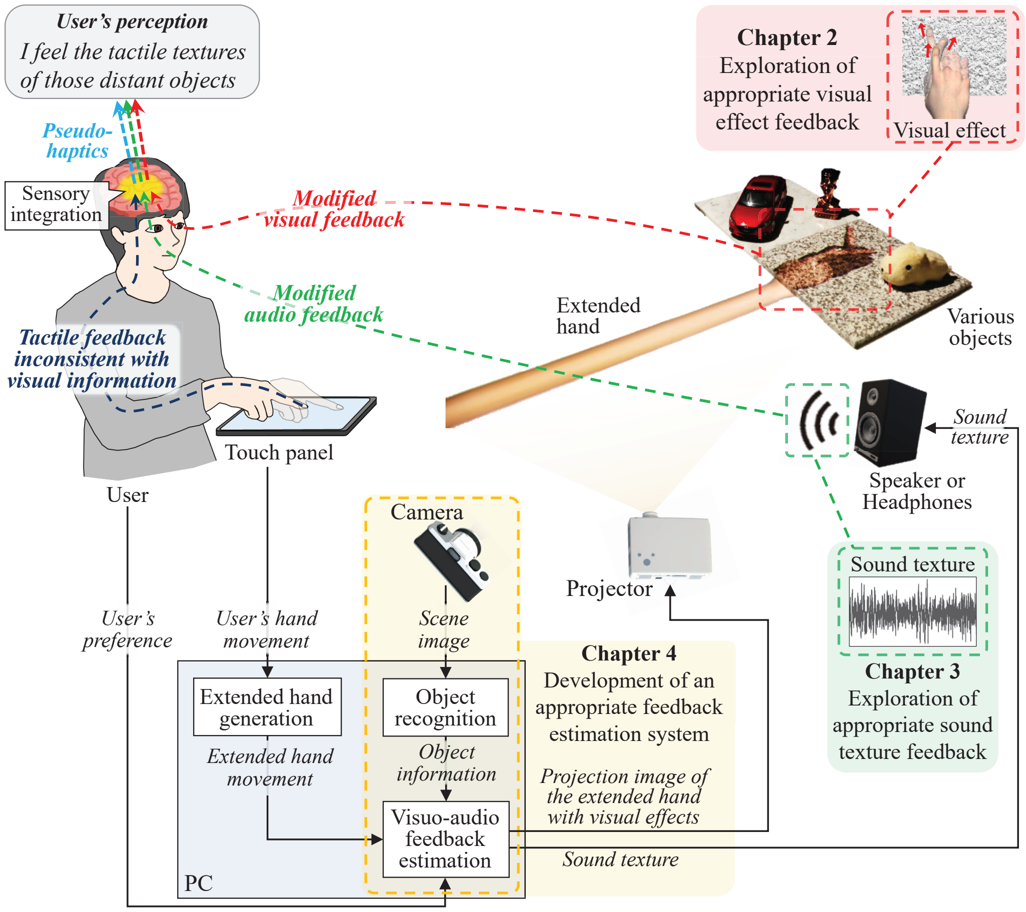


Figure 1.2: Overview of this thesis. This thesis aims to enable users to feel the tactile sensations of objects beyond their physical reach without wearing haptic feedback devices. ExtendedHand allows users to touch unreachable objects with the extended hand, but users cannot feel the tactile sensation of the object touched by the extended hand; users receive the tactile sensation of only a touch panel surface for controlling the extended hand. In this thesis, I add visual effects to the extended hand and playback sound textures through headphones or loudspeakers. When users receive this modulated visual and auditory feedback, their brains override the actual tactile sensation (sensations of touch panel surface) and induce pseudo-haptics. Finally, users can perceive the tactile sensation of the object touched by the extended hand.

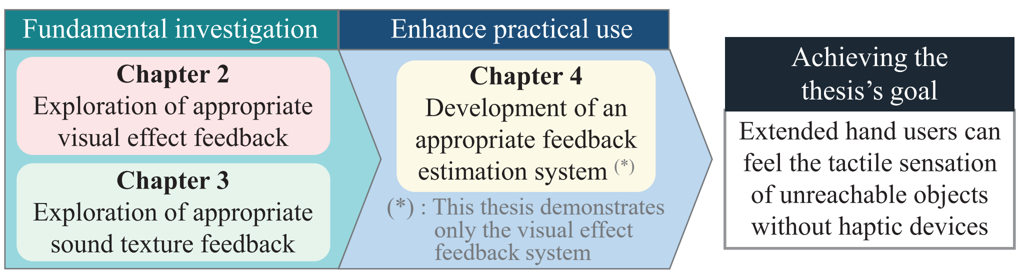


Figure 1.3: Structure of this thesis.

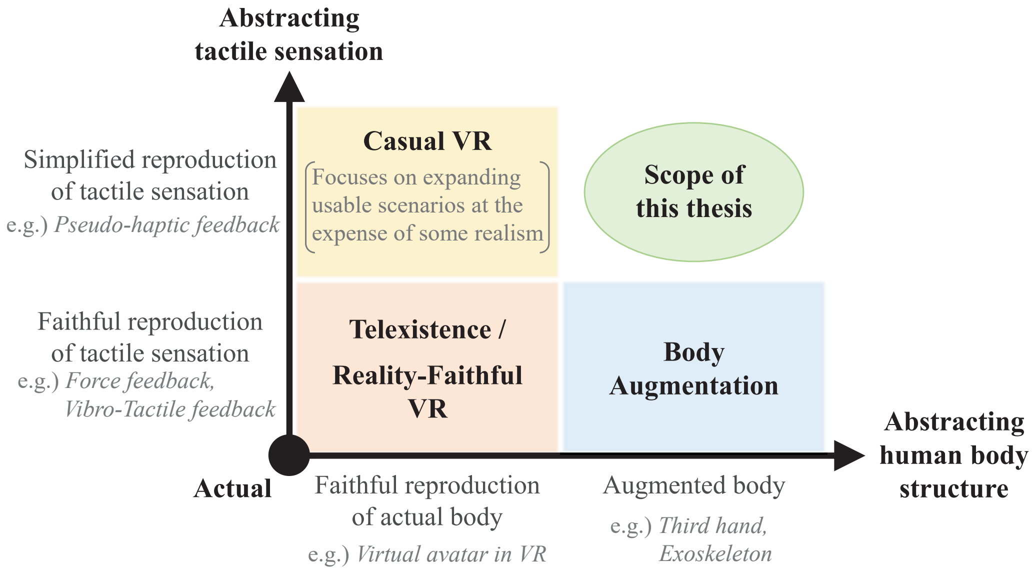


Figure 1.4: Positioning of this thesis within related academic fields.

1.4 Essential Challenges of This Thesis

Figure 1.4 illustrates the positioning of this research within related academic fields. As introduced in Section 1.1, body augmentation technologies are currently being studied in various ways. However, nearly all these efforts either implicitly ignore feedback for augmented bodies or adopt actual tactile feedback [5, 15, 16, 17]. Similarly, pseudo-haptic feedback was initially developed in the field of graphical user interfaces, such as mouse displays [6, 42, 43], and has since been widely applied to actual hands [44, 45] and one-to-one scale virtual hands [46, 47]. However, it has yet to be applied to augmented bodies. This dissertation addresses the largely unexplored area of applying pseudo-haptic feedback to augmented bodies.

A key challenge in this study is clarifying what visual and auditory feedback is appropriate for generating pseudo-haptic sensations for users with augmented bodies. Users perceive the extended hand as their own extended “hand” that they can manipulate freely. However, as shown in Figure 1.5, the extended hand differs from an actual hand in terms of appearance, body structure, and sensory inputs. Consequently, the experience of touching objects with the extended hand is distinct from the experience of touching objects with an actual hand. In such situations, what kind of visual and auditory feedback would enable users to perceive the tactile sensations of objects naturally? Should the feedback mimic the experience of touching with an actual hand, or should it employ an exaggerated, unrealistic representation? Chapters 2 and 3 of this thesis reveal the design of visual and auditory feedback suitable for users with the extended hand.

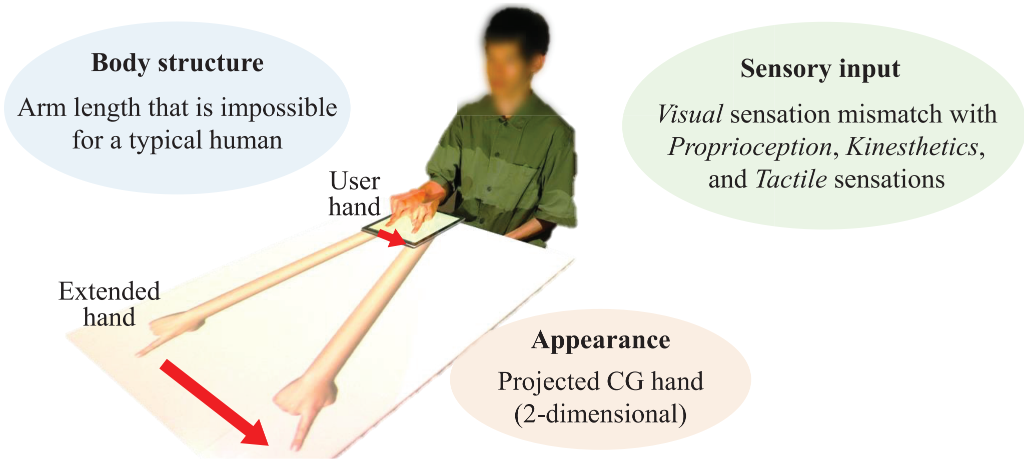


Figure 1.5: Difference between an actual hand and the extended hand.

As the study progresses, it becomes evident that the appropriate visual and auditory feedback for users with the extended hand often requires exaggerated changes compared to the changes that occur when touching objects with their hands. Furthermore, the degree of this exaggeration depends not only on the physical characteristics of the touched objects but also varies significantly based on individual user preferences. In Chapter 4, I address the challenge of developing a system that can estimate the appropriate feedback for each user, considering both the properties of the objects and the users' preferences.

In this doctoral thesis, I overcome these challenges and identify design guidelines and practical implementation methods for visual and auditory feedback that allow users to perceive the tactile sensations of various objects without disrupting their extended hand experience.

1.5 Contributions

The main contribution of this thesis is developing a solution that enables users to perceive the tactile sensations of distant objects without wearing any devices. Another contribution of this thesis is the clarification of appropriate visual and auditory feedback for users with the extended hand that, while mimicking human hands, is distinct from them. This feedback ensures that users can perceive the tactile sensations of objects without disrupting their extended hand experience. The broad contribution is organized in the remaining chapters of this thesis as *design of visual effect feedback for extended hand users*, *design of sound texture feedback for extended hand users*, and *Development of an Appropriate Feedback Estimation System*.

Design of Visual Effect Feedback for Extended Hand Users

Pseudo-haptic feedback is a field that originated from mouse display systems, and methods for presenting various tactile sensations in a variety of situations have been investigated. Nevertheless, the exploration of presenting different tactile sensations to a surrogate hand, which the user feels as their own, has been scarce.

In Chapter 2, I design three visual effects tailored explicitly to the "extended hand" by extracting the core findings from related research on pseudo-haptic feedback. These three visual effects aim to convey sensations of unevenness, slipperiness, and softness, respectively. I demonstrate the effectiveness of these visual effects in conveying the corresponding tactile sensations through a user study. Furthermore, through additional user studies, I identify guidelines for setting up visual effects that do not disrupt the user's extended hand experience and show that the intensity of the tactile sensation perceived by users can be modulated on several levels.

Design of Sound Texture Feedback for Extended Hand Users

As discussed in Section 1.4, although ExtendedHand enables users to touch objects beyond their physical reach by using the extended hand, the experience differs from touching an object with their hand.

In Chapter 3, I clarify whether sound texture feedback in such experiences should adhere to the laws of the physical world or be based on augmented rules. Specifically, through a user study, I demonstrate that the sound pressure of sound textures should apply a distance attenuation law similar to real-world physics. Additionally, another user study shows that when the extended hand slowly traces an object, the sound texture feedback should match the speed of the extended hand's movement. On the other hand, when the extended hand traces an object quickly, the sound texture feedback should correspond to a slower speed than the actual speed of the extended hand to ensure that the user perceives the object's tactile sensation naturally.

Development of an Appropriate Feedback Estimation System

For the practical application of the proposed tactile feedback method, it is essential to recognize objects touched by the extended hand and estimate the appropriate visual and auditory feedback for them. Results of Chapters 2 and 3 indicate that the appropriate visual and auditory feedback needs to exaggerate the phenomena experienced when touching objects with actual hands, and this exaggeration must be customized to each user.

In Chapter 4, I propose an automated visual effect estimation system for ExtendedHand that incorporates an RGB-D camera and deep neural networks. This system is trained with user preference data to estimate visual feedback tailored to individual users. Through a user evaluation, I demonstrate the proposed system can that estimate visual effects suitable for both the object and the user, allowing users to naturally perceive the tactile sensations of objects, even in scenarios where ExtendedHand does not have information about the objects in the scene.

1.6 Outline of Dissertation

The remaining chapters of this dissertation are structured as follows:

Chapter 2. Visual Effect Feedback for Extended Hand Users. This chapter addresses methods for inducing perceptions of tactile sensations from visual information. Specifically, this chapter proposes visual effect designs to elicit sensations of three textures: roughness, smoothness, and softness. Additionally, this chapter evaluates the tactile presentation capabilities of these visual effects and considerations for their implementation through user studies.

Chapter 3. Sound Texture Feedback for Extended Hand Users. This chapter explores methods of enabling users to perceive tactile sensations through sounds emitted via headphones or speakers. Specifically, this chapter reveals how to appropriately set the sound pressure and timbre of sound textures in scenarios where users touch objects using the projected extended hand, rather than their actual hands, through user studies.

Chapter 4. Adaptive Pseudo Tactile Feedback System for Extended Hand Users. This chapter focuses on generating visual effects suitable for touched objects, even in scenarios where ExtendedHand does not have information about the object's location or type in the scene. To achieve this, I propose a system combining RGB-D cameras with deep learning called Responsive-ExtendedHand. Through a user study, I demonstrated the prototype's performance in estimating suitable visual effects.

Chapter 5. Discussion and Conclusion. This chapter summarizes this thesis's efforts, contributions, and limitations and outlines future research directions.

Chapter 2

Visual Effect Feedback for Extended Hand Users

In this chapter, I introduce the work on applying pseudo-haptic feedback based on visual effects to the ExtendedHand interface. This method enables users to perceive the texture, such as unevenness, smoothness, and softness of objects touched by the extended hand, without the need for any wearable devices.

The chapter opens with an exploration of the motivation behind the work, followed by a review of related studies on pseudo-haptic feedback. I then describe the design of three types of visual effects developed to enhance tactile perception. Subsequently, I present user studies that evaluated the tactile presentation capabilities of each visual effect and discuss the considerations necessary for their implementation.

2.1 Introduction and Motivation

As stated in Chapter 1, this doctoral thesis aims to enable users to perceive the tactile sensations of objects touched by the extended hand without haptic devices. To achieve this, I focus on pseudo-haptic feedback, which provides modulated visual information to users and causes users to perceive pseudo-haptic information. Pseudo-haptic feedback was first reported by Lécuyer *et al.* [6] and has since been employed in various studies to deliver a range of tactile sensations to users in different contexts. However, the exploration of providing various tactile sensations through a surrogate hand perceived as part of one's own body, such as the extended hand (projected CG hand) targeted in this thesis, has been less explored.

This chapter proposes a pseudo-haptic feedback method that enables users of the extended hand to perceive various tactile sensations of the objects it touches. Specifically, I add visual effects to the images of the extended hand when it touches an object. From the visual information of the extended hand with visual effects touching the object, users are induced to feel the tactile sensations of the object (refer to Figure 1.2 in Chapter 1 for details).

A preliminary study [1] designed six types of visual effects and performed a qualitative evaluation. In this chapter, I introduced three refined visual effect designs that aim to provide roughness, slipperiness, and softness sensations. Further, I evaluate each proposed visual effect, demonstrating that it allows users to perceive the corresponding tactile sensation. It also clarifies considerations when adding visual effects to the extended hand and the range of tactile sensations that can be expressed.

2.2 Related Work on Pseudo-Haptic Feedback

Since the study by Lécuyer *et al.* in 2000 [6], which modulated the stiffness of a virtual spring on a screen using pseudo-haptic feedback, various methods have been proposed to provide users with different tactile sensations in various situations using pseudo-haptic feedback [44, 48, 49]. In the early stages of pseudo-haptic feedback research, systems primarily focused on using displays and mice. Notably, methods were proposed to present various tactile sensations by adaptively changing the ratio of the user's hand movement to the mouse cursor's movement on the display (referred to as the C/D ratio). These sensations included the stiffness of virtual springs on the display [6], bump and hole shapes [42], resistance, and wind flow [42, 43]. Additionally, Argelaguet *et al.* [48] proposed a method that changes the perceived softness by deforming the image content on the display to appear concave when the user clicks on it with a mouse.

Subsequently, methods for using pseudo-haptic feedback in various scenarios beyond mouse-display systems have also been proposed. Achibet *et al.* [46, 50] proposed a method to allow users to enhance haptic perception without interaction limitations in VR by combining simple and cost-effective haptic devices with pseudo-haptic effects. Ban *et al.* [49, 51] changed the size and shape of a physical object as perceived by users by deforming the image of the user's hand and the object when the user touches the physical object in the MR environment. Issartel *et al.* [52] changed the weight of a virtual object using a virtual effector in the MR system. Ho *et al.* [45] and Punpongsanon *et al.* [44] changed warmth and softness perception using projection-based MR systems. Although pseudo-haptic feedback has been utilized in various interfaces, including VR systems, no studies have aimed to produce haptic sensations for extended hand interfaces.

I aim to provide users with tactile sensations of objects without physical haptic devices by using pseudo-haptic feedback techniques for the projected CG hand (extended hand).

2.3 Method

I propose a pseudo-haptic method for allowing ExtendedHand users to feel tactile sensations by adding a visual effect to the extended hand. For the ExtendedHand interface, I utilized the touch-panel-based ExtendedHand proposed by Ueda *et al.* [19]. Users can manipulate the extended hand, which is projected from a video projector, by moving their hand on the touch panel (see Fig. 1.2).

Several studies on rubber hand illusion and virtual hand illusion have shown that it is crucial for the virtual hand to move synchronized with the user's hand movements [27, 53, 54]. Based on this finding, an important design guideline for the visual effects is to change the movement and structure of the extended hand to match the movement of the user's hand to the extent that the user can imagine it. Sudden changes in the extended hand may make the user unable to resolve why the extended hand changes and the user would find the extended hand strange, thereby degrading the reality of the user's body augmentation experience. In the following subsections, I will introduce the design and implementation of visual effects aimed at providing tactile sensations of objects.

2.3.1 Design of Visual Effects

I propose three visual effects that can provide three tactile sensations: unevenness, slipperiness, and softness. These are the basic sensations that constitute tactile sensations[55]. I 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".

Shaking-finger (S-F)

I applied vibration to produce the tactile sensation of unevenness. Touchy [56] demonstrated that vibrating a white cursor on a display made users feel the sensation of unevenness. In the Shaking-finger effect, only the fingertip of the pointing finger shakes. Figure 2.1 illustrates the Shaking-finger effect applied to a extended hand. I implemented the Shaking-finger effect by rotating the metacarpophalangeal joint (third joint) of the pointing finger touching an object according to the following equation:

$$Rot_Y = A_v \sin(2\pi t \|\vec{v}\|/\lambda), \quad (2.1)$$

$$Rot_Z = A_v \cos(2\pi t \|\vec{v}\|/\lambda), \quad (2.2)$$

where Rot_Y, Rot_Z are the rotation angles about the Y-axis and Z-axis in Fig. 2.2, respectively. In addition, t is the elapsed time after the extended hand touches the object, v is the speed of the extended hand, and λ is the average distance from the center of a bump to the center of the next bump

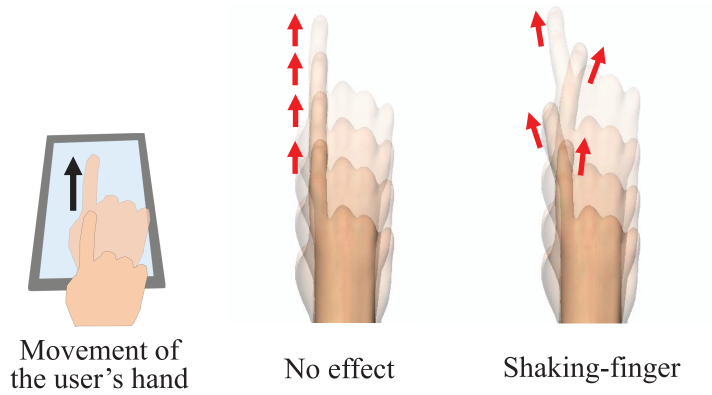


Figure 2.1: Extended hand image applying the Shaking-finger effect. When the extended hand moves, the touching finger of the extended hand shakes.

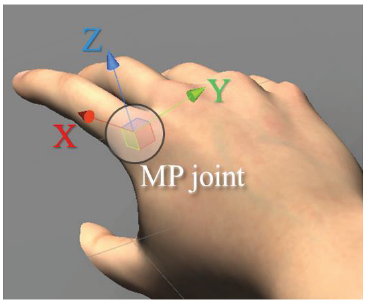


Figure 2.2: Coordinate system of the metacarpophalangeal (MP) joint (third joint).

in an uneven object with many bumps. A_v [rad] is a variable that determines the amplitude of the shaking, and it is calculated by the following equation:

$$A_v = \begin{cases} G_A A_{real}(v/\lambda)^2 & (v/\lambda < th) \\ G_A A_{real} & (v/\lambda \geq th), \end{cases} \tag{2.3}$$

where A_{real} [mm] is a value representing the maximum movement width of the fingertip in a real environment, and G_A [rad/mm] is a coefficient that converts A_{real} [mm] to angle [rad]. th [1/s] is a threshold for changing the behavior of A_v. When the moving speed of the extended hand is slow (satisfy $v/\lambda < th$), the shaking amplitude is set to be small. In this chapter, I set the parameter th to 1. The adjustable parameters are A_{real}, which determines the shaking amplitude of the fingertip, and λ, which represents the unevenness of objects.

Increasing-speed (I-S)

For producing a slippery sensation, I designed the Increasing-speed effect, which increases the moving speed of the extended hand when it

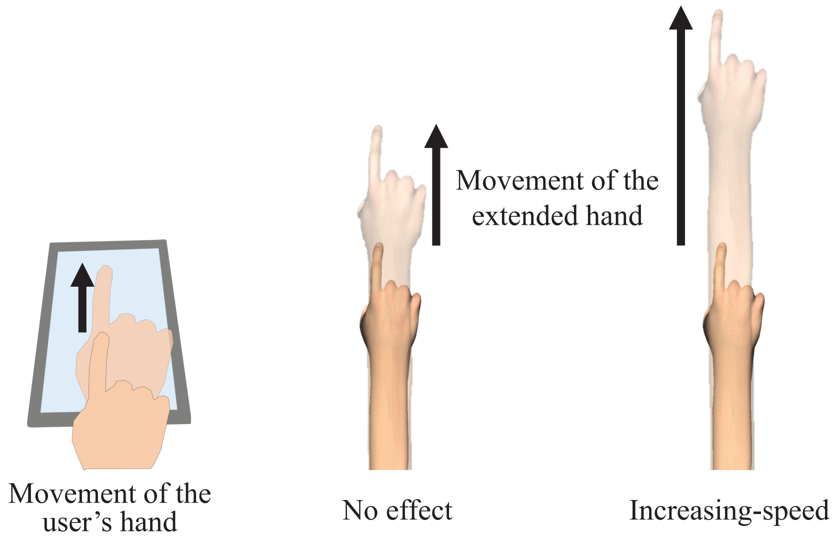


Figure 2.3: Increasing-speed effect. The moving speed of the extended hand is increased when the extended hand touches an object.

traces an object (see Fig. 2.3). This effect was designed based on the fact that when a person moves their finger with a certain force while touching an object, the moving distance of their finger increases as the touched object becomes more slippery. I focused on modulating the C/D ratio, which is frequently used in pseudo-haptic feedback studies. I 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.

Deforming-object (D-O)

For producing the softness sensation, I designed the Deforming-object effect to deform an object to make it appear concave. I focused on studies in which softness perception can be controlled by changing the appearance and shape of object surfaces [44, 48]. I implemented this visual effect using the Deformation Lamps technique [57]. The 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.* [48], and 3) create a luminance motion image from the reference image and pseudo-concave image. Figure 2.4 displays an image of the extended hand with the Deforming-object effect.

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]

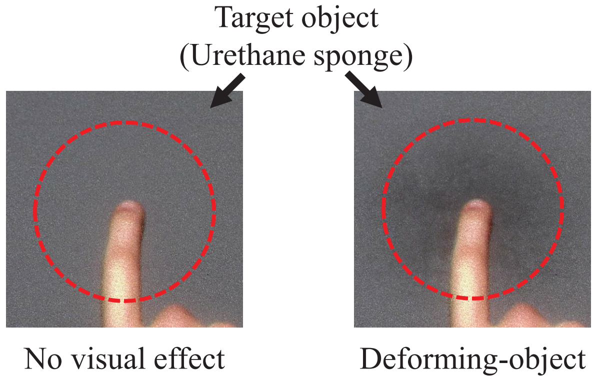


Figure 2.4: Deforming-object effect. An object touched by the extended hand is deformed so that it appears concave.

is the maximum amount of texture deformation. These parameters are defined by the method of Argelaguet *et al.* [48].

The parameter d_{shade} is the darkness of shade. According to the Shadows and Creases proposed by Argelaguet *et al.* [48], I also added the shade effect to the pseudo-concave image (I fixed the parameter K at 10, which is the number of creases). I determined that the shade created by this method was dark under the projection environment; thus, I 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.* [48]. 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 $d_{shade} = 0$.

2.4 Experiments

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

2.4.1 Experimental System

I implemented a prototype system of the extended hand interface with pseudo-haptic feedback used in the experiments. I used a hand model created by SuperDasil as the extended hand[1], and controlled the extended hand and visual effects using Unity 2019. I used a PC with a touch panel

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

Table 2.1: Parameter values of visual effects. I set low and high levels so that participants could clearly discriminate 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

(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.

I set the C/D ratio of the extended hand to 1:5. This signifies that the extended hand moves 50 mm when the user's hand moves 10 mm on a touch panel. I measured the delay time from the touch panel input to the extended hand movement, and the result was 150 ms. Shimada *et al.* [58] reported that ownership did not decrease when the delay time was less than 200 ms. The delay time of the system satisfies this requirement, and none of the participants reported problems with delay of the movement of the extended hand during the experiments.

2.4.2 Sufficiency of Visual Effects (Experiment A)

I investigated whether the proposed visual effects led users to feel my intended tactile sensations. I also explored whether the users' perception changed by modifying the intensity of the visual effects.

Visual effects and hypotheses

I created two intensity levels, high and low, for each of the three visual effects (Shaking-finger, Increasing-speed, and Deforming-object described in Section 2.3.1). Table 2.1 presents the parameter values for each visual effect. I selected low and high values so that participants could clearly discriminate the differences between the two levels. In addition, I added the "no visual effect" condition as the reference. The no visual effect condition signifies that no proposed visual effects were added to the extended hand when it touched a target object. Therefore, a total of seven visual effects were used in this experiment.

The 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.

Experimental setup and procedure

I conducted this experiment based on a study [59] that confirmed the strength of the pseudo-haptic effect using Scheffé's pairwise comparison method [60]. That is, a participant repeated a task in which they touched two target objects (A and B, each providing a different visual effect) with the extended hand and answered questions comparing them. Figure 2.5 presents the experimental setup. For the material of the object to be touched by the extended hand, I 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. I placed the two objects 550 mm from the edge onto a white desk. The extended hand was projected of this desk. The entire projected area was 910 mm in length and 540 mm in width.

Before starting the trials, I provided each participant with time to become accustomed to operating the extended hand. In this experiment, the participants were required to manipulate the extended hand with only their index fingers. Each trial was as follows. The participants touched target objects A and B on the desk with the extended hand. At that time, they 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?

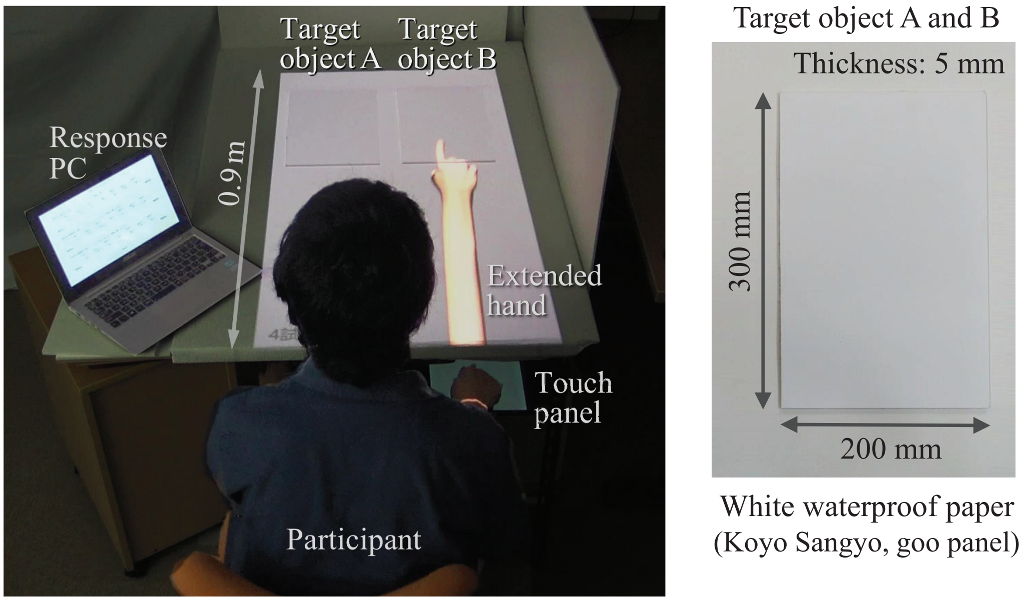


Figure 2.5: Experimental setup. A video projector mounted on the ceiling projects a extended hand onto a white table. A participant manipulates the extended hand by moving his/her right hand on a touch panel. When the extended hand touches one of the objects, a visual effect is applied to the extended hand.

I 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. I 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 ($= 21 \times 3$). I 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. I conducted an interview with each participant after the experiment. In total, it took 40 min for each participant to complete the procedures.

Results

I used Scheffé's method of paired comparison (Ura's version [60]) as the verification method. Figure 2.6 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.

Unevenness In the unevenness perception results, an ANOVA revealed that the main effect was significant (F = 743.62, $p < 0.001$). I calculated the confidence intervals (CIs) of the difference between each condition using a yardstick Y. There were significant differences (99.9% CI, ±0.1820)

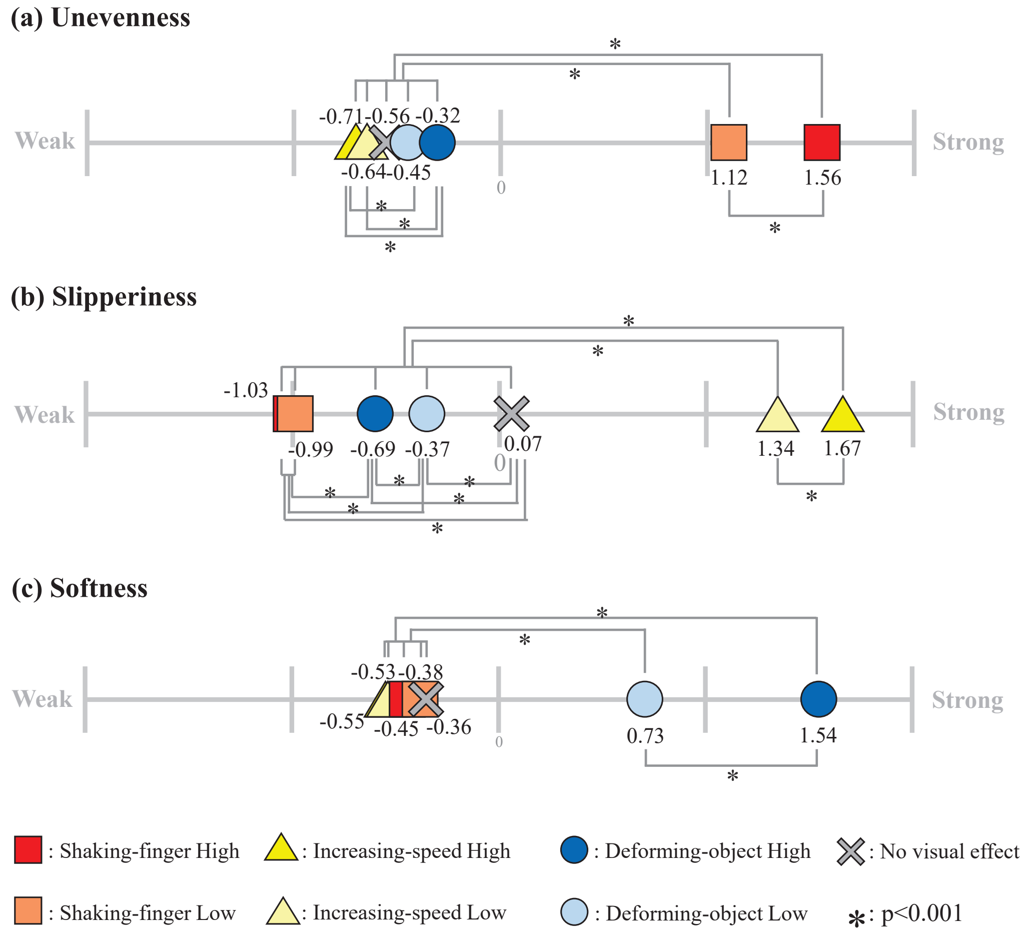


Figure 2.6: Perceived strength of the pseudo-tactile effects caused by visual effects (*: $p < 0.001$). Higher positive values indicate that participants felt the tactile texture more strongly.

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.

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.

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.

Discussion

The results indicate that each visual effect produced its intended pseudo-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 the hypotheses were supported.

Several significant unexpected differences appeared are evident in Fig. 2.6(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. Some participants reported that the more slippery their sensation was, the less uneven their sensation was. Therefore, the Increasing-speed effect for producing slipperiness recorded a low score in unevenness.

2.4.3 Determining Appropriate Parameters (Experiment B)

In Experiment A, I confirmed that the tactile sensations experienced by users were affected by the magnitude of the intensity of the visual effects. However, setting the intensity of the visual effects to be too high can compromise a user's ownership of the extended hand. For example, if the intensity of the Shaking-finger is too high, the user will find the extended hand strange because the extended hand fingers bend in a direction not possible with human fingers. In this experiment, I examined 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.

Visual effects

I prepared eight intensities for each visual effect. First, I set the maximum and minimum values of each parameter of the visual effects (Table 2.2). I selected the maximum value at which almost all users feel a sense of strangeness, while the minimum was equivalent to no visual effects. I 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:

$$X(\alpha) = \alpha X_{max} + (1 - \alpha)X_{min}. \tag{2.4}$$

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

Table 2.2: 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 2.4.2 except A_{real} of Shaking-finger, γ of Increasing-speed, and r, d_{shade} of Deforming-object. I 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

of an intensity level. Therefore, the larger the value of α, the larger the intensity of the visual effect.

Target objects

For the target objects touched by the extended hand, I selected three flat plates with different characteristics for each sensation of unevenness, slipperiness, and softness. Figure 2.7 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 was 10 mm for uneven objects and soft objects, and 5 mm for slippery objects.

Uneven objects (Fig. 2.7(a)) I 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.

Slippery objects (Fig. 2.7(b)) I 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 2.4.2) was 0.63 for Japanese paper, 0.50 for Bristol paper, and 0.17 for the Naflon sheet.

Soft objects (Fig. 2.7(c)) I used a Melamine-faced MDF plate, polyethylene sponge, and urethane sponge as soft objects. To ensure that each object had different softness levels, I measured the forces required to produce a 7-mm dent in each object. I 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.

Experimental setup and procedure

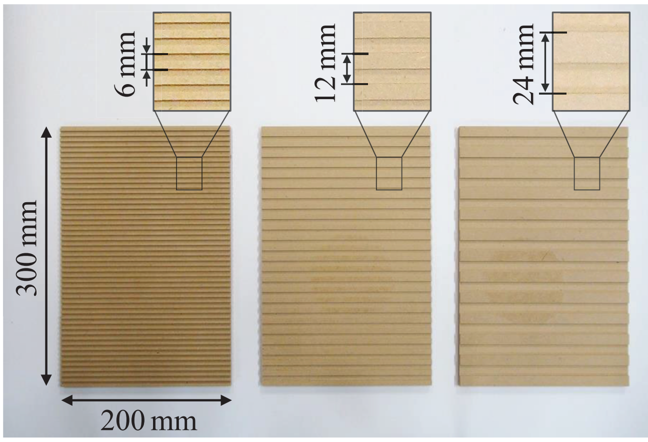
The experimental setup was the same as in Experiment A in Section 2.4.2, except that there was only one target object on the desk. The experiment consisted of "an object impression survey" to evaluate the participants' perceptions of the objects, and a "main experiment" to investigate the participants' perceptions when they touched an object with the extended hand. In the following paragraphs, I describe the procedure of the two experiments.

Object impression survey First, I investigated the participants' perceptions of an object under each of the two conditions. The first condition was the looking-only condition. I 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) affixed to the top surface of the desk. The participant then answered one of the following three questions that corresponded to the tactile texture of the target object.

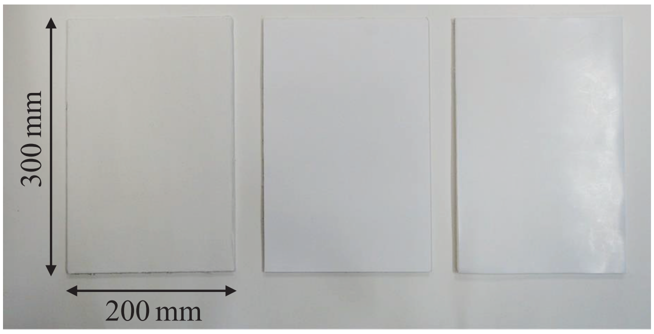
- For uneven objects (Fig. 2.7(a))
  Comparing the target object and background object, which one do you feel is more uneven?
- For slippery objects (Fig. 2.7(b))
  Comparing the target object and background object, which one do you feel is more slippery?
- For soft objects (Fig. 2.7(c))
  Comparing 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.

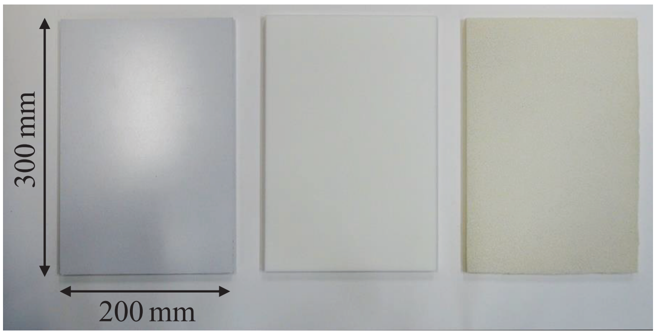
After the looking-only condition was completed for all target objects, I executed the second condition (touching-with-looking condition). In this condition, a participant actually touched the target object and background object with his/her hand while looking at the objects and answered the same question.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



(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 2.7: 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.

Main experiment After the object impression surveys, I conducted the main experiment in which participants touched the target object with the extended hand. In each trial, the participants touched the target object by manipulating the extended hand. When the extended hand touched the target object, the system produced a visual effect on the extended 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?”

I set each of the eight intensities of the visual effects to repeat eight times; therefore, each participant performed 64 trials for each object. I 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. I balanced the order in which each object was used across participants. I 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. I interviewed each participant after all the trials. In total, it took 80 min to perform all of the procedures for each participant.

Results

Object impression survey Figure 2.8 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. I 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 ($p < 0.05$).

Main experiment For each participant, I 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. I refer to this rate as the perception rate. Figure 2.9 presents the average values of the perception rate for all intensities.

Next, I calculated the appropriate intensity ranges for the visual effects by the following procedure (see Fig. 2.10). First, for each participant's data, I 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". I call each rate $rate_{small}$ and $rate_{large}$. Then, I fitted both $rate_{small}$ and $rate_{large}$ to the psychometric curves of the following equations:

$$f_{small}(x) = \frac{1}{1 + exp(\frac{x-A}{B})}, \tag{2.5}$$

$$f_{large}(x) = 1 - f_{small}(x). \tag{2.6}$$

I calculated x, where the fitted $f_{small}(x)$ equals 0.5. I call this x the lower end. Similarly, I calculated x where the fitted $f_{large}(x)$ equals 0.5, and call this x the upper end. I 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%. I determined the effective area for each participant. In Fig. 2.11, the top part 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, I performed an ANOVA with the type of objects as a factor. I 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.

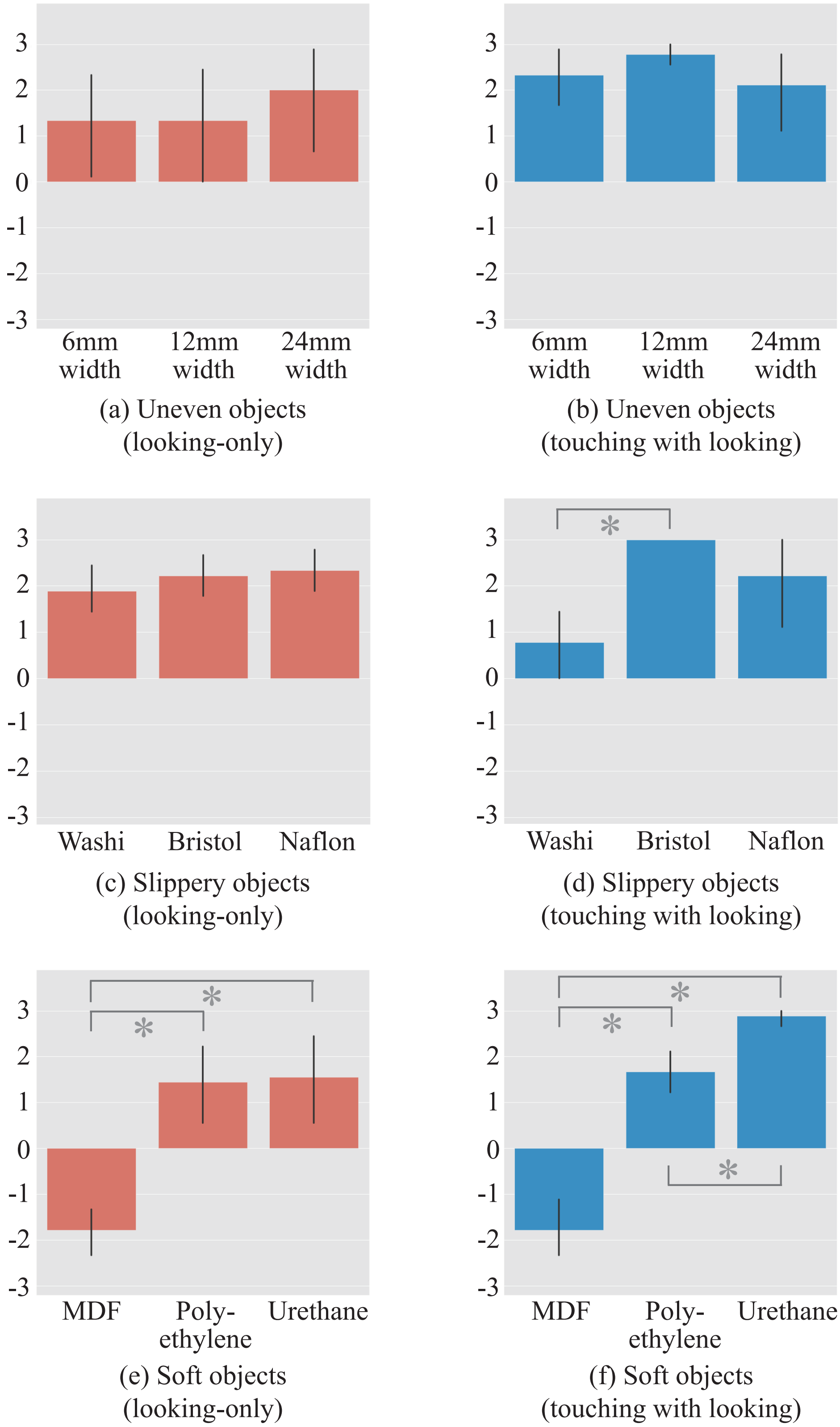
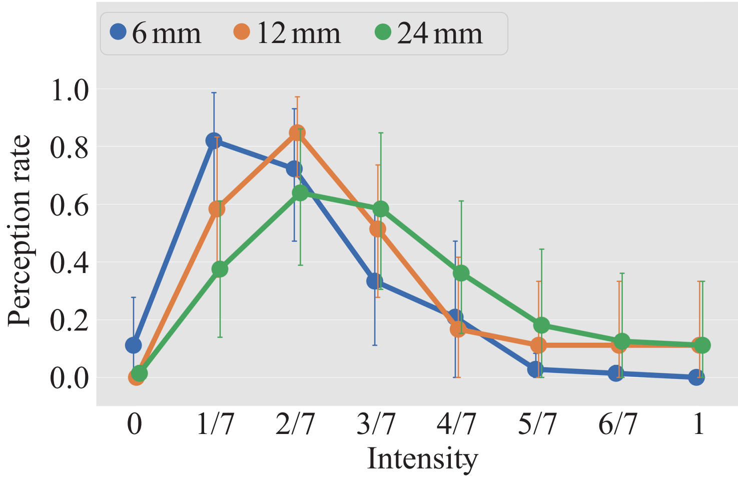
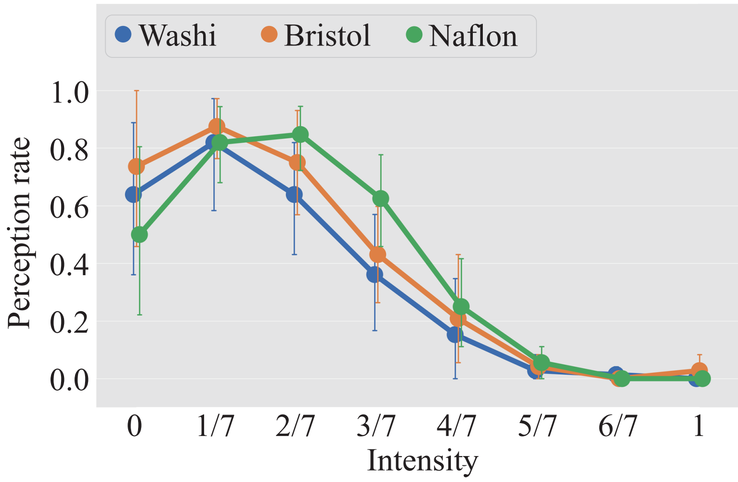


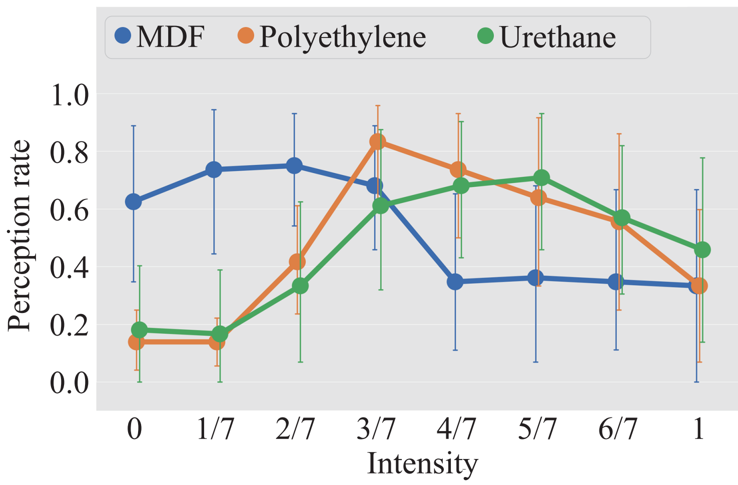
Figure 2.8: Results of the object impression survey. Higher positive values indicate that participants perceived the corresponding tactile sensation more strongly with the target object than with the background object.



(a) Uneven objects



(b) Slippery objects



(c) Soft objects

Figure 2.9: 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.

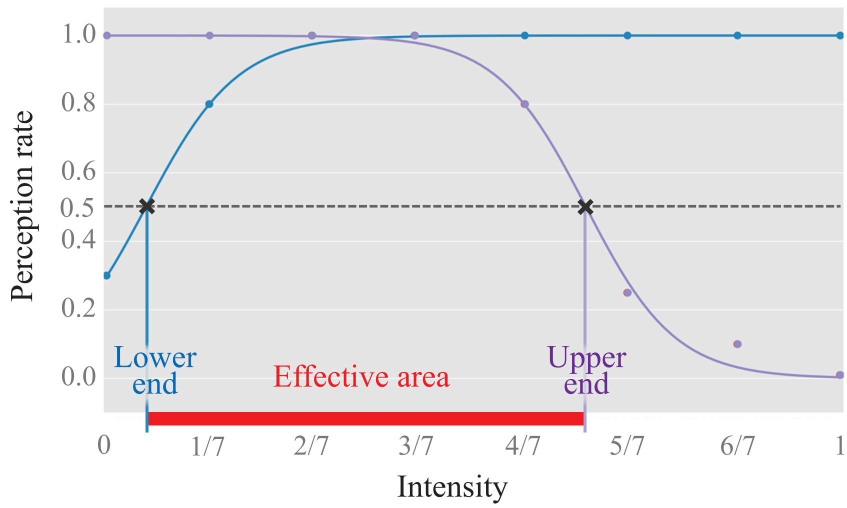


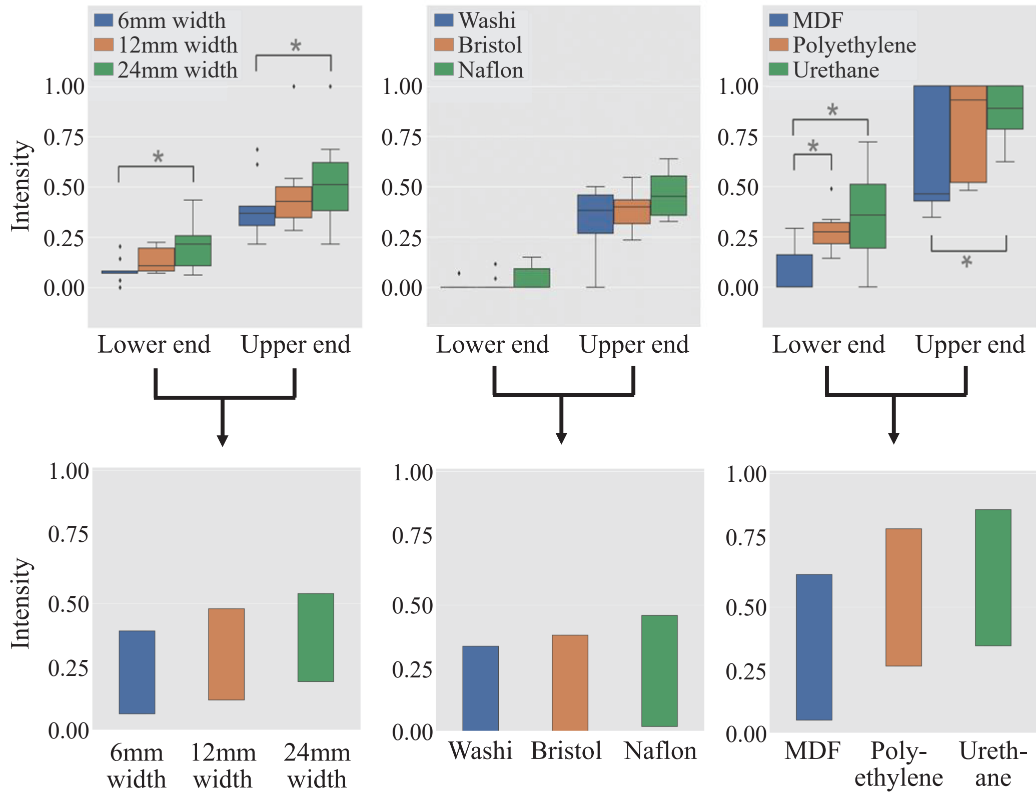
Figure 2.10: Procedure for determining the appropriate intensity range. Red points represent the perception rate of a participant, while blue and purple points represent the rates at which the participant did not say "feel a sense of strangeness due to small changes in visual effects" and "feel a sense of strangeness due to large changes in visual effects," respectively. Blue and purple curves are psychometric curves that fit those rates, respectively. I 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%.

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 ($p < 0.05$).

Discussion

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. 2.8(a) and 2.8(b). On the other hand, the results of multiple comparisons did not reveal which objects participants felt were more uneven under either condition. I prepared the target objects according to the 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.



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

Figure 2.11: Result of the effective areas. (Top) Box plots indicating the lower and upper ends of the effective areas (*$p < 0.05$). (Bottom) Average effective areas. I 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.

For slippery objects, the participants felt that all of the objects were slippery simply by looking at them, as displayed in Fig. 2.8(c). In addition, participants recognized how slippery the objects were by touching them, as displayed in Fig. 2.8(d).

For soft objects, the participants felt that the objects were soft, with the exception of the Melamine-faced MDF plate, as illustrated in Fig. 2.8(e). In addition, the degree of softness was recognized by touching, as illustrated in Fig. 2.8(f).

Shaking-finger and uneven objects The results indicate that the lower and upper ends change as the bump width of the object changes. Figure 2.11(a) 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.

Increasing-speed and slippery objects The results indicate that the lower and upper ends tend to change as the slipperiness of the object changes. Figure 2.11(b) 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. 2.11(b) 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.

Deforming-object and soft objects The results presented in Fig. 2.11(c) 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 the extended hand.

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 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 the extended 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.

2.4.4 Resolution of Pseudo-Tactile Sensation (Experiment C)

In this experiment, I measured the just noticeable differences (JNDs) of the visual effects to examine how many levels of tactile sensation a user

Table 2.3: Parameter values of visual effects. I set the lower/upper end of the effective areas of the corresponding object as the minimum/maximum values. I used an MDF plate whose bump width was 12 mm as an uneven object; thus, I 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

was able to perceive within the effective area determined in Experiment B in Section 2.4.3.

Visual effects

I set one reference intensity and six comparison intensities for each visual effect by the following procedure. First, I set maximum and minimum values for each parameter of the visual effects. Table 2.3 presents these values. I set the reference intensity to $\alpha = 0.5$ in (2.4). In addition, I set six comparison intensities that varied by $\pm 15\%, \pm 30\%, \pm 45\%$ 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 (2.4).

Target objects

For target objects touched by the extended hand, I selected one of the objects used in Section 2.4.3 as follows.

- Unevenness: MDF plate with a bump width of 12 mm (Fig. 2.7(a) (middle))
- Slipperiness: Bristol paper (Fig. 2.7(b) (middle))
- Softness: Polyethylene sponge (Fig. 2.7(c) (middle))

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

Experimental setup and procedure

I used the JND methodology [61]. Each participant touched each of two objects (object A and object B) with a extended hand, which produced visual effects of different intensities. Each participant the 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 2.4.2.

Before starting the trials, I provided time for each participant to become accustomed to the operation of the extended hand. In each trial, the participant touched objects A and B twice by manipulating the extended hand. 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. 2.7(a) (middle))
  Comparing object A and object B, which one do you feel is more uneven?
- For slippery object (Fig. 2.7(b) (middle))
  Comparing object A and object B, which one do you feel is more slippery?
- For soft object (Fig. 2.7(c) (middle))
  Comparing object A and object B, which one do you feel is softer?

There were six comparison intensities for one reference intensity, and I 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). I balanced the order and position in which each comparison intensity was provided. I also balanced the order in which each object was provided among participants.

I 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. I conducted an interview with each participant after the experiment. In total, it took 55 min for each particiapant to complete the procedures.

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. I calculated the ratio of the number of correct choices to the number of iterations. Figure 2.12 illustrates the distribution of the accuracy of the participants for each comparison intensity. For each sensation of unevenness, slipperiness, and softness, I 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 ($p < 0.05$).

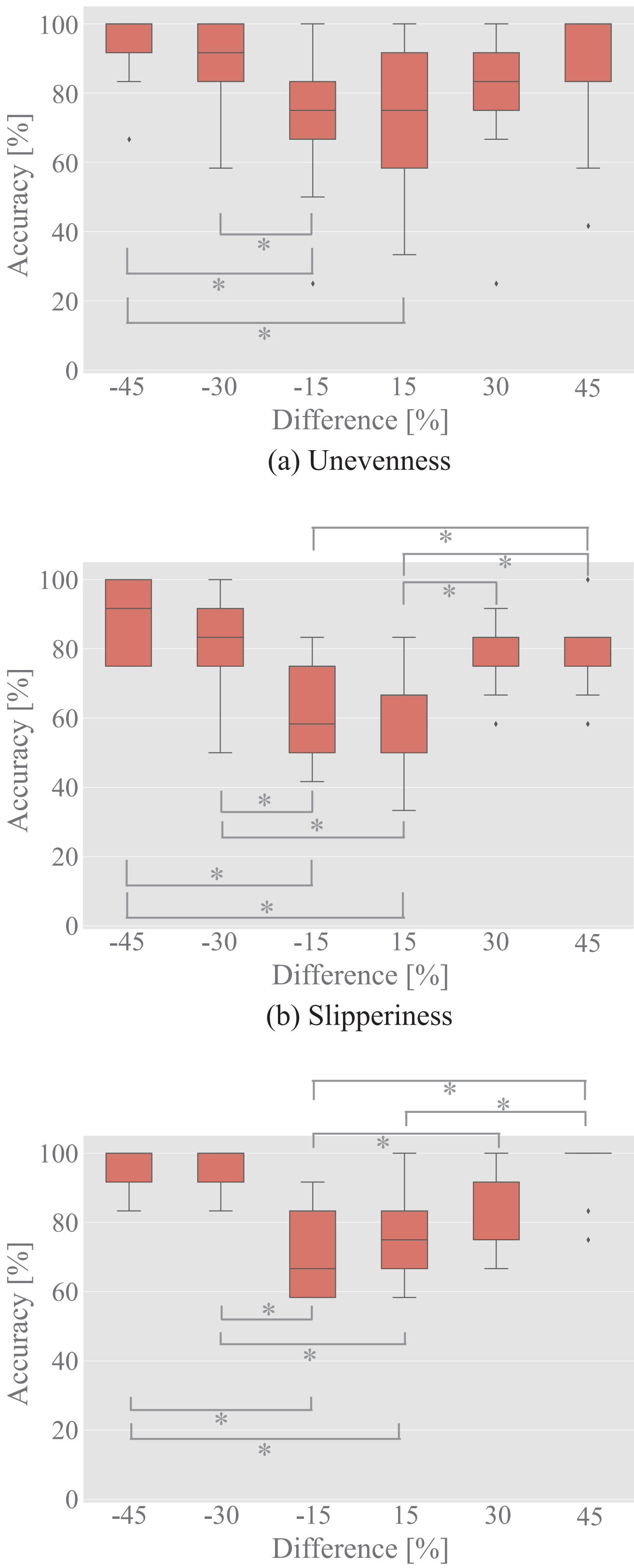
Shaking-finger A difference of -45% is significantly more accurate than that of $\pm15\%$. A difference of -30% is also significantly more accurate than that of -15%.

Increasing-speed A difference of $\pm45\%$ and -30% is significantly more accurate than that of $\pm15\%$. A difference of $+30\%$ is significantly more accurate than that of $+15\%$.

Deforming-object A difference of $\pm45\%$ and -30% is significantly more accurate than that of $\pm15\%$, and a difference of $+30\%$ is significantly more accurate than that of -15%.

I analyzed the JNDs that could be perceived by the participants. Instead of considering the accuracy value, I considered the rate at which the participants judged the comparison intensity created a stronger sensation than the reference intensity (see Fig. 2.13). I obtained the Weber fraction by fitting the psychometric curve (2.5) 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). I 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).

Assuming that I can determine the resolution of pseudo-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.



(a) Unevenness

(b) Slipperiness

(c) Softness

Figure 2.12: Distribution of accuracy for each comparison intensity.

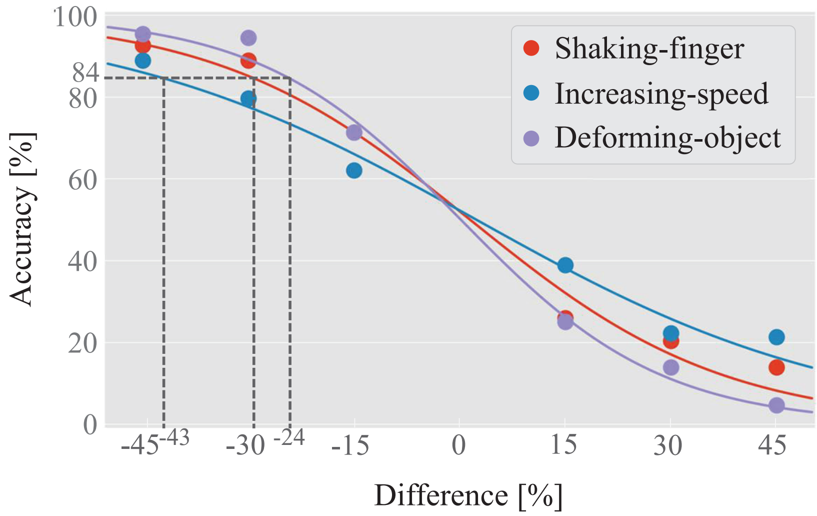


Figure 2.13: Plot of the psychometric curve fitted to the data. The PSE for all curves matches the condition in which the difference between the reference intensity and comparison intensity is zero.

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 $\pm15\%$ in the unevenness sensation. I 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 extended hand's fingertip, the smoothness by the moving speed of the extended 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 extended hand depended on the operating speed of the participant.

2.5 Conclusion

In this chapter, I proposed a novel pseudo-haptic feedback method for providing users with tactile sensation of objects in the extended hand interface without the use of haptic devices. I 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 2.4.2), I demonstrated that visual effects make users feel each intended tactile sensation. In Experiment B (Section 2.4.3), I 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, I found a common intensity range according to the property of the target object used in Experiment B. I also investigated the resolution of the proposed pseudo-tactile sensations in the appropriate intensity ranges in Experiment C (Section 2.4.4). 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, the proposed method achieves various tactile sensations without haptic devices in the extended hand interface.

Chapter 3

Sound Texture Feedback for Extended Hand Users

In this chapter, I explore the application of auditory feedback to the extended hand. In Particular, I investigate how to configure auditory feedback for users with the extended hand.

The chapter begins with a description of the background and research questions for this initiative, followed by a presentation of the findings of related studies. I then describe the experimental system and two user studies and conclude with a summary.

3.1 Introduction and Motivation

In Chapter 2, I proposed a pseudo-haptic feedback method in which visual effects are added to the extended hand when it touches an object. This method enables users to perceive the tactile sensation of the object. Alternatively, in VR and MR research, various methods aim to offer tactile sensations to users, not solely through visual stimuli but also auditory cues [62, 63]. Auditory stimuli can be easily presented to users using standard audio devices such as headphones or speakers, making them highly applicable in ExtendedHand.

In this chapter, my focus is on integrating auditory feedback into ExtendedHand. Specifically, when the extended hand touches an object, the system presents the user with a sound that matches the object, referred to as "sound texture." This auditory feedback allows the user to experience the sensation of touching the object and perceive its tactile properties, even without haptic devices. Figure 1.2 provides an overview of the method. With ExtendedHand, users can reach objects that are typically out of their physical hand's reach by using the extended hand, enabling impossible actions with their own body. However, in such situations, it is not immediately clear how the sound texture feedback should be governed. Two research questions arise, as illustrated in Fig. 3.1.

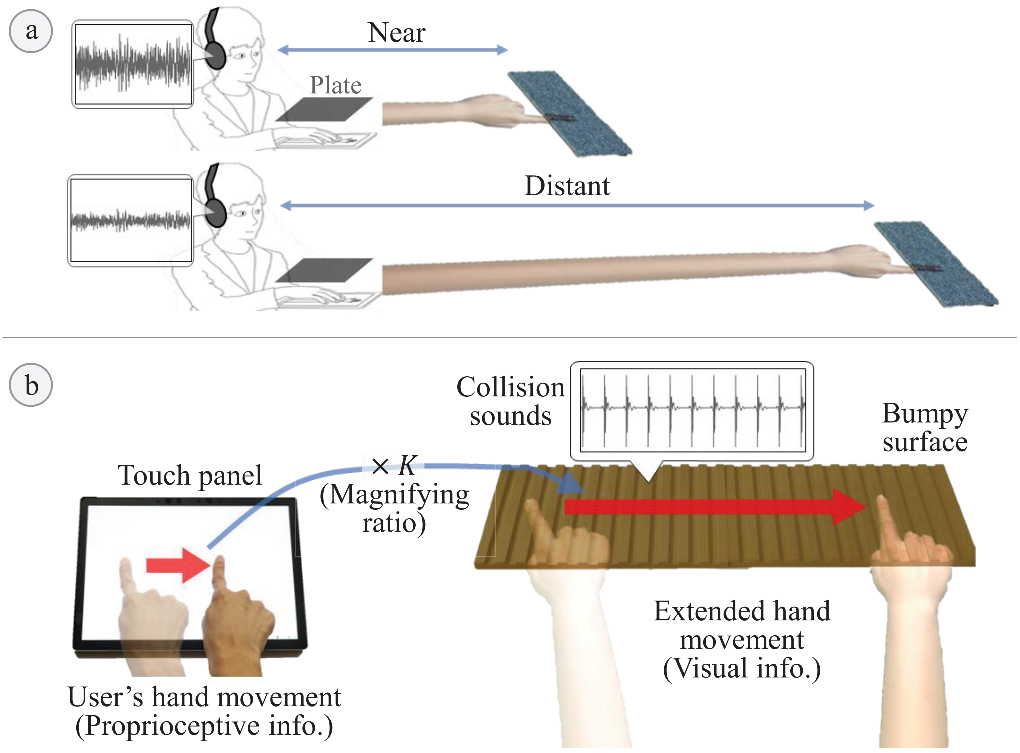


Figure 3.1: Research questions of this study: (a) When a user touches objects placed at various distances, should the sound pressure of sound textures be lower as the distance increases? (b) In ExtendedHand, where the movement of the user's hand is amplified by a factor of K in the extended hand, should the occurrence of collision sounds be synchronized with movement of the user's hand or the movement of the extended hand?

Research Question 1 addresses **how to set the sound pressure of the sound texture feedback based on distance** (see Fig. 3.1(a)). In ExtendedHand scenarios, users interact with objects at various distances, ranging from those within their reach to those beyond it. According to physical laws, the sound pressure reaching the user's ears decreases as the distance from the sound source increases. Therefore, the sound texture may become nearly inaudible when the extended hand touches distant objects. While adhering to physical laws, it remains unclear whether users would find this level of sound pressure natural when touching objects with the extended hand. Additionally, there are studies suggesting that our perception of auditory stimuli is influenced by our body image [64, 65]. Thus, it is unclear whether we should directly apply the physics-based attenuation of sound pressure due to distance when users perceive, through the extended hand, that they are generating sound by touching an object as a substitute for their own hand.

Research Question 2 explores **whether to provide the user with a sound texture that matches the physical hand or the extended hand** (see Fig. 3.1(b)).

In ExtendedHand, the movements of the user's hand are amplified and reflected in the movements of the extended hand to facilitate interactions with distant objects. As a result, the movement of the extended hand becomes faster than that of the user's physical hand. When we touch objects with our hands, the generated sound varies depending on how we touch them. It is unclear whether users would perceive sound textures that align with the proprioceptive information of their hand or the visual information of the extended hand as more appropriate. In this chapter, I will refer to the sound texture generated when tracing an object with a real hand at a speed of U [mm/s] as the "tracing speed of the sound texture is U [mm/s]."

In this chapter, I investigate the two research questions that stem from the unique characteristics of ExtendedHand, which humans have not experienced before. Specifically, I conducted experiments to determine the sound pressure level and tracing speed of sound textures based on the distance to the touched object and the movement speed of the extended hand.

3.2 Related Work

3.2.1 Auditory Feedback for Hand-Object Interaction

When humans interact with objects, auditory stimuli play an important role in material recognition [66, 67, 68], enhancing interaction immersion [69, 70], and improving task performance [69, 71], alongside visual and tactile stimuli. Several studies have reported that, even in VR or MR scenarios where haptic feedback is not available, auditory feedback can convey a sense of touching virtual objects and their tactile properties [72, 73, 62, 63].

Furthermore, several studies have reported that manipulating auditory stimuli can have a significant impact on our perception of tactile sensations related to objects [74, 75, 76, 77]. A well-known example of this is the parchment-skin illusion. In this phenomenon, when users rub their hands together, the illusion of feeling a dry, parchment-like texture is created by enhancing the high-frequency components of the generated sound [40, 41]. Besides, Kanek *et al.* reported that various factors related to button click sounds, such as sound pressure and frequency, can influence a user's perception of the weight or heaviness of the button click [63].

Based on these reports, incorporating auditory feedback into Extended-Hand used in this study is a promising approach to enhance the user's extended hand experience. In this research, I aim to provide users with touching sensations by presenting sounds that match the objects touched by the extended hand.

3.2.2 Auditory Stimuli and Human Body Image

Several studies have reported that auditory stimuli can influence users' perception of their body image. For instance, in the Marble-Hand illusion, when a user's hand is hit gently by a small hammer, the sound of this impact is gradually replaced with that of a hammer hitting a piece of marble. As a result, users perceived their hands as heavier and harder [78]. Additionally, Tajadura *et al.* conducted an experiment where participants tapped a surface while progressively extending their right arm sideways. In this experiment, when sounds were generated from a location twice the distance of the tap point and presented to the participants, their perception of tactile distance increased significantly [79, 80]. Furthermore, it has been suggested that this illusion can also influence actions reaching for objects farther away [81].

Vice versa, it has been suggested that the perception of auditory stimuli might be influenced by human body image. For instance, when we use cues like sound pressure to predict the distance to a sound source, there is a tendency to overestimate the distance to the source within the peripersonal space (within our arm's reach, approximately 1 m), while underestimating it in more distant spaces [64]. This tendency has also been observed in the context of MR [82] and VR [83]. In an experiment conducted by Serino *et al.* [65], participants were presented with simultaneous auditory and tactile stimuli and were required to respond promptly only when a specific tactile stimulus was presented. The results showed that participants responded more quickly to tactile stimuli when auditory stimuli occurred within their peripersonal space than when the sound originated from a farther space. Interestingly, the results also revealed that a brief period of using a long cane enabled participants to respond quickly to tactile stimuli when sounds were produced at the tip of the cane, which is relatively farther away.

Based on these findings, since we perceive auditory stimuli through our bodies, our body image would influence auditory perception and vice versa. In the case of the ExtendedHand, it deals with a more expanded body than what previous related research has addressed. This study aims to elucidate the appropriate manner of providing sound texture feedback concerning this extended body.

3.3 Experimental System

I developed an experimental system specifically for two user studies described in Sections 3.4 and 3.5. Figure 3.2 illustrates the appearance of this system. Participants could manipulate a projected CG hand (extended hand) on a table by moving their hand on a touch panel. Additionally, when the extended hand traced a target object placed on the table, a sound

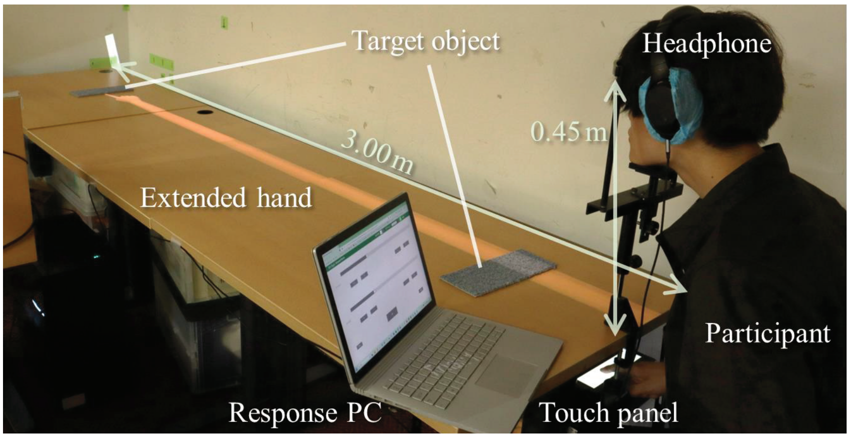


Figure 3.2: Experimental system. An extended hand is projected from two projectors mounted on the ceiling. Users can operate the extended hand through the touch panel below a table. When the extended hand touches objects, the sound textures are played through headphones, providing users with sound texture stimuli.

texture matching the object was played through headphones, providing the user with sound texture stimuli.

I constructed this experimental system using Unity 2021 on a PC (CPU: Intel, Core i7-13700, RAM: 32GB, GPU: NVIDIA, GeForce RTX 4080). Two projectors (Optoma, ML1050ST+) were ceiling-mounted to project the extended hand onto the table measuring 0.7 m $\times$ 3.0 m. To reflect the hand's movement on the touch panel to the extended hand, I employed the ExtendedHand system proposed by Ueda *et al.* [19]. Users sat in a chair and manipulated the extended hand using the touch panel (Microsoft, Surface Pro 4) placed under the table. The delay time from touch panel input to the extended hand movement was 150 ms. The C/D ratio (the ratio between real hand and extended hand movements) was fixed at 5.0 for consistency throughout this study.

In this experimental setup, I assumed that the positions, shapes, and types of objects were known in advance and pre-configured this information into the system. Furthermore, I prepared sound textures by recording the sounds produced when tracing objects at varying speed and forces using a finger. When the system detected the index fingertip of the extended hand overlapped with an object, it played the sound resulting from applying HRTF (Head-related transform function) to the corresponding sound texture for the object through headphones (Sony, WH-1000XM3), thereby presenting the sound texture to participants. I used Google's Resonance Audio Plugin[1] for the application of HRTF. I configured the position of the touch points of the extended hand and the participants' ears to apply

[1]Google, Resonance Audio, https://resonance-audio.github.io/resonance-audio/ (accessed on 20 July 2023)

HRTF. During this process, I disregarded sound reflections from objects such as tables and surrounding walls, only considering the direct path from the sound source to the participants' ears.

3.4 Investigation of Sound Pressure of Sound Texture

I conducted a user study to establish guidelines for setting the sound pressure level of sound textures based on the distance between a user and a touched object when the user traces the object with the extended hand. Additionally, we empirically know that a generated sound varies with the speed at which objects are traced. Therefore, I included the tracing speed of the extended hand as an experimental condition.

The experiments presented in this section and the next section were approved by the Research Ethics Committee of Osaka University (No. R2-28), and written informed consent was obtained from each participant.

3.4.1 Experimental Setup and Procedure

The experimental setup is described in Section 3.3. In this experiment, tufted carpets (Toli, GA1043) were used as the objects touched by the extended hand, as shown in Fig. 3.3. For the sound texture when touching the carpets, I used a sound that was recorded using a microphone (AG-PTEX, Z02) while tracing the carpet with a silicone finger model (FAN-MAKE, QT-134). The force applied to the carpet was set at 0.4 N, and the speed of tracing the carpet was 300 mm/s. I used 300 mm/s as the common intermediate speed between the two conditions of tracing speed with the extended hand, which were 200 mm/s and 400 mm/s. While I considered utilizing publicly available sound datasets, I opted to create my own sound data since I specifically required sound texture corresponding to a tracing speed of 300 mm/s. Figure 3.4 shows the waveform and power spectrum of the recorded sound texture. As mentioned in Section 3.3, the participants were presented with sounds produced by applying an HRTF to the recorded sound texture. In this experiment, sound pressure attenuation due to distance was turned off, allowing participants to adjust the sound pressure. To reduce exposure to ambient sounds, the noise-canceling feature of the headphones was utilized.

The procedure of the experiment was as follows: Participants received an explanation of the experiment and provided their informed consent. They then practiced operating the extended hand and the experimental task for 5 minutes. During the experiment, participants were required to touch the touch panel with an approximate force of 0.4 N using their index finger and operate the extended hand. The force applied to the touch panel was

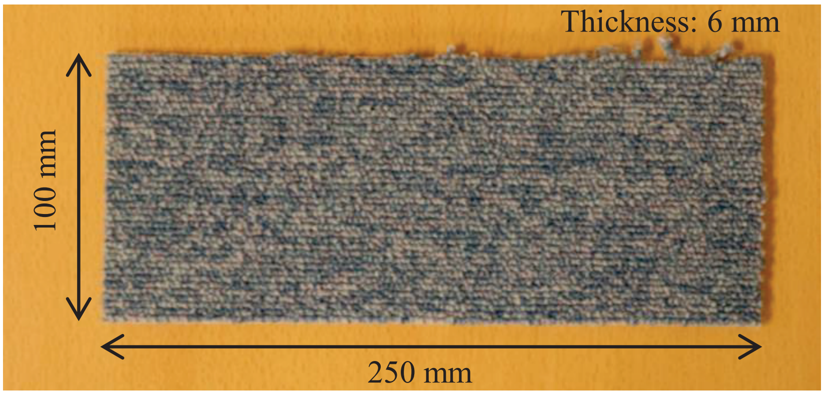


Figure 3.3: Carpet object used in Section 3.4 experiment. The dimensions of the carpet were 250 mm in width, 100 mm in length, and 6 mm in thickness. I used six identical carpet objects in the experiment.

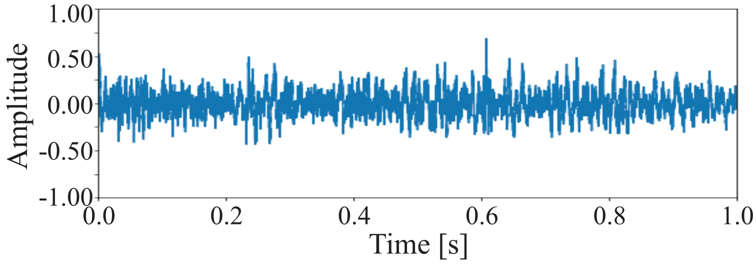
measured by a scale placed below it, with verbal feedback provided by the experimenter. Additionally, participants were required to trace a length of 150 mm back and forth along the long side of the carpet at a specified speed using the extended hand. To assist participants in performing these operations accurately, a red point indicating the desired movement was displayed by the system. Participants used this point as a reference while operating the extended hand.

After the practice session, participants performed the main experimental task, which involved the following steps:

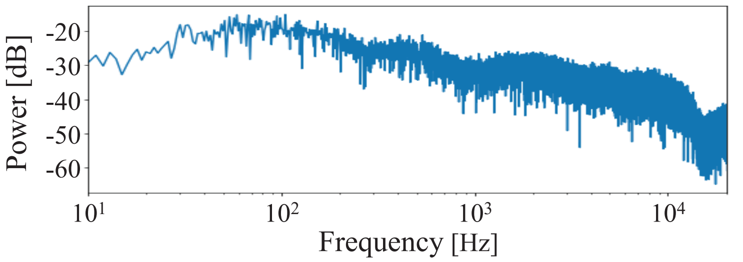
Step 1: The experimenter placed the carpet object at two distances, D_i and D_j, from a set of six different distances (0.5, 1.0, 1.5, 2.0, 2.5, 3.0 m).

Step 2: Participants touched the objects at distances D_i and D_j using the extended hand at a fixed speed V. While doing so, a sound texture was presented through headphones. Participants set the sound pressure of the sound texture for each object to make it feel most natural when tracing the object with the extended hand, referencing both objects. The sound pressure levels could be adjusted within a range of 24 dB(A) to 60 dB(A) based on the position of a corresponding slider bar on a response PC. The sound pressure levels were defined as the average sound pressure of the sound texture emitted from the headphones, measured by a noise meter (Thanko, RAMA11O08) placed near the headphone sound presentation unit.

Step 3: A new carpet object was placed at a distance D_k where no object had been placed previously. Participants set the sound pressure for this object using the same process as in Step 2. They could touch objects for which they had already set the sound pressure and listen to the set sound pressure. Participants adjusted the sound pressure for the object at D_k while referring to the objects they had set earlier.



(a) Waveform



(b) Power spectrum

Figure 3.4: Sound used in Section 3.4 experiment. I obtained this sound data by tracing the carpet object shown in Fig. 3.3 with a silicon finger model. The applied force on the object was 0.4 N, and the tracing speed was 300 mm/s. Actual sound data is available at https://yushisato.com/projects/soundtexture_eh/.

Step 4: Participants sequentially set the sound pressure for the remaining three distance levels among the six as the experimenter placed objects.

Steps 1 to 4 constituted one block, and participants completed six blocks, three for each of the two movement speeds (200 mm/s, 400 mm/s). In other words, participants set the sound pressure 36 times. The order of movement speeds and object placements were randomized and adjusted between participants to mitigate order effects.

After completing the main task, participants were instructed to fill out a questionnaire (see Table 3.1) using a 7-point Likert scale. The questionnaire included questions about Ownership and Agency and their dummy (Ownership control and Agency control) to ensure that participants felt and manipulated the extended hand as if it were their own [27]. Sound agency questions were also included to measure whether participants perceived that the sound was generated by touching the carpets with the extended hand. A Sound-matching question was included to assess whether the sound textures used in the experiment matched the carpets. Additionally, a Natural-touching question aimed to gather information about participants' tactile perception experiences. Participants were also asked to verbally share their policies for setting sound pressures and provide their impressions of the sound textures.

I recruited 16 participants whose dominant hand was right and whose ages ranged from 21 to 28 (13 males and three females). The average time

Table 3.1: Questionnaire, consisting of 10 statements divided into six different categories.

Category	Questionnaire
Ownership	Q1: I felt as I was looking at my own hand Q2: I felt as if the projected hand was my hand
Ownership control	Q3: I felt as if my real hand were turning the projected hand Q4: It seems as if I had more than one right hand
Agency	Q5: The projected hand moved just like I wanted it to, as if it was obeying my will Q6: I felt as if I was controlling the movements of the projected hand
Agency control	Q7: I felt as if the projected hand was controlling my will Q8: I felt as if the projected hand was controlling my movements
Sound matching	Q9: I felt the sound was consistent with the object
Natural Touching	Q10: I felt I was touching the object naturally with the projected hand

for each participant to complete the experiment was approximately 50 minutes.

3.4.2 Results

Main results

Figure 3.5 presents the result of the set sound pressure levels. I performed the two-way repeated measures ANOVA with the distance and movement speed as factors. The ANOVA result showed a significant difference in the distance factor ($F(5, 75) = 79.47$, $p < 0.01$, $\eta_p^2 = 0.84$). Post-hoc multiple comparisons with Bonferroni correction revealed that farther one had a lower sound pressure in all combinations of two distances ($p < 0.05$). On the other hand, I did not find any significant differences in the movement speed factor ($F(1, 15) = 2.97$, $p > 0.1$, $\eta_p^2 = 0.17$), and the interaction effects($F(5, 75) = 1.05$, $p > 0.1$, $\eta_p^2 = 0.07$).

Based on the diffusion of energy from a point source, the sound pressure $P(D)$ [dB(A)] at a point located at a distance D [m] from a point sound source can be expressed as $P(D) = -20\log_{10}(D/D_0) + P_0$ [dB(A)], where D_0 [m] is the reference distance and P_0 [dB(A)] is the sound pressure at distance D_0 [m] [64]. Using a reference distance of $D_0 = 0.5$ m, I fitted the data of distance D and set sound pressure P for each participant to the equation $P(D) = a\log_{10}(D/0.5) + b$ and calculated the values of coefficients a and b. Figure 3.6 shows the results of the calculated coefficients a and b. I tested whether the value of a was equal to the value based on

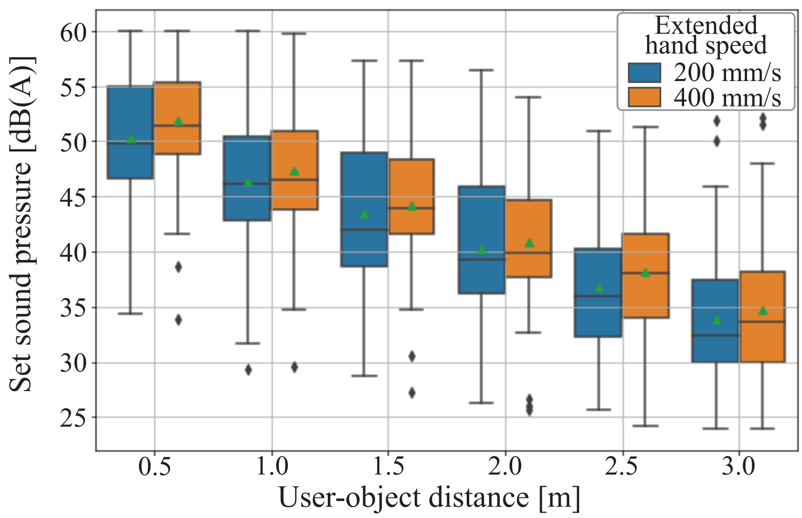
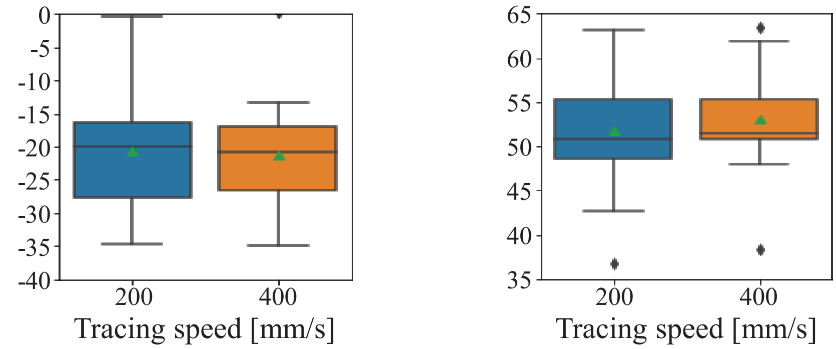


Figure 3.5: Distribution of sound pressure levels set by participants



(a) Calculated value of a

(b) Calculated value of b

Figure 3.6: Calculated values of coefficients a and b.

the physical phenomenon, which is $a = -20$, for each distance. The t-test did not show a significant difference at either distance ($p > 0.1$).

Scores for questionnaire

Figure 3.7 shows the evaluation results in response to the questionnaires in Table 3.1. I conducted a t-test for Ownership and its control category, and the results revealed a significant difference between them ($p < 0.05$). Similarly, I performed a t-test for Agency and its control category, and the results indicated a significant difference between them ($p < 0.01$). These results enhanced the credibility of the participants' survey responses. All participants scored higher than four on Sound agency, indicating that they all perceived that touching the carpets with the extended hand caused the sound.

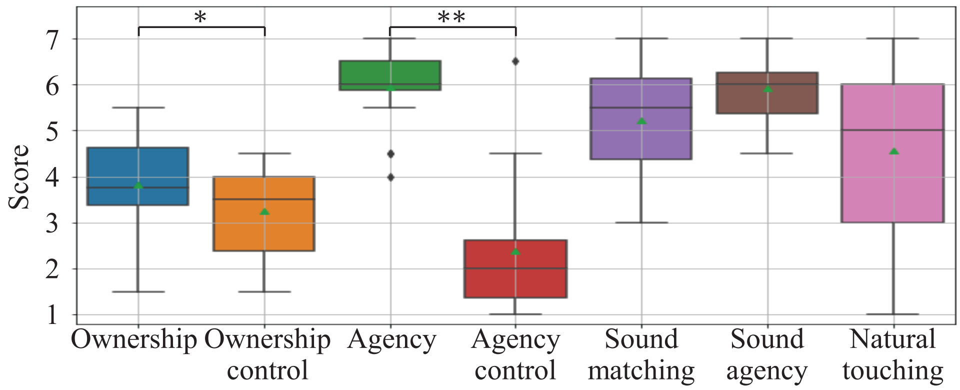


Figure 3.7: Results of the questionnaires in Table 3.1.

Setting policy and impressions

The participants' verbal feedback at the end of the experiment was as follows: Regarding the policy for setting sound pressures, all participants except one mentioned that they adjusted the sound pressure based on the distance to the carpets. Furthermore, seven participants stated that they increased the sound pressure for faster speed. Additionally, seven participants reported setting the sound pressure higher than they would expect to generate when touching the carpet with their hands. This adjustment was done to compensate for the lack of tactile stimulation from the carpet.

Regarding their impressions of sound, nine participants mentioned that sound texture feedback enhanced their ability to perceive the sensation of touching the carpets compared to not having sound texture feedback during the manipulation practice. Furthermore, 14 participants expressed a preference for hearing sound, even when touching distant objects where sound would not typically be heard. Additionally, five participants found it challenging to determine if the extended hand was in contact with carpets at a distance solely based on visual information. However, with sound texture feedback, they were able to easily discern whether the extended hand was touching the object.

3.4.3 Discussion

As intended, participants perceived sound textures being generated when they touched the carpets with the extended hand. The results under this condition indicated that it is appropriate for the sound pressure to decrease in a way that aligns with the physical phenomenon. This suggests that the experience of the extended hand does not affect the sound decay over distance. However, as the participants verbally commented, it was suggested that participants could benefit in many ways from being able to hear the sound texture. Therefore, it is indicated that, while applying distance-based attenuation within close proximity, there should be a deliberate design choice to maintain a minimum sound pressure when the distance becomes too great and the sound pressure decreases excessively.

The sound pressure levels set by the participants were generally higher than the sound produced by physically touching the carpet. As a reference, when I traced the carpet using my index finger with a force of 0.5 N and a speed of 300 mm/s, the sound pressure measured at a distance of 0.5 m was 44 dB(A). However, the average sound pressure set by the participants at the same distance exceeded 50 dB(A), as shown in Fig. 3.5. One possible reason, as indicated by participant comments, could be an attempt to compensate for the lack of tactile stimulation from the carpet by relying more on auditory information. This tendency to enhance another sensory stimulus in the absence of a tactile stimulus was also observed in a previous study, where tactile sensations were induced through visual effects in Extended Hand [2].

Regarding movement speed, this experiment did not detect any significant differences. Some participants commented that they increased the sound pressure when the movement speed was faster. However, upon reviewing their results, it was found that four of them had not made such settings. Based on these findings, it was considered that there is little need to alter sound pressure levels based on the magnitude of movement speed. Although the carpet was used as the target object in this experiment, future research should be conducted on a variety of objects because the characteristics of sound textures vary greatly depending on the objects.

3.5 Investigation of Tracing Speed of Sound Texture

I conducted a user experiment to investigate the appropriate tracing speed of sound textures based on the movement speed of the extended hand and user-object distance. This aimed to establish a guideline for setting the tracing speed of sound texture feedback in extended hand experience.

3.5.1 Experimental Setup and Procedure

I conducted this experiment in the same environment as Section 3.4, as shown in Fig. 3.2. In this experiment, I used a wooden board with a regular bump pattern, as shown in Fig. 3.8. I selected this wooden board as it allowed participants to intuitively and accurately judge the differences in sound texture tracing speeds. In this experiment, I needed to prepare sound textures at various tracing speeds. To achieve this, I traced the wooden board with a silicone finger model (FANMAKE, QT-134) at

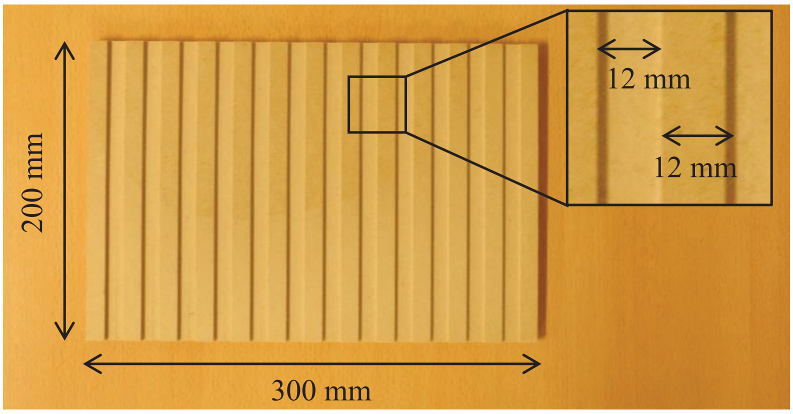
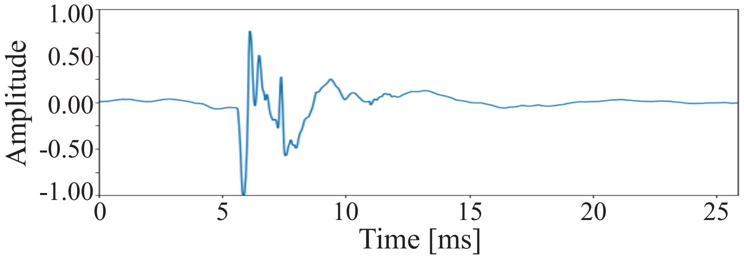


Figure 3.8: Wooden board with a regular texture pattern used in Section 3.5 experiment. The dimensions of the board were 300 mm in width, 200 mm in length, and 9 mm in thickness, with a bump depth of 3 mm. I used two identical boards in the experiment.

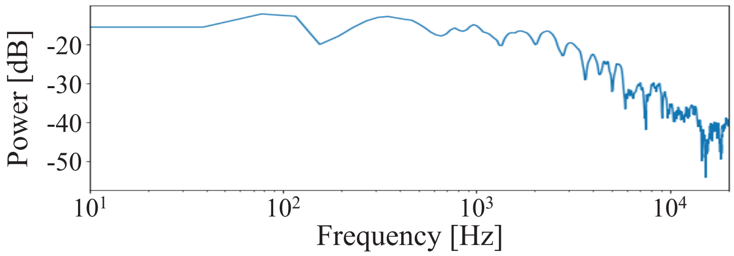
different speeds and recorded the resulting sounds with a microphone (AGPTEK, Z02). The force applied to the carpet material was 0.4 N, and the tracing speeds ranged from 50 mm/s to 600 mm/s in 5 mm/s increments. Upon analyzing the recorded sounds, I found that regardless of the tracing speed, the waveform shown in Fig. 3.9(a) was generated when passing over a single bump with the finger model. Therefore, in this study, I created sound textures at tracing speeds of U mm/s by arranging the unit waveform as shown in Fig. 3.9(a) at intervals of U/L [s], where L represents the bump's period, which was 24 mm.

I used an adjustment methodology. The experimental procedure was as follows. Participants initially received an explanation of the experiment and provided their informed consent. Subsequently, I placed the wooden board in front of the participants and asked them to freely trace the board along its long side with their hands. I recorded participants' tracings to investigate how fast they traced the board without prior knowledge. Afterward, the participants practiced operating the extended hand and the experimental task for 5 minutes. Similar to the experiment in Section 3.4, participants were required to touch the touch panel with a force of approximately 0.4 N using their index finger and operate the extended hand. Additionally, they were required to trace a length of 150 mm back and forth along the long side of the wooden board at a specified speed with the extended hand. The system displayed a red point indicating the desired movement, and participants used this point as a reference to operate the extended hand. Furthermore, I monitored the force with which participants touched the touch panel using a weight scale.

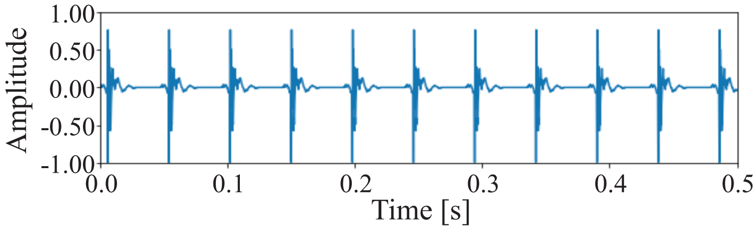
After the practice session, participants repeatedly performed the main task as follows: Participants touched the wooden board placed at distance D with the extended hand at a specified speed V. While the extended



(a) Unit waveform



(b) Power spectrum of unit waveform



(c) Waveform at tracing speed of 500 mm/s

Figure 3.9: Sound used in Section 3.5 experiment. I recorded this sound by tracing the wooden board in Fig. 3.8 with a silicone finger model. (a) shows the waveform generated when the finger model passed over a single bump, and (b) is its power spectrum. I synthesized the sound when tracing the uneven board with a pattern period $L = 24$ mm at a speed V [mm/s] by arranging the waveform of (a) for each V/L [s]. (c) is the synthesized sound when $V = 500$ mm/s. Actual sound data is available at https://yushisato.com/projects/soundtexture_eh/

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hand traced the wooden board, a sound texture was presented to the participants. The tracing speed U of the sound texture was determined based on the position of a slider bar displayed on a PC. Participants set the tracing speed of the sound texture by adjusting the position of the slider bar so that they felt most natural when touching the object with the extended hand. The tracing speed could be set within the range of 50 mm/s to 700 mm/s, with increments of 1 mm/s.

Participants performed this task for each of the six extended hand movement speeds (100 mm/s, 200 mm/s, 300 mm/s, 400 mm/s, 500 mm/s, 600 mm/s) and two distances (0.5 m, 2.0 m) three times each, for a total of 36 tasks. I randomized and balanced the order of conditions across participants.

After completing the main part, participants were instructed to complete the questionnaire provided in Table 3.1 using a 7-point Likert scale, similar to the experiment described in Section 3.4. Additionally, participants were asked to verbally indicate how many times they believed a sound occurred when passing through one bump. I posed this question because, in reality, a collision sound is produced when passing from a convex to a concave of the board. However, some participants might have believed that a sound also occurred when transitioning from a concave to a convex of the board, so I inquired about their perceptions. Furthermore, participants verbally reported their policies for setting tracing speeds and their impressions of the sound textures.

I recruited 16 participants whose dominant hand was right and whose ages ranged from 21 to 30 (14 males and two females). The average time for each participant to complete the experiment was approximately 60 minutes.

3.5.2 Results

Main results

I present the results of the set tracing speeds in Fig 3.10. Although only one collision sound was produced when a physical finger traversed through one bump on the wooden board, six participants mistakenly believed that two collision sounds occurred. Thus, I adjusted their tracing speed values by halving them. I performed a two-way repeated-measures ANOVA with the extended hand movement speed and distance as factors. The ANOVA result showed a significant difference in the movement speed factor ($F(5, 75) = 97.91$, $p < 0.01$, $\eta_p^2 = 0.87$), the distance factor ($F(1, 15) = 12.49$, $p < 0.01$, $\eta_p^2 = 0.45$), and the interaction effects ($F(5, 75) = 2.49$, $p < 0.05$, $\eta_p^2 = 0.14$). Post-hoc analysis of the interaction effects revealed that, under movement speeds of 300 mm/s, 400 mm/s, and 500 mm/s, the farther distance resulted in significantly greater tracing speeds ($p < 0.05$, Bonferroni correction). Additionally, in each distance condition, for all combinations of movement speed, except for 400 mm/s and 500 mm/s, 400 mm/s and 600 mm/s, 500 mm/s and 600 mm/s (and only for a distance of 0.5 m conditions, 200 mm/s and 300 mm/s), it was observed that higher movement speed led to faster tracing speeds of the sound texture ($p < 0.05$, Bonferroni correction). In the post-hoc analysis of the main effect of movement speed, significant differences were observed in the same combinations as in the post-hoc analysis of the interaction effect at a distance of 2.0 m ($p < 0.05$, Bonferroni correction).

Next, the tracing speed U [mm/s] of sound textures when tracing objects at speed V [mm/s] with the actual hand can be expressed as $U(V) = V$ [mm/s]. Therefore, for each participant and at each distance, I fitted the data of the extended hand's movement speed V [mm/s] and set tracing

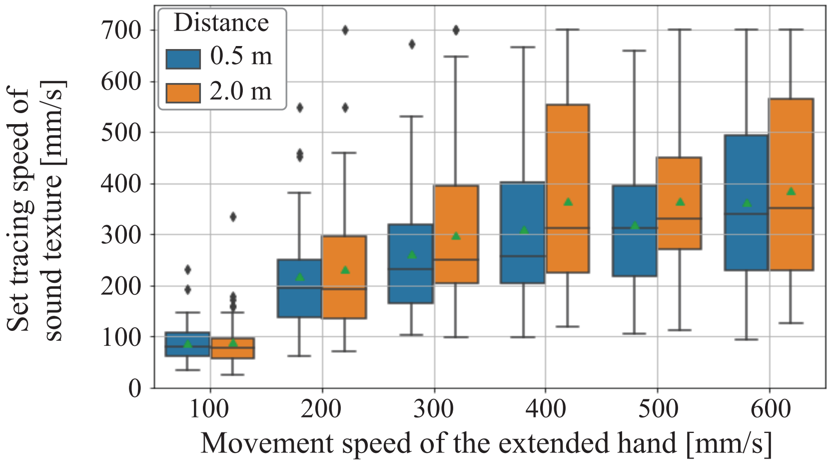
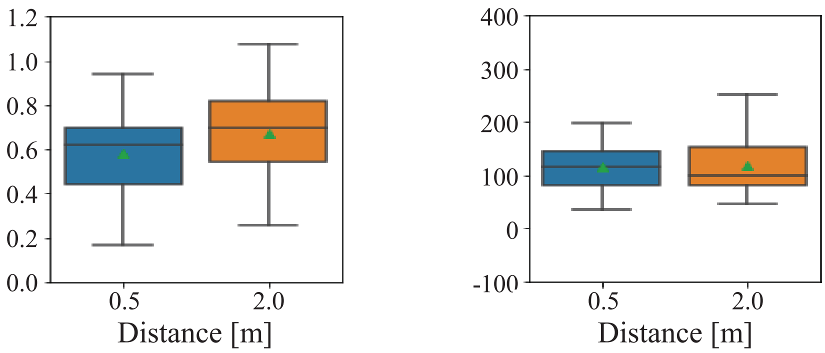


Figure 3.10: Distribution of tracing speeds set by participants



(a) Calculated value of c

(b) Calculated value of d

Figure 3.11: Calculated values of coefficient c and d.

speed U [mm/s] to the equation $U(V) = cV + d$ and calculated the values of coefficients c and d. Figure 3.11 shows the results of the calculated coefficients c and d. I tested whether the value of c was equal to the value of $c = 1$, which is the value when traced by an actual hand. The t-test showed a significant difference in both the distances of 0.5 m and 2.0 m ($p < 0.001$).

Freely tracing

I analyzed the speed at which participants freely traced the wooden board with their hands at the beginning of the experiment. I calculated the speed based on the time it took to trace a distance of 200 mm at the center of the board. Figure 3.12 shows the results of the speed. The mean and standard deviation of the speed were 394±110 mm/s.

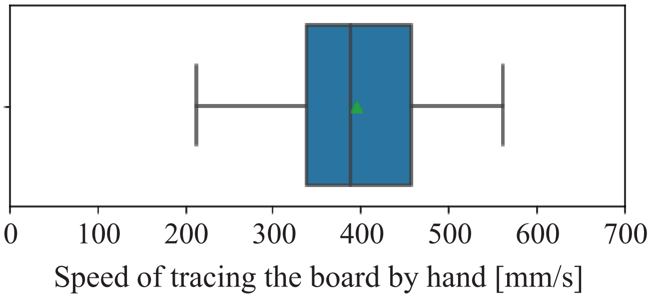


Figure 3.12: Results of the tracing speed when participants freely traced the wooden board with their hands.

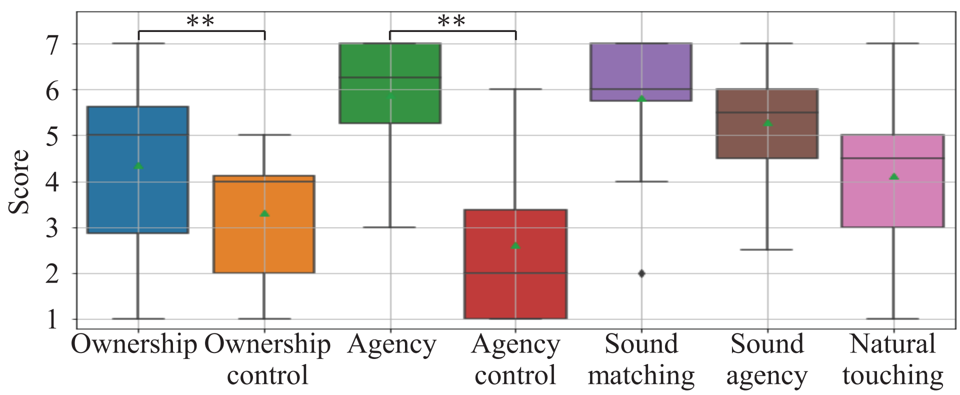


Figure 3.13: Results of the questionnaires in Table 3.1.

Scores for questionnaire

Figure 3.13 shows the evaluation results in response to the questionnaires in Table 3.1. I performed a t-test for Ownership and its control category, and the results showed a significant difference between them ($p < 0.05$). Similarly, I performed a t-test for Agency and its control category, and the results showed a significant difference between them ($p < 0.05$). These results bolstered the credibility of the participant survey responses. All participants, except for one, scored four or higher on Sound agency. This suggests that nearly all participants perceived that they were touching the boards with the extended hand, which in turn generated the sound.

Setting policy and impressions

The participants' verbal feedback at the end of the experiment was as follows: Regarding the policy for setting tracing speeds, all participants primarily relied on visual cues from the extended hand rather than their physical hand. Three participants mentioned the challenge of recognizing the number of bumps passed during faster movement speeds of the extended hand, which led them to adjust the tracing speed intuitively. Additionally, five participants chose a slower tracing speed of the sound texture in order to have clearer recognition of each collision sound when the movement speed of the projected hand was faster.

Furthermore, participants reported that the distance to the boards influenced their perceptions. Three participants noted that the distant board appeared to have smaller bump periods, resulting in a faster tracing speed of the sound texture. In addition, five participants reported that when tracing the distant board, they felt the need to move their actual hand more significantly in order to manipulate the extended hand in the indicated manner.

3.5.3 Discussion

The experimental results suggested that when the movement speed of the extended hand was slow, the tracing speed of the sound texture should match the movement speed of the extended hand. On the other hand, when the movement speed of the extended hand was fast, it was appropriate for the tracing speed of the sound texture to be slower than the extended hand's movement speed. We could interpret this result as follows: According to the participants' verbal feedback, they primarily adjusted the tracing speed of the sound texture based on the visual information of the extended hand. When the movement speed of the extended hand was slow, participants could easily perceive how many bumps the extended hand had crossed through visual observation. Since visual information was highly reliable, participants relied solely on visual cues to set the tracing speed. As a result, there was an approximate alignment between the movement speed of the extended hand and the tracing speed of the sound texture.

In contrast, when the extended hand moved quickly, participants struggled to visually distinguish the number of bumps crossed by the extended hand. In these situations, participants likely relied on sensory cues other than vision, such as proprioceptive senses. The C/D ratio in this experiment, the C/D ratio was 5.0, meaning that when the extended hand moved 50 mm, the participant's hand only moved 10 mm. As a result, participants may have felt that their hand was not moving much, leading to fewer instances of bump crossing and, consequently, fewer occurrences of the collision sound. In other words, participants' proprioceptive senses supported a slower tracing speed for the sound texture. Additionally, participants' impressions of the bump board could have provided another cue. During the free tracing task, participants traced the board with their hand at speeds ranging approximately between 350 mm/s and 450 mm/s, as shown in Fig. 3.12. This finding suggests that participants generally do not trace objects at speeds as fast as 600 mm/s and may struggle to imagine the sound produced at such high speeds. In such cases, participants may have preferred sounds that corresponded to tracing speeds they could more easily envision. In summary, participants' reliance on proprioceptive senses and their impressions of the bump board likely influenced their preference for slower tracing speeds when visual information was less reliable, such as when the extended hand moved quickly.

The experimental results also indicated that as the distance increased, the tracing speed increased, particularly between 300 mm/s and 500 mm/s. This could be attributed to the fact that as the distance increased, the bumps on the surface of the wooden board appeared smaller within the participant's field of view. While there is a phenomenon known as size constancy in object perception, it is generally acknowledged that objects are not perceived as being exactly the same size [84, 85]. Participants would have felt as though they were touching objects with finer periodic patterns, potentially leading to a greater number of perceived bumps. Furthermore, in this study, I maintained a constant C/D ratio regardless of the distance. As a result, the movement of the extended hand within the participant's field of view became smaller as the distance increased. Participants subjectively felt that they moved their hands to a greater extent to achieve the indicated manipulation, which may have led them to perceive an increase in the number of bumps crossed by the extended hand.

Based on these results, it is suggested that when applying sound texture feedback to ExtendedHand, it may be more appropriate to design the tracing speed of sound textures to be proportional to the logarithm of the movement speed of the extended hand. The results also indicated that the user's field of view regarding changes in object and extended hand size varies with distance, which could potentially affect tracing speed. Therefore, when designing the tracing speed, it may be necessary to take distance into consideration.

3.6 Conclusion

In this chapter, I worked on providing users with the sensation of touching objects by presenting sound textures corresponding to the objects when the extended hand touched them. I focused on the unique characteristics of the extended hand, which amplifies the user's hand movements and allows users to touch objects that would normally be out of reach. Through user studies, I investigated how sound textures' sound pressure and tracing speed should be adjusted in such interactions.

As a result, the sound pressure level of sound textures should generally follow the same sound pressure attenuation pattern as in physical phenomena. However, even as the distance increases and the sound pressure decreases, it is advantageous to maintain a sound pressure level that remains audible to the user. The results also indicated that when the extended hand's speed is slow, it is appropriate to match the tracing speed of the sound texture to the extended hand's speed. However, when the extended hand's speed is fast, it was shown to be more appropriate to make the tracing speed of the sound texture slower than the extended hand's speed due to a decrease in the reliability of visual information. This research has provided fundamental and valid design guidelines for sound texture feedback when utilizing extended bodies.

Chapter 4

Adaptive Pseudo Tactile Feedback System for Extended Hand Users

In this chapter, I propose the Responsive-ExtendedHand, which integrates an RGB-D camera into the ExtendedHand system to automatically generate visual effects suitable for an object touched by the extended hand. This system enables appropriate visual effect feedback even though ExtendedHand does not have prior information about the position of objects in the scene, allowing users to feel the tactile sensations of touched objects naturally.

The chapter begins with an exploration of the motivation behind the work, followed by a review of related studies on scene recognition using deep learning. I then describe the Responsive-ExtendedHand system and experiments conducted and conclude with a summary.

4.1 Introduction and Motivation

In Chapters 2 and 3, I proposed methods providing pseudo-tactile sensations from visual and auditory stimuli, respectively, and identified feedback guidelines suitable for touching objects with the extended hand. On the other hand, these efforts were conducted as a psychological experiment to induce pseudo-tactile sensations; the position and properties of objects were known, and the application to practical situations where objects with various properties exist in various locations was not considered.

This information is pre-modeled and stored as a scene model in VR applications. However, the ExtendedHand interface targeting MR space requires online recognition and acquisition of object information at different locations in the scene.

In this chapter, I introduce a new function that senses the usage scene, recognizes information about the location and type of objects online, and adaptively applies the appropriate visual effect to the object touched by the extended hand. This enables the user to naturally perceive the tactile sensation of the touched object, even without prior information about the objects in the scene. I call the proposed system Responsive-ExtendedHand, which enhances the real-world applicability of ExtendedHand. To realize this system, I use an RGB-D camera to observe objects' shape and surface texture near the extended hand. I then employ U-Net [86] to estimate appropriate visual effects online based on the RGB-D images obtained. In this chapter, I present the construction of Responsive-ExtendedHand and clarify its performance through a user study.

4.2 Related Work on Scene Recognition using Deep Learning

When recognizing scene information, it is common to create an observation system using a sensor such as an RGB camera. The sensor values obtained are then used to extract and estimate the desired target information. Deep learning methods have gained significant attention in recent years for these purposes. Various approaches have been proposed to utilize deep learning to estimate object categories in RGB images. These approaches include methods that predict a single category for the entire image [87], methods that estimate categories for multiple objects in the image [88], and methods that estimate categories for each pixel in the image [86]. Furthermore, diverse estimation methods have been developed for specific categories. For example, some methods predict a universal set of 1,000 categories [87], while others focus on narrower domains, such as estimating 23 types of materials [89]. This diversity allows for a wide range of estimation possibilities, depending on the system's specific needs, as long as large-scale training datasets are available.

For ExtendedHand, it may be possible to estimate appropriate feedback based on the object touched by the extended hand using a deep learning framework. In particular, for tactile stimulus feedback [37, 38], vibration data from tracing an object can be used as appropriate tactile stimulus feedback based on the findings of previous studies [90, 91]. Several studies have already published large datasets of objects and vibration data when tracing them [92, 93]. However, in the case of visual effect feedback [2, 94], there is currently no dataset available that combines objects and visual effects. Additionally, research findings and the data collection experiment described in Section 4.4.2 indicate that suitable visual effects for the same object highly rely on user preferences. Thus, creating a large dataset with multiple users and training the network on that dataset does not guarantee high accuracy.

In this chapter, I present a personal user system that aims to estimate appropriate visual effects for an object and apply them to the extended hand

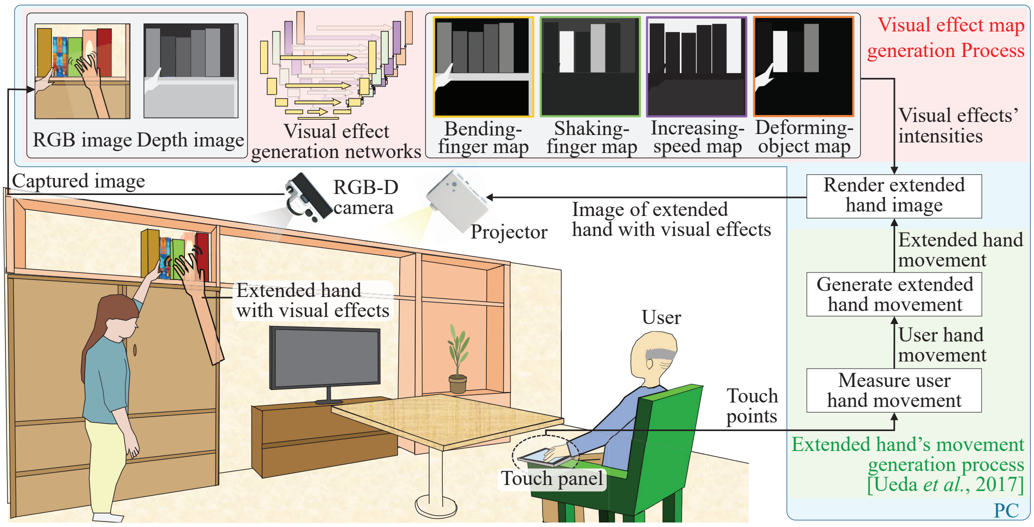


Figure 4.1: Overview and process flow of Responsive-ExtendedHand. The system generates visual effects suitable for the object being touched by the user-operated extended hand by employing an RGB-D camera and deep learning framework. This enables the user to feel the tactile sensation of the object through pseudo-haptics by viewing the extended hand with the visual effects, even without prior object information in the scene.

when it touches the object. To achieve this, I utilize RGB-D images and train a network on customized datasets consisting of object and visual effect data for each individual. While I rely on established deep learning techniques and a dataset of approximately 100 images per individual, I realize the system that can make users naturally perceive the tactile sensation of the object touched by the projected hand without prior information about various objects.

4.3 Responsive-ExtendedHand

4.3.1 System Design

I present an overview and system flow of Responsive-ExtendedHand in Fig. 4.1. When the user moves their hand on a touch panel, the movement is amplified and reflected in the motion of the extended hand. The extended hand is projected onto a real scene using a video projector. An RGB-D camera captures the area surrounding the extended hand. When the system detects that the extended hand is overlapping an object in the RGB-D image, it adds visual effects suitable for the object to the extended hand and its surrounding area. The user can experience the tactile sensation of the object by seeing the extended hand with the visual effects, even though their hand is touching the touch panel.

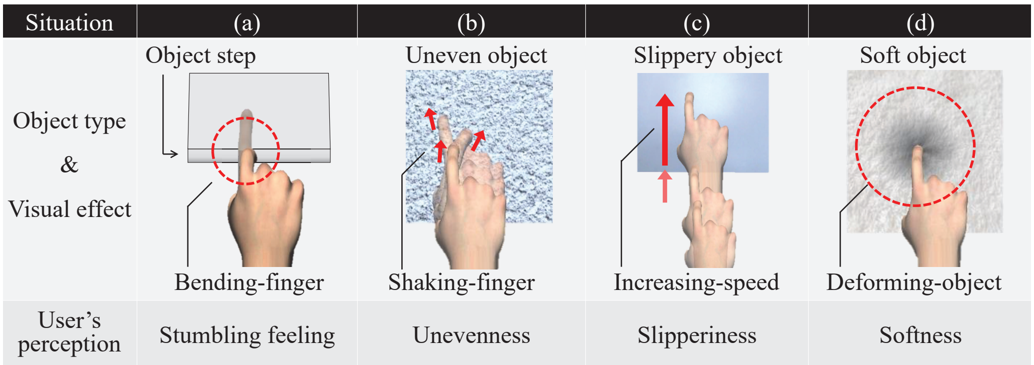


Figure 4.2: Visual effects that are applied when the extended hand touches an object. (a) Bending-finger effect for an object's height difference [94, 95], (b) Shaking-finger effect for an uneven object [2], (c) Increasing-speed effect for a slippery object [2], and (d) Deforming-object effect for a soft object [2].

Although the appropriate visual effects for object characteristics vary depending on user preferences, the proposed system fundamentally focuses on the following four situations, as introduced in Chapter 2 and related studies [94, 95], as illustrated in Fig. 4.2:

(a) Bending-finger effect for an object's height difference,

(b) Shaking-finger effect for an uneven object,

(c) Increasing-speed effect for a slippery object,

(d) Deforming-object effect for a soft object.

4.3.2 System Flow

Responsive-ExtendedHand consists of two components: (A) Reflecting the user's hand movement and gestures onto the extended hand (green color area of the process flow in Fig. 4.1); and (B) Adding the appropriate visual effects to the extended hand by analyzing the scene (pink color area in Fig. 4.1). For component (A), I utilize ExtendedHand [19], which measures the user's hand movement from a touch panel input. Component (B) is further divided into the following four processes:

(B)-1 Visual sensing of the scene area around the extended hand,

(B)-2 Extraction of objects' physical properties from the sensor values,

(B)-3 Estimation of the appropriate visual effect based on the object's physical properties,

(B)-4 Modulation of the virtual hand image according to the estimated visual effect.

Here, processes (B)-2 and (B)-3 can be combined into a single process using a deep learning approach, if data on the relationship between the sensor values and the appropriate visual effect are available. These processes are explained in detail in the following.

Area sensing

I use an RGB-D camera as a sensor to capture the scene, which can measure the area around the extended hand without physical contact. This camera can extract material information from RGB color images. Additionally, it can gather information about objects' shapes and surface structures unaffected by texture or shading from Depth images. These features are essential for distinguishing object regions and determining the appropriate visual effects.

It is important to note that solely relying on RGB-D images makes it impossible to differentiate objects with similar appearances and shapes but varying hardness. The system prioritizes making users feel they are naturally touching objects rather than conveying the proper physical properties. Therefore, the system configuration solely depends on an RGB-D camera, which plays a role similar to the user's eyes.

The system clips only the projection area after geometrically transforming the captured RGB-D image using a pre-prepared pixel-to-pixel correspondence matrix between the RGB-D camera and the projector. This study limits the target object to a thin planar object and employs a homography transformation matrix as the correspondence matrix.

Visual effect map generation

The proposed system utilizes a deep learning framework to generate visual effect maps from the clipped RGB-D image. These maps determine the intensities of the visual effects for each pixel of the clipped RGB-D image (see Fig. 4.1). In this system, I utilize U-Net [86] to generate the visual effect maps (referred to as the *visual effect generation networks*). U-Net is a neural network that performs pixel-by-pixel segmentation of image input. Notable features of U-Net include its skip-connection structure, which accurately preserves boundary information for objects in the image. Additionally, U-Net can achieve high precision in identification even with limited data by utilizing data augmentation [86]. Considering that these features align with the requirements of the proposed system, I have chosen U-Net. This system uses separate networks for each visual effect to ensure easy scalability for potential additional types of visual effects in the future. In this system, the encoder and decoder layers of U-Net consist of eight layers each. The output layer uses a Sigmoid function to output values in the range of $[0, +1]$.

First, I resize the clipped RGB-D image to 256×256 pixels and then normalize the pixel values to the range of $[-1, +1]$. This normalized image is then used as the input for each network. Each network generates a visual effect map that holds the intensity values $[0, +1]$ of the corresponding visual effect for each pixel. The methodology for collecting training data and the training process is explained in Section 4.3.3.

Visual effect addition

To apply visual effects to the extended hand, the system retrieves the pixel value from each visual effect map that corresponds to the fingertip position of the extended hand. The system then applies the corresponding visual effect with an intensity that matches the pixel value to the extended hand. If there are multiple types of visual effects with non-zero intensity values, the proposed system combines them. The Bending-finger effect is specifically designed to be applied only at object boundaries. This is accomplished by applying the effect only when the pixel value corresponding to the fingertip position of the extended hand changes by more than a threshold value (set empirically to 0.1) compared to its value in the previous frame.

4.3.3 Training of *Visual Effect Generation Networks*

As mentioned in Section 4.3.2, training the *visual effect generation networks* requires a dataset of RGB-D images and their corresponding visual effect maps. The four visual effects shown in Fig. 4.2 are exaggerated representations of the physical phenomena that occur when an object is touched by a physical hand, which differ from the actual physical phenomena. Furthermore, the dataset collection experiment described in Section 4.4.2 shows that the appropriate visual effect for the same object varies depending on the user's preference. Therefore, in this study, the system is configured for each user, and a dataset is prepared for each individual user.

A user follows a specific process to create the dataset, as illustrated in Fig. 4.3(a). They creates visual effect maps based on their preference for each object on the projection surface. This involves defining the object regions in the RGB-D images and setting appropriate visual effects intensities. The user replaces the objects on the projection surface with different types of objects for a limited number of iterations to complete the dataset. Subsequently, the dataset is expanded through the use of data augmentation [96]. During network training, the RGB-D images are inputs, while the corresponding visual effect maps serve as the ground truth (Fig. 4.3(b)).

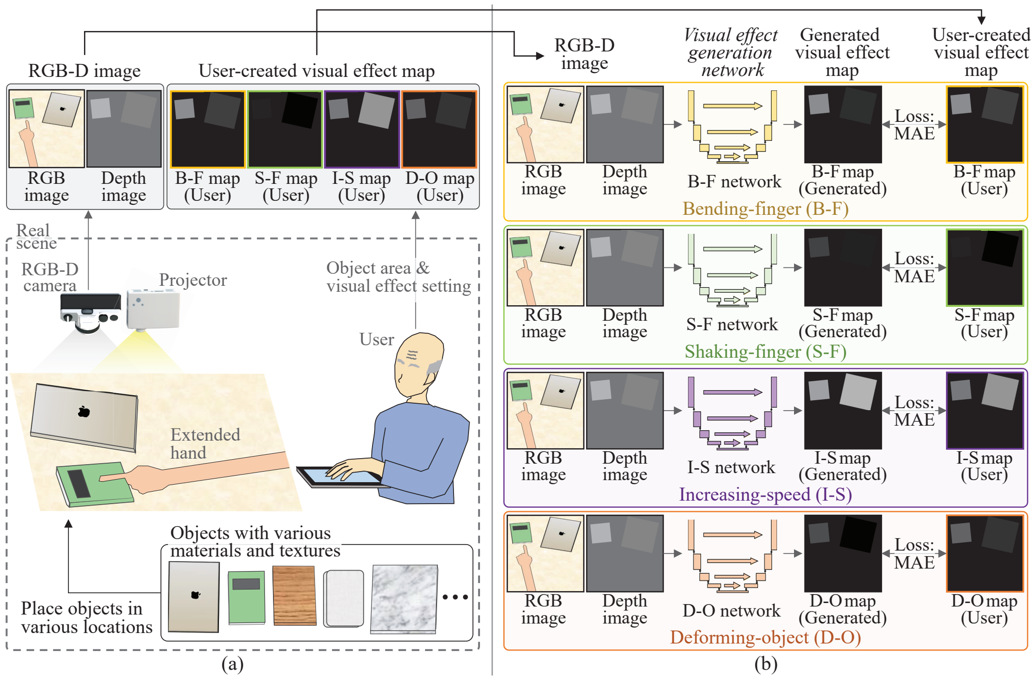


Figure 4.3: Procedure for training *visual effect generation networks*. (a) Creation of the training dataset. The user places different objects in the scene and configures the object area and appropriate visual effects for each object. The system stores the paired data of the captured RGB-D image and the user-created visual effect maps. (b) Training of the *visual effect generation networks*. The system trains each network using the RGB-D images as input and the user-created visual effect maps as ground truth.

4.4 System Implementation

I implemented the prototype system of Responsive-ExtendedHand based on Section 4.3.

4.4.1 Hardware Configration

Figure 4.4 shows the appearance of the implemented system. The user used the extended hand on a white tabletop in this system. A projector (NEC, NP-L51WJD) was mounted on the ceiling and projected images onto a 540 mm $\times$ 910 mm area on the tabletop at 60 fps. An RGB-D camera (Intel, RealSense L515) next to the projector captured the projection surface at 30 fps. A touch panel (Microsoft, Surface Pro 3) placed beneath the tabletop enabled the user to manipulate the extended hand. The C/D (control-display) ratio was empirically set at 1:5. In other words, when a user moved their hand by 10 mm on the touch panel, the extended hand on the tabletop would move by 50 mm. Another PC (Microsoft, Surface Book 3) was employed to generate visual effect maps, control the extended hand's movements, and render the projection images.

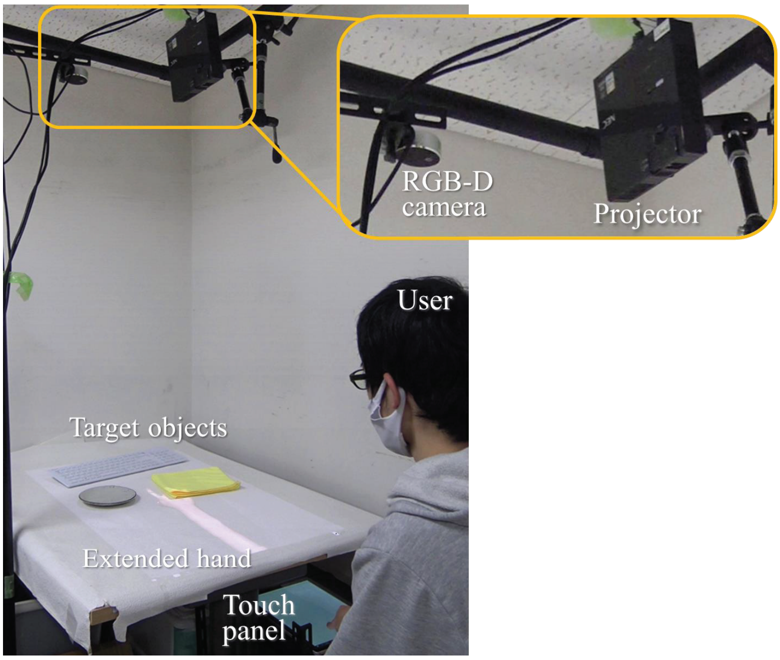


Figure 4.4: Appearance of the implemented system. The extended hand is projected onto a white table from a projector mounted on the ceiling. An RGB-D camera mounted next to the projector captures an RGB-D image of the projection area.

4.4.2 Creation of Training Dataset

In this implementation, 15 participants, aged 21 to 24, created datasets for training the *visual effect generation networks*. Each participant created 105 data points.

The experiments conducted in this section and Section 4.5 were approved by the Research Ethics Committee of Osaka University (No. R2-28). Additionally, I obtained written informed consent from each participant.

Visual effect

I linearly normalized the intensity (degree of change) for each of the four visual effects shown in Fig. 4.2 within the range of $[0, +1]$. I refer to these intensities as t_{B-F}, t_{S-F}, t_{I-S}, and t_{D-O}, respectively. At the minimum intensity ($t = 0$), the corresponding visual effect was not applied. On the other hand, at the maximum intensity ($t = 1$), the corresponding visual effect change was overemphasized. In this case, almost all participants perceived the change in the extended hand as being caused by factors other than the characteristics of the touched object. The specific changes produced at minimum and maximum intensity were determined in Table 4.1 using the design parameters format introduced in Chapter 2 and a previous study [95].

Table 4.1: Design parameter values for the visual effects at maximum and minimum intensity.

Bending -finger [95]	l_{th} [mm] (Amount of finger joint bending)			
$t_{B-F}=0$	0.0			
$t_{B-F}=1$	100.0			
Shaking -finger	A_{real} [mm] (Finger tip amplitude)	λ [mm] (Finger vibration period)		
$t_{S-F}=0$	0.0	10.0		
$t_{S-F}=1$	2.0	10.0		
Increasing -speed	γ (Rate of speed increase)			
$t_{I-S}=0$	1.0			
$t_{I-S}=1$	2.0			
Deforming -object	r [mm] (Area)	$time$ [ms] (Duration)	d [mm] (Depth)	d_{shade} (Shade darkness)
$t_{D-O}=0$	0.0	400	0.1	0.3
$t_{D-O}=1$	100.0	200	1.7	0.3

Target object

Based on relevant research [89, 97], I selected seven commonly used indoor materials: ceramic, fabric, metal, paper, plastic, stone, and wood. For each material, I chose five objects with distinct surface textures. As a result, the 35 objects shown in Fig. 4.5 were prepared as objects that the extended hand touched. In this study, I excluded objects with low reflectance or significant height variations that cannot be effectively corrected using homography transformation. The white tabletop was also considered the background and not included as part of the target objects.

Collection procedure

Participants were given the task of adjusting the appropriate intensities of visual effects for objects. To perform this task, participants used their index finger to operate the extended hand at a speed of approximately 200 mm/s. Ample practice was provided beforehand to ensure participants could achieve this speed.

At the beginning of each trial, an experimenter placed two or three objects on the white tabletop. These objects belonged to the same group, as indicated in Fig. 4.5, and their placement locations were randomly determined by the system to avoid overlap. The system then instructed the participant to trace one of the objects using the extended hand. As the extended hand overlapped with the object, four visual effects were added. The participant adjusted the intensity of each of the four visual effects by operating the position of the four sliders on the MIDI controller (Worlde,

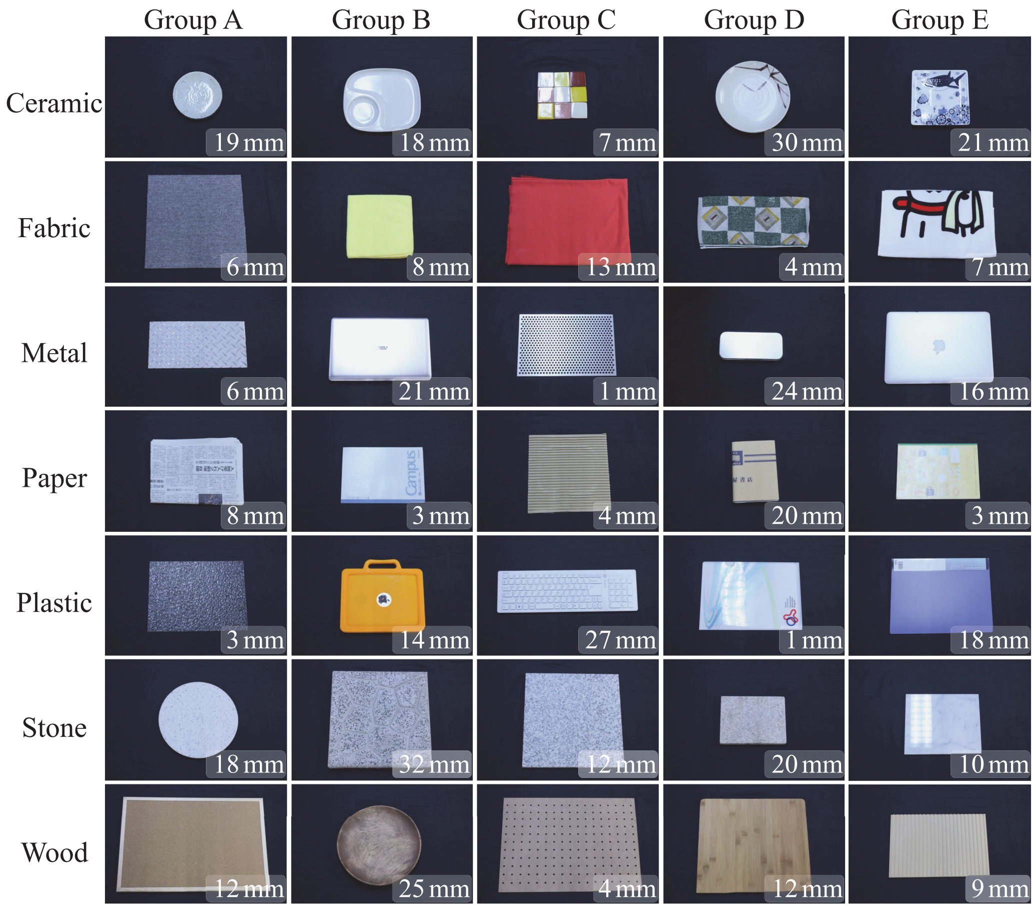


Figure 4.5: 35 different objects used in training and evaluation. The size of each image is approximately 500 mm in width and 300 mm in height. The numerical values indicate the maximum thickness of the objects.

EasyControl.9). The goal was for the participant to set the four intensities at which they felt most natural touching the object with the extended hand.

Once the participant decided on the visual effects, the system recorded the RGB-D image and the intensities of the set visual effects. After the recording, the participant was instructed to perform the same task on the remaining objects on the table. This process continued until the task was completed for all the objects. Then, a new set of objects was placed for the next round of tasks.

Each participant performed this task three times for each of the 35 objects, resulting in a total of 105 trials. The entire task, including explanation time and breaks, took approximately two hours to complete. The order in which the objects were touched and the combinations of objects placed on the table were randomized.

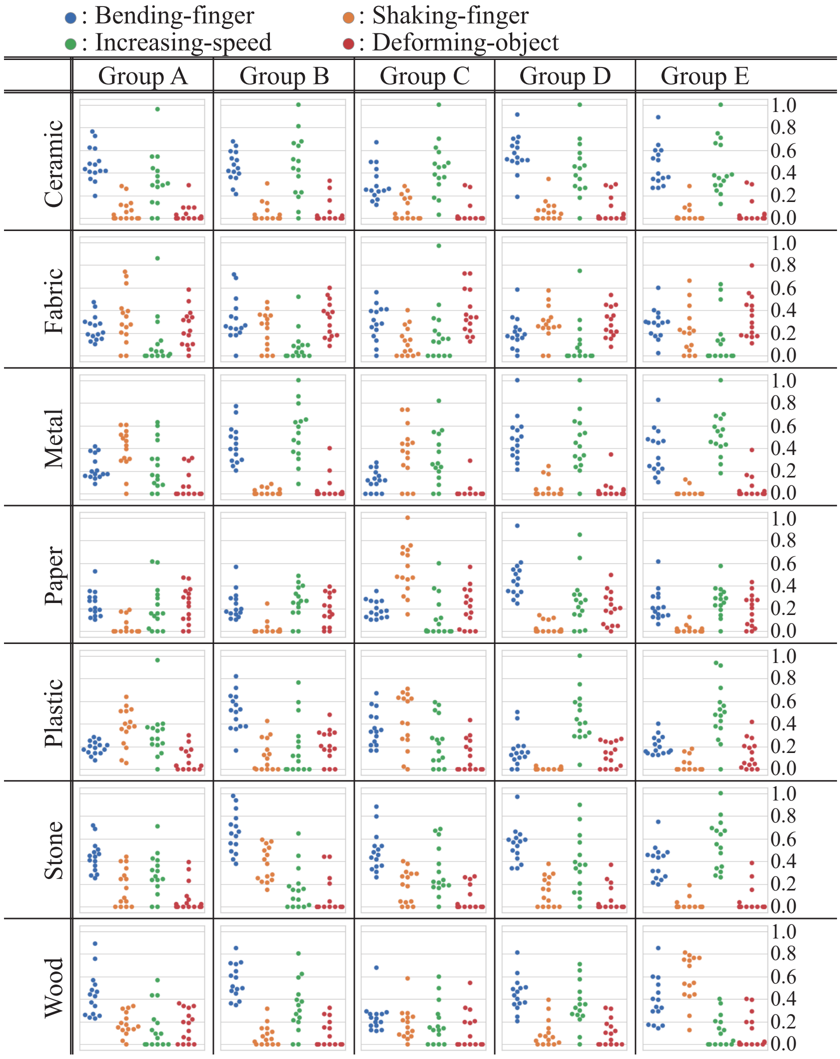


Figure 4.6: Distribution of the intensities of the visual effects set by the participants for each of the 35 objects. Each dot represents an individual participant. The median values are used since each participant sets visual effects three times for each object.

Created dataset

I collected 105 RGB-D images and their corresponding visual effect maps per participant. Figure 4.6 shows the distribution of the intensities of the four visual effects that each participant set for each object. Since each participant set the intensities three times for each object, I used the median value as a representative measure. These results highlight significant variations in the intensities set by each participant for the same object, especially for the Increasing-speed effect.

4.4.3 Trainig of *Visual Effect Generation Networks*

I trained the *visual effect generation networks* using the dataset created in Section 4.4.2. As mentioned in Section 4.3.3, for this study, I trained separate networks tailored to each participant using datasets created by each participant.

Considering the practical application scenarios of the proposed system, it is not feasible to require users to pre-set appropriate visual effects for all objects in the scene. Therefore, the system needs to accommodate two categories of objects: **known objects**, which were included in the data for network training, and **unknown objects**, which were not included in the network training. To evaluate both known and unknown objects in the user study in Section 4.5, I used data from 28 out of 35 objects for network training. The remaining seven objects were kept unknown for the purpose of evaluation.

Training condition

For each participant's 105 data points, I utilized 84 data from three evaluations of 28 out of 35 objects for training. I selected these 28 objects from four out of the five groups shown in Fig. 4.5. Therefore, the training data consisted of four instances of each of the seven materials. The selection of the four groups was balanced across participants and randomized.

I expanded the dataset from 84 to 2,520 data points, increasing it thirtyfold using data augmentation techniques [96], such as brightness modulation and geometric transformations. Next, I trained each of the four *visual effect generation networks* using the expanded dataset. I used a batch size of 10 and employed the Adam optimization algorithm with a learning rate of 10^{-3}. I used the Mean Absolute Error (MAE) loss function and ran the training for 50 epochs. During each epoch, I used 20% of the training data as validation data.

Prediction results for unknown objects

I generated visual effect maps from RGB-D images of 21 data points (seven objects, each evaluated three times) excluded from the training using the trained networks for each participant. Figure 4.7 illustrates examples of the generated visual effect maps. I computed the Mean Absolute Error (MAE) between the generated maps and the ground truth maps created by the participants. Additionally, I separated the MAE calculations into the the background area (where the white table appears in the RGB-D images) and the target object area (where the target objects appear in the RGB-D images). Table 4.2 presents these results. Furthermore, I computed the MAE for each of the 35 objects. Figure 4.8 presents the results.

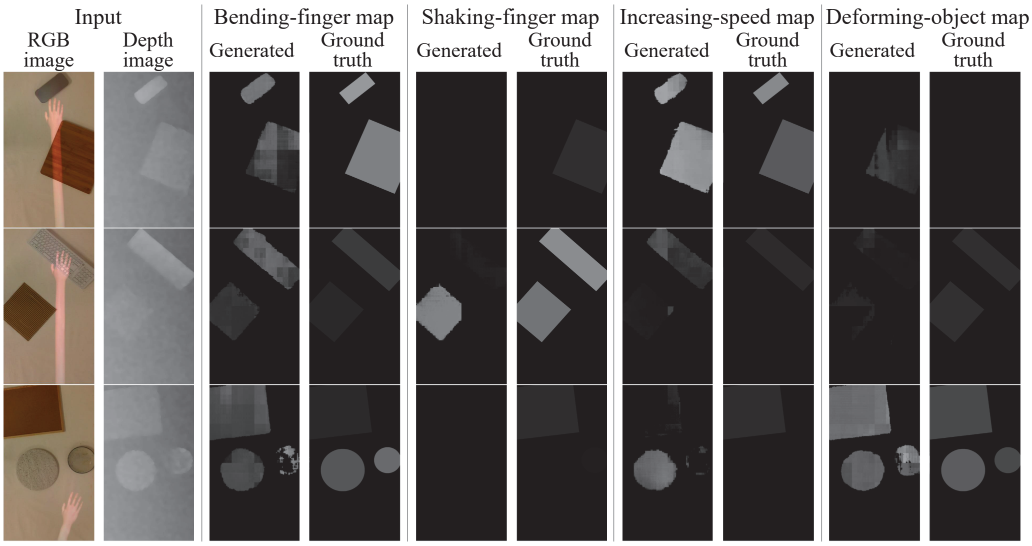


Figure 4.7: Examples of the generated visual effect maps. These maps were generated by the trained visual effect generation networks using RGB-D images that were not included in the training.

Table 4.2: Results of MAEs. MAEs were calculated for the entire map, as well as for the regions corresponding to the background and target object areas of the input RGB-D images, respectively. The values represent the mean and standard deviation.

Type of visual effects	MAE for the whole map	MAE for the background area of the map	MAE for the target object area of the map
Bending-finger map	0.05 ± 0.03	0.01 ± 0.01	0.17 ± 0.09
Shaking-finger map	0.06 ± 0.04	0.01 ± 0.01	0.19 ± 0.13
Increasing-speed map	0.07 ± 0.03	0.01 ± 0.01	0.21 ± 0.11
Deforming-object map	0.04 ± 0.03	0.01 ± 0.01	0.12 ± 0.09

The average MAE for the background area across all four visual effects generation networks was 0.01. This suggests that the networks were capable of recognizing the background region (the white tabletop). On the other hand, the average MAE for the target object area ranged between 0.12 and 0.21 across the four networks. For the target object area, the networks must not only identify the object's presence but also recognize its characteristics and determine the appropriate intensities of the visual effects. Therefore, it is inevitable that the MAE for the target object area was worse than that of the background area.

Focusing on individual objects, the average MAE values for most objects ranged from 0.1 to 0.3 across the four networks, shown in Fig. 4.8. Since there were no materials with notably large or small MAE values, it is suggested that the four networks do not exhibit a particular proficiency or deficiency for specific object material types.

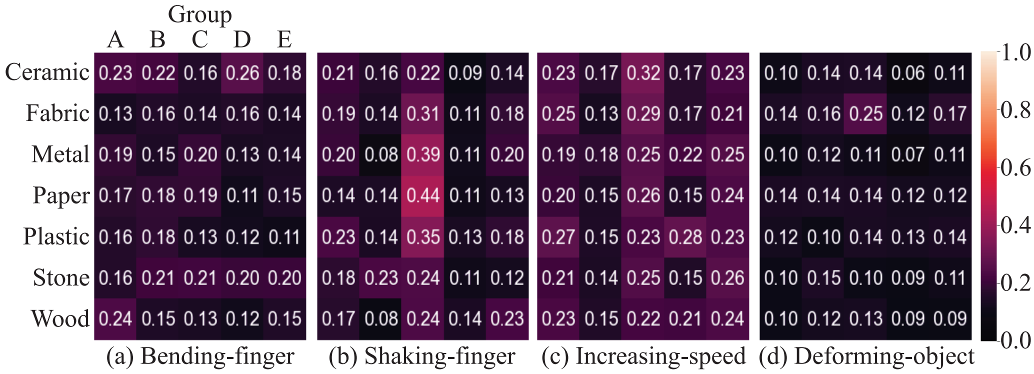


Figure 4.8: MAE results for each of the 35 objects. The values represent the mean.

However, the MAE for objects in Group C, particularly paper, metal, and plastic materials, was notably poorer than that of other objects in the Shaking-finger generation network. One potential explanation for this observation is that there were relatively many objects with uneven surfaces in Group C. In contrast, other groups had fewer objects with such uneven surfaces (such as stone materials in Groups A and B, metal materials in Group A, and wood materials in Group E). The MAE values might have been compromised because the Shaking-finger's intensity was estimated for uneven objects that were not extensively contained in the training data of the network.

Comparing the types of visual effects, the MAE values of the deforming object generation network were notably better than the others. This would occur because the intensity of the Deforming-object effect set by participants for each object was mostly 0.5 or below (see Fig. 4.6). As a result, the variance of the set Deforming-object's intensity for different objects was smaller than that of the other visual effects.

In this section, I have discussed the generation accuracy of the *visual effect generation networks* in terms of MAE values. However, how much these MAE values influence user perception is still unclear. This study aims to determine whether the proposed system can naturally convey the tactile sensation of objects to the user without prior object information. I will verify this aspect through the user study in Section 4.5.

4.4.4 Online Processing

I integrated the *visual effect generation networks*, trained in the previous section, into the prototype system shown in Fig. 4.4. Subsequently, I conducted evaluations in the environment depicted in Fig. 4.4. The time it took for the user's hand movement to be reflected in the motion of the extended hand was 150 ms. Shimada *et al.* [58] reported that users do not consciously notice delays below 200 ms, so the implemented system met this requirement.

In the implemented system (using a GPU: NVIDIA, GeForce GTX 1650), it took approximately 200 ms to generate a visual effect map with an image size of 256 $\times$ 256 pixels. The motion generation process for the extended hand and the visual effect generation process were handled in separate threads. Therefore, this delay did not affect the motion of the extended hand. This means that while providing visual effects to rapidly moving objects in the usage scene may be challenging, it is possible to provide suitable visual effects for relatively stationary objects with occasional changes in position or shape, even on less powerful PCs.

4.5 User Evaluation

I conducted a user study to assess the performance of the proposed system in a typical scenario where there is no prior information available about objects in the scene. This study aimed to determine whether users can naturally perceive the tactile sensations of objects touched by the extended hand.

4.5.1 Condition

Participant

The participants in this experiment were the same 15 individuals who participated in the dataset creation described in Section 4.4.2.

Visual effect addition

I used the system implemented in Section 4.4.3 to generate visual effects. Specifically, I trained the *visual effect generation networks* using data from 28 objects (four groups), as shown in Fig. 4.5. I will refer to this condition as the **Prop condition**.

Furthermore, for comparison, I introduced the following two conditions requiring the prior object information:

Perfect condition: In this condition, when the extended hand touched an object, the system provided the visual effects that were set by the respective participant for the object during the dataset creation in Section 4.4.2. I used the median value since each participant set the visual effects three times for each object.

Const condition: In this condition, when the extended hand touched an object, the system provided the same visual effects regardless of the type of the touched object. The visual effects were the average values set by each participant for all objects during the dataset creation in Section 4.4.2.

Target object

As mentioned in section 4.4.3, I prepared two categories of objects to be touched by the extended hand: **Known objects**, which were included in the training data of the *visual effect generation networks*, and **Unknown objects**, which were not included.

Each category consisted of seven objects (corresponding to one group in Fig. 4.5), one for each of the seven materials. For known objects, one group was chosen from the four groups used during training. For unknown objects, one group that was not used during training was selected. The selection of each group was randomized to ensure balance among participants.

4.5.2 Procedure

The experiment was conducted in the same environment described in Section 4.4.2, shown in Fig. 4.4. Initially, participants practiced manipulating the extended hand. Similar to Section 4.4.2, they used a single index finger to control the extended hand at a speed of approximately 200 mm/s. They received ample practice to become proficient in this operation. Following the practice session, participants repeated the following task:

Step 1: The experimenter arranged two or three objects on the white tabletop, ensuring that they did not overlap. The system randomly determined the types and placement of these objects.

Step 2: The system instructed the participant to touch one of the objects. The participant used the extended hand to touch and trace the indicated object. During this interaction, visual effects were applied to the extended hand under one of three conditions: Prop, Perfect, or Const. After the interaction, participants responded to the following two questions on a 7-point Likert scale (-3: Strongly disagree — $+3$: Strongly agree):

- **Q1:** Did you feel as though you were touching the object naturally with the projected extended hand?
- **Q2:** Did you perceive the tactile sensation of the object?

For Q1, participants were instructed to evaluate whether the appearance and movement of the extended hand overlapping the object were acceptable, rather than whether they resembled the appearance and movement of an actual hand touching the object. As mentioned at the beginning of this section, this study aimed to determine on whether participants could naturally perceive the tactile sensation of the object. I selected these questions because this criterion could be examined by analyzing the frequency of high scores for both Q1 and Q2.

Step 3: After answering the questions, participants were instructed to perform the same task on another object on the tabletop that they had yet to assess. When participants performed the task for all objects on the tabletop, they started from **Step 1** for another set of objects.

Each participant touched 14 objects (seven known and seven unknown) under each of the three visual effect addition conditions, resulting in a total of 42 times performing this task. The order of conditions was randomized and balanced across the participants. After completing all the tasks, participants verbally provided their impressions.

4.5.3 Results

Figure 4.9 presents the evaluation results for Q1 and Q2 in each condition. In this figure, the horizontal axis represents the scores for Q1 (-3 to $+3$), and the vertical axis represents the scores for Q2 (-3 to $+3$). Each cell shows the number of votes corresponding to the respective scores.

Visual effect addition factor (Fig. 4.9(a))

This user study aimed to determine whether participants naturally perceived the tactile sensation of objects touched by the extended hand. Therefore, as described in Section 4.5.2, I examined the rate of each participant who scored one or higher on both Q1 and Q2 in each condition (highlighted in the green box in Fig. 4.9(a)). The mean and standard deviation were as follows: Prop: 44.3%±22.8%, Perfect: 49.0%±23.7%, Const: 35.7%±24.2%. I performed an ANOVA with the visual effect addition as a factor. The ANOVA result showed a significant difference ($F(2, 14) = 3.51$, $p < 0.05$). Post-hoc multiple comparisons with Bonferroni correction revealed that the rate in the Perfect condition was significantly higher than in the Const condition ($p < 0.05$).

Target object factor (Fig. 4.9(b))

I performed the same analysis of results for the target object factor, and the results were as follows: Known objects: 47.6%±30.1%, Unknown objects: 41.0%±21.4%. The t-test result did not reveal any significant differences ($t(14) = 0.97$, $p > 0.05$).

Results for each object (Fig. 4.10)

I evaluated each of the 35 objects. I counted instances where both Q1 and Q2 received scores of 1 or higher. The results are shown in Fig. 4.10. Each object was evaluated twice by three participants under the Prop, Perfect, and Const conditions (For the Prop condition, three participants evaluated the objects once under the Known object condition and once under the Unknown object condition). Therefore, each object had a maximum of six assessments per condition.

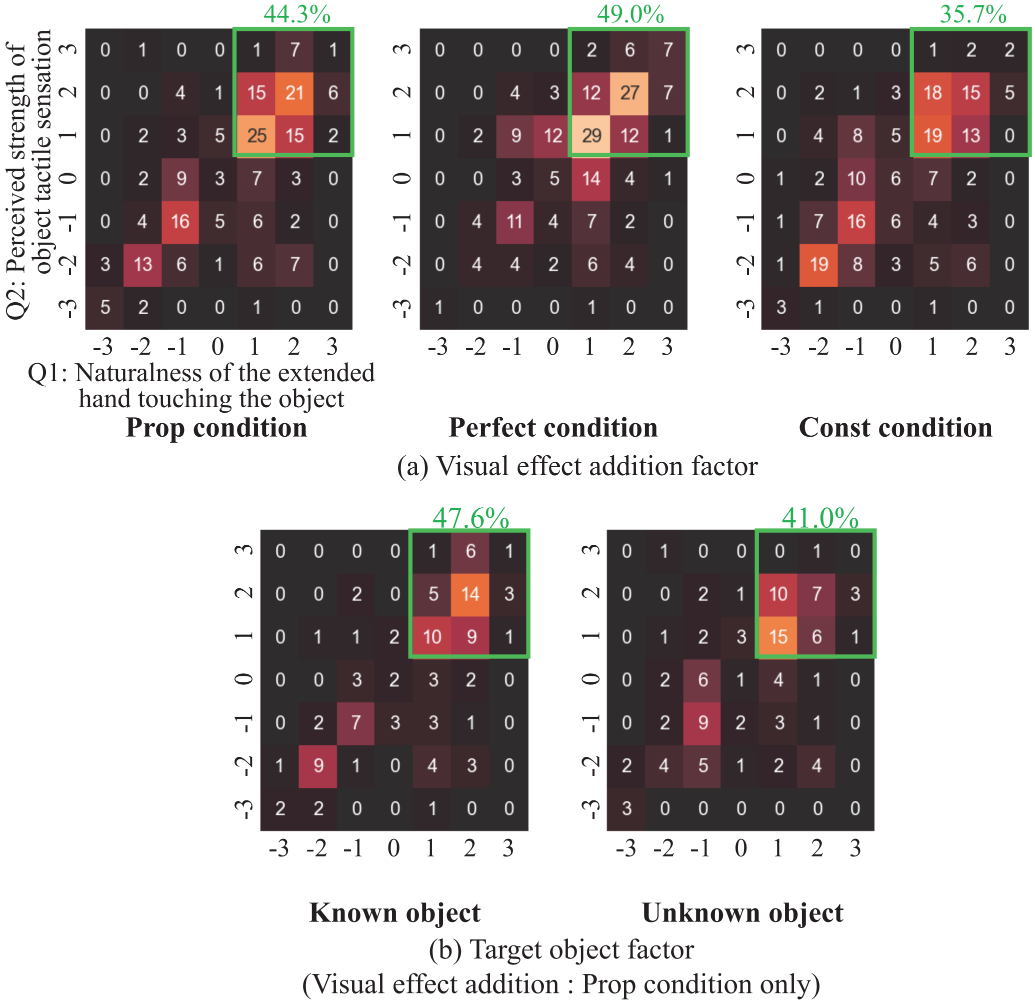


Figure 4.9: Results of participant evaluations. Each cell value represents the number of times the corresponding Q1 and Q2 were answered. The green percentages indicate the rate of participants who naturally perceived the tactile sensation of the objects (Q1>0 and Q2>0).

Participants' comments

In the verbal feedback from the participants, all of them mentioned that the appearance of visual effects that matched the objects enhanced the sensation of touching them. However, in 12 cases, participants reported that the appearance of visual effects that did not match the objects felt unnatural (e.g., it was unnatural for the Deforming-object to appear when touching a hard stone; or it was unnatural that the shaking finger did not appear for objects with uneven surfaces). Additionally, there were four reports indicating that the visual effect appeared in places where no object existed.

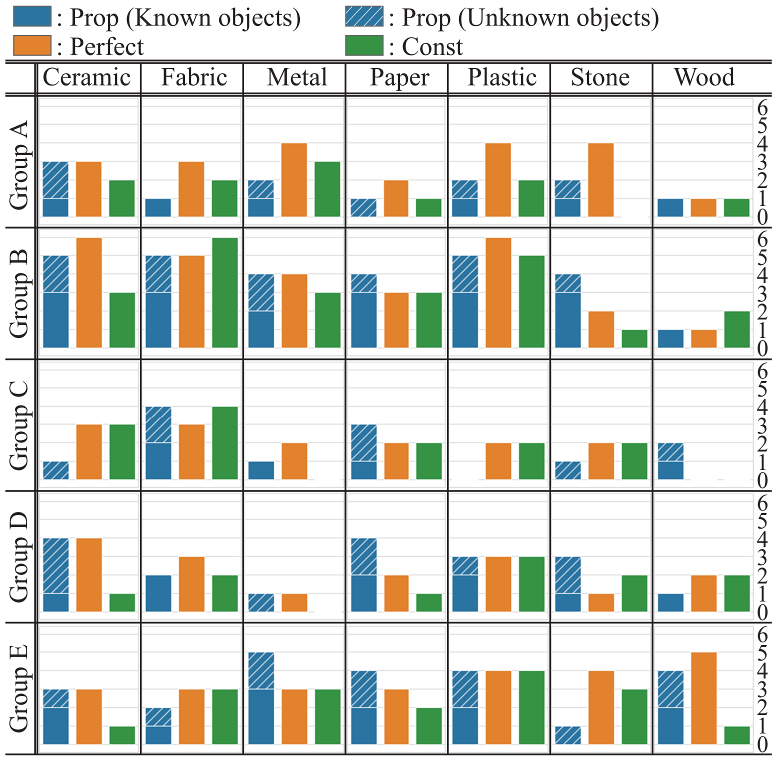


Figure 4.10: Results of participant evaluations for each of the 35 objects. The vertical axis on each graph represents the number of times participants naturally perceive the object' tactile sensation (Q1>0 and Q2>0). Each object was evaluated a total of six times under each condition, so the maximum value on the vertical axis is six.

4.5.4 Discussion

The proposed system aims to enable users to naturally perceive the tactile sensations of different objects touched by the extended hand without prior information about the objects. To assess this, I analyzed the rate of scores one or higher in both Q1 and Q2. The Perfect condition used the visual effects set by the participants for each object in Section 4.4.2. As a natural consequence, the Perfect condition had the highest average value of 49.0% among the three conditions. On the other hand, the average difference between the Prop and Perfect conditions was 4.7%, which was not statistically significant. This means that I cannot definitively conclude that there is no difference between the two conditions. It suggests that the proposed system (Prop condition) may perform worse than when object information is pre-set (Perfect condition).

However, the typical usage scenario for ExtendedHand does not provide information about the location and types of various objects in the scene. In these scenarios, the results showed that the proposed system could naturally make users perceive the tactile sensation of objects touched by the extended hand with high validity, with the preparation of about 100 data points. This is compared to the scenario where object information is provided in advance (Prop/Unknown Object condition: 41.0%, Perfect condition: 49.0%). Although the proposed system may be inferior to manually setting visual effects, it is considered the first example of generating pseudo-haptic sensations for unknown objects by incorporating online object recognition.

Examining the results for each object (Fig. 4.10), it is evident that several objects consistently obtained low scores regardless of the visual effect addition factor, such as the metal object in Group D and the wood object in Group A. This suggests that there is a limitation to the range of tactile sensations expressed by the four visual effects used in this study.

Although there are exceptions due to the small number of data, the results shown in Fig. 4.10 also indicate the following tendency: the Prop condition generally obtained slightly lower scores compared to the Perfect condition for all objects, rather than significantly lower for a specific material. This finding aligns with the results presented in Section 4.4.3, where the MAE values ranged from 0.1 to 0.3 for all objects. In light of this, potential improvements could be achieved by refining the data augmentation techniques in the training data [98] or utilizing transfer learning approaches [96].

4.6 Conclusion

In this chapter, I proposed Responsive-ExtendedHand, which integrates scene observation using an RGB-D camera and online object recognition using deep learning techniques into ExtendedHand to adaptively estimate appropriate visual effects for objects touched by the extended hand. The system aimed to allow the user to perceive the tactile sensations of the objects, even without prior information about the objects in the scene. The user evaluation results indicated that the proposed system performed slightly worse than the Perfect condition, which requires complete information about the location and type of the objects. However, it successfully enabled users to naturally perceive the tactile sensation satisfactorily without needing such information.

Future work will focus on generating appropriate visual effects for unspecified users by considering not only the RGB-D image but also the user's preferences. Additionally, this chapter primarily addressed situations where few objects are sparsely distributed. However, I intend to expand the system's capabilities to handle situations where objects are densely distributed.

Chapter 5

Discussion and Conclusion

In this chapter, I briefly recapitulate this thesis's contributions and discuss the proposed solution's limitations. Additionally, I present several future research directions based on the foundation laid by this work.

5.1 General Discussion

In this dissertation, I challenged enable users to feel the tactile sensations of distant objects when touching them with a projected extended hand without needing tactile feedback devices. To address this challenge, I proposed solutions based on modulating visual and auditory feedback to elicit pseudo-tactile sensations. Here, I summarize the efforts and contributions from Chapters 2 to 4.

5.1.1 Summary of Chapters

Chapter 2 designed three visual effects that evoke tactile sensations of roughness, smoothness, and softness. These effects were designed by applying the essence of findings of existing pseudo-haptic research to fit the extended hand. A user study confirmed that each visual effect successfully allowed users to perceive the corresponding tactile sensations. Further studies demonstrated that the visual effects could represent tactile intensity at three to five different levels without breaking the user's extended hand experience.

Chapter 3 focused on methods for enabling users to feel the tactile sensations of objects through sound texture feedback. Mainly, I pursued the design of appropriate sound texture feedback for scenarios where users touch an object not with their hands but through the extended hand. The result of a user study indicated that the sound pressure of sound textures should adhere to real-world physical laws when the distance is within 3 m. Additionally, other study's results suggested that when users trace an object slowly with the extended hand, the tracing speed of the sound texture should match the speed of the extended hand's movement. Conversely, when users trace the object quickly, a slower tracing speed of the sound texture than that of the extended hand's movement is preferable to ensure users feel the tactile sensations of the object naturally.

Chapter 4 introduced the Responsive-ExtendedHand system, which uses an RGB-D camera and deep learning techniques to estimate appropriate visual effects for objects touched by the extended hand, even in the absence of prior information about the objects. The results of Chapter 2 and the data collection study in Chapter 4 revealed that suitable visual effects for objects are not uniquely determined by the material properties of the objects alone but are significantly influenced by individual user preferences. Despite these conditions, by collecting dozens of individual data samples and training the *visual effect generation networks*, I demonstrated that the system can achieve about 80% of the performance set by users. Although I focused solely on visual effects in this chapter, the findings can be easily extended to sound textures.

5.1.2 Industrial and Academic Contributions

Throughout this dissertation, I have established a comprehensive solution that enables users to experience the tactile sensations of various objects using the extended hand in everyday indoor scenes without the need for special devices. This solution allows users to touch and feel objects that are typically out of reach, such as stuffed animals on a shelf, or objects that are forbidden to be touched, like museum exhibits.

The greatest strength of this solution lies in its high ubiquity. The proposed solution can be used with a visual display (projector), an auditory display (headphones or speakers), and an RGB-D camera, and does not impose any physical burden on the user. This advantage enables tactile feedback to be always available in scenarios where accurate tactile information was previously deemed less critical and where the physical burden of device attachment outweighed the benefits, such as in communication scenarios using ExtendedHand [19, 24]. As discussed in Section 1.2, providing tactile feedback not only helps users understand the physical properties of objects but also enhances the embodiment and realism of the user's extended hand experience [27, 30, 31].

Additionally, although this study focused solely on ExtendedHand, the proposed feedback design and estimation system would be easily applied to VR environments, online video calls, and telepresence systems [35, 99]. Therefore, the outcomes of this study contribute to the realization of a society where everyone can easily experience the benefits of tactile feedback anywhere, at any time.

From an academic perspective, as shown in Fig. 1.4 of Section 1.4, this study is the first to investigate the appropriate visual and audio feedback designs for tactile feedback in the context of the extended hand that mimics but differs from human hands in the absence of direct tactile stimuli. A notable finding revealed by this study is that users tend to prefer amplified changes over the natural changes that occur when touching objects with their actual hands.

Previous studies have reported phenomena such as the Proteus effect, where users tend to behave in ways that match their avatar when using one that differs in appearance from their actual body [100], and the Slime Hand Illusion, where users perceive their hands as being stretched beyond what is physically possible when viewing a stretching slime [101]. These findings suggest that humans tend to perceive and act in ways that align with their surrogate body.

The findings from this study indicate that even when stimuli differ from actual physical phenomena, the environment should also provide stimuli that match the surrogate body. With the increasing prevalence of VR and human augmentation technologies, humans are expected to encounter bodies that differ from their original ones, ranging from bodies that extend human structures [102, 103] to those that deviate from human structures [104, 105]. This study suggests that feedback design in such scenarios needs to be carefully considered.

5.1.3 Limitations

Through this study, I also revealed significant limitations of the proposed method. First, there is an inherent limitation to the range of tactile sensations that can be conveyed to users. To express stronger tactile sensations, significant modifications in visual and auditory information are necessary. However, these modifications can significantly increase the discrepancy between the user's actual hand sensation and the extended hand experience, potentially disrupting the user's experience of the extended hand. Therefore, the proposed method makes it challenging to represent strong tactile sensations. Furthermore, warmth, coldness, and hardness are basic tactile sensations [55]. In my preliminary study [1], I designed visual effects intended to convey these sensations, but they could only be presented to a limited number of users. Representing these tactile sensations effectively to most users with pseudo-haptic feedback may be difficult.

Another limitation of the proposed method is its inability to reproduce tactile information accurately. This method is not appropriate in situations where proper tactile feedback is necessary. The proposed method is best suited for scenarios where it allows the user to feel as if they are touching objects with the extended hand without physically restraining their hands.

5.2 Future Research Directions

In this section, I will explore the unresolved challenges that extend beyond the scope of this dissertation and propose potential directions for future research.

5.2.1 Understanding Tactile Feedback Capabilities through Integration of Visual and Auditory Feedback

In this research, I proposed the pseudo-haptic feedback method using both visual and auditory feedback. However, I conducted formal validation independently for each feedback modality. An outstanding challenge is to evaluate whether integrating both types of feedback can enhance the intensity of tactile perception for users and expand the range of tactile sensations that can be expressed. Although not specific to pseudo-haptic feedback, several studies have reported that providing both visual and auditory feedback can have a more positive impact compared to presenting each modality separately [66, 75]. Similar positive effects could be achieved in the context of ExtendedHand. Additionally, investigating which modality — visual or auditory — dominates could be a fascinating topic. As noted in the participant comments of Section 3.4.2, this may depend on the distance to the object being touched. Clarifying these factors will contribute to establishing more effective feedback designs.

5.2.2 Understanding User Preferences for Appropriate Feedback Types for Different Objects

In the user study from Section 2.4.3 and the data collection study in Section 4.4.2, I investigated the appropriate types and intensities of visual effects for individual objects. The results revealed that suitable visual effects for an object are influenced not only by the object's material and surface texture but also by user preferences, which showed significant individual variability. In Chapter 4, I developed a user-specific system as the first phase of the visual effect generation system, neglecting the significant impact of individual preference differences.

One future research direction is to address these individual preference differences. To achieve this, it is necessary to collect data from a much larger number of users (more than 100) regarding appropriate feedback types for various objects. With this data, it will be possible to investigate whether individual preferences can be grouped into several categories or develop models that predict user preferences from a small amount of data. If successful, this could overcome the limitations of the current user-specific system and enable the realization of a feedback generation system for a broad user base.

5.2.3 Visual and Auditory Feedback Beyond the Reproduction of Object Tactile Sensations

In this dissertation, the primary focus has been on reproducing the natural tactile sensations of objects touched by the extended hand using visual and auditory feedback. A promising future direction is to explore how visual and auditory feedback can convey information beyond object tactile sensations. For instance, as shown in Experiment C of Section 2.4.4, varying the intensity of visual effects can modulate tactile sensations of objects. Expanding on this idea, visual and auditory feedback could potentially allow users to perceive imperceptible information, such as infrared or CO_2 levels, at the location indicated by the extended hand. My ongoing collaborative research aims to integrate sensory organs into the extended hand to detect such information [106, 107, 108], potentially expanding users' perceptual experiences and influencing their behavior.

Another exciting research direction is using visual and auditory feedback to express the physiological state of the operator to both the operator and those around them. While visual effects have been proposed for the hand part of the extended hand in this study, visual effects have not been applied to the long arm part. A fascinating exploration would be to display pulses and veins on this extended arm and apply visual effects to them.

5.3 Conclusion

This doctoral thesis aimed to enable users to feel the tactile sensations of objects through a projected CG hand (extended hand) by inducing pseudo-haptics through visual and auditory feedback, without the need to wear any devices. I have revealed design methods for visual effect feedback and sound texture feedback that allow users to perceive tactile sensations naturally. In addition, I have developed a system that can estiate appropriate feedback for objects touched by the extended hand, making it applicable in actual scenarios. These efforts have helped overcome the physical limitations that prevent human hands from interacting with unreachable targets, allowing users to do so anytime and anywhere without physical burden.

This thesis has focused on enabling users to feel the tactile sensations of objects touched by the extended hand. However, considering the brain's plasticity, there is potential for users to intuitively perceive a broader range of information through continuous visual and auditory feedback. The features of this method, which facilitate accessible and continuous use without physical burden, along with the insights gained from feedback design through this research, can contribute to future studies in this field.

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Acknowledgements

I would like to express my deepest gratitude to my research supervisor, Prof. Dr. Kosuke Sato, for his unwavering support and invaluable guidance throughout my time in graduate school. His insightful feedback was crucial in helping me overcome the challenges in my research. Beyond academic guidance, his wisdom as an educator has profoundly shaped my perspective on life. I am deeply appreciative of his mentorship and hope to pass on these lessons to future generations.

I extend my sincere thanks to Assoc. Prof. Dr. Daisuke Iwai for his sharp insights and advice on my research. His input was crucial to my work. I am also grateful to Assoc. Prof. Dr. Parinya Punpongsanon, Assoc. Prof. Dr. Takefumi Hiraki, and Asst. Prof. Dr. Haruka Matsukura for their teachings and support, which significantly contributed to my research.

I wish to thank Prof. Dr. Youji Iiguni and Prof. Dr. Kenjiro Tadakuma, members of my doctoral dissertation jury committee, for their guidance and thorough review of my dissertation. Their feedback pushed me to refine my arguments and strengthened the overall quality of my work.

My gratitude extends to the members and committee of the Humanware Innovation Program (HWIP). HWIP provided me with financial support and the invaluable experience of engaging in interdisciplinary research. I am deeply thankful for these opportunities. In particular, I would like to express my sincere thanks to Prof. Dr. Taro Maeda and Dr. Kozo Kimura for serving as my advisors over the years.

I also want to acknowledge the staff, seniors, peers, and juniors in the SENS Laboratory. The lively discussions during lab meetings and the camaraderie we shared made the long hours of research more enjoyable. Your assistance and daily conversations were a constant source of motivation and inspiration throughout my research journey.

Lastly, I am profoundly grateful to my family for their unwavering support, both financially and emotionally. Your encouragement was the cornerstone of my journey, providing me with the strength to persevere through the toughest moments. Thank you for believing in me and for being my greatest advocates.

This dissertation was partially supported by a Japan Society for the Promotion of Science (JSPS) - DC2 Fellowship (Grant No. JP23KJ1454), JSPS KAKENHI (Grant No. JP16H02859), and the Japan Science and Technology Agency, the Establishment of University Fellowships Toward the Creation of Science Technology Innovation (Grant No. JPMJFS2125).

List of Publications

In this section, all the publications, along with the awards, that have resulted both from the research presented as the part of this thesis and excluded from the scope of this thesis are listed in the following.

Awards

- **Interactive Presentation Award (PC Nomination)**
  IPSJ INTERACTION, 2023, Tokyo, Japan.
- **Student Research Award**
  IEEE Kansai Section, 2020.
- **Encouragement Award**
  The Institute of Systems, Control and Information Engineers, 2020.
- **SCI Student Presentation Award**
  The Institute of Systems, Control and Information Engineers, 2019, Osaka, Japan.
- **Huawei Award**
  The 8th Science Intercollege, 2019, Tokyo, Japan.

Journal Publication

- Yushi Sato, Daisuke Iwai, and Kosuke Sato, "Responsive-ExtendedHand: Adaptive Visuo-Haptic Feedback Recognizing Object Property with RGB-D Camera for Projected Extended Hand," *IEEE Access*, Vol. 12, pp. 38247–38257, March 2024.
- Yushi Sato, Daisuke Iwai, and Kosuke Sato, "Sound Texture Feedback for a Projected Extended Hand Interface," *IEEE Access*, Vol. 12, pp. 27673–27682, February 2024.
- Yoshihiro Okamoto, Yushi Sato, Daisuke Iwai, and Kosuke Sato, "Haptic Augmentation to Distant Object with Laser Speckle Vibrometer at Projected Virtual Hand," *Transactions of the Virtual Reality Society of Japan*, Vol. 28(3), pp. 165–174, September 2023. (*in Japanese*)
- Akira Watanabe, Takuya Uchida, Yushi Sato, Daisuke Iwai, and Kosuke Sato, "A Minimal Representation and Hovering-and-Contact Presentation of Contour-Based Projected Hand by Laser Scanning Projector," *Transactions of the Virtual Reality Society of Japan*, Vol. 27(2), pp. 152–162, June 2022. (*in Japanese*)
- Yushi Sato, Takefumi Hiraki, Naruki Tanabe, Haruka Matsukura, Daisuke Iwai, and Kosuke Sato, "Modifying Texture Perception with

Pseudo-Haptic Feedback for a Projected Virtual Hand Interface," *IEEE Access*, Vol. 8, pp. 120473–120488, July 2020.

International Conference Publication

- Yushi Sato, Daisuke Iwai, and Kosuke Sato, "Pseudo Tactile Feedback for Extended Hand Users," to be presented as an invited talk at *the 31st International Display Workshops (IDW 2024)*, December 2024.
- Naoya Yoshimura, Yushi Sato, Yuta Kageyama, Jun Murao, Satoshi Yagi, and Parinya Punpongsanon, "Hugmon: Exploration of Affective Movements for Hug Interaction using Tensegrity Robot," In *Proceedings of the 2022 ACM/IEEE International Conference on Human-Robot Interaction (HRI 2022)*, pp. 1105–1109. Online, March 2022.
- Yushi Sato, Naruki Tanabe, Kohei Morita, Takefumi Hiraki, Parinya Punpongsanon, Haruka Matsukura, Daisuke Iwai, and Kosuke Sato, "Pseudo-Haptic Feedback in a Projected Virtual Hand for Tactile Perception of Textures," In *the 2019 IEEE World Haptics Conference (WHC 2019)*, Hands-on Demos, DM2.09, Tokyo, July 2019.
- Yushi Sato, Naruki Tanabe, Kohei Morita, Takefumi Hiraki, Parinya Punpongsanon, Haruka Matsukura, Daisuke Iwai, and Kosuke Sato, "Pseudo-Haptic Feedback in a Projected Virtual Hand for Tactile Perception of Textures," In *Adjunct Proceedings of the 2019 IEEE World Haptics Conference (WHC 2019)*, pp. WP1P.09:1–2, Tokyo, July 2019.
- Naruki Tanabe, Yushi Sato, Kohei Morita, Michiya Inagaki, Yuichi Fujino, Parinya Punpongsanon, Haruka Matsukura, Daisuke Iwai, and Kosuke Sato, "fARFEEL: Providing Haptic Sensation of Touched Objects using Visuo-Haptic Feedback," In *Proceedings of the 26th IEEE Conference on Virtual Reality and 3D User Interfaces (IEEE VR 2019)*, pp. 1355–1356. Osaka, March 2019.

Domestic Conference, Symposium, Talk (in Japanese, (*) indicating translated title)

- Yushi Sato, Ao Ishikawa, Yuto Takeuchi, Daisuke Iwai, and Kosuke Sato, " Presentation of Hovering-and-Contact Sensations Using Visuo-Audio Effects in the Projection-Based Extended Hand Interface," to be presented at *the 29th Annual Conference of the Virtual Reality Society of Japan (VRSJ)*, September 2024.
- Ao Ishikawa, Yushi Sato, Daisuke Iwai, and Kosuke Sato, "Sound Image Presentation to a Projected Extended Hand Using Reflected Sound from Super Directional Loudspeakers," to be presented at *the 29th Annual Conference of the Virtual Reality Society of Japan (VRSJ)*, September 2024.

- Shun Hanai, Yoshihiro Okamoto, Yushi Sato, Daisuke Iwai, and Kosuke Sato, “Invisible Information Discrimination of Distant Objects by Haptic Augmentation based on Wrist Mounted Laser Speckle Vibration Measurement,” to be presented at *the 29th Annual Conference of the Virtual Reality Society of Japan (VRSJ)*, September 2024.
- Ao Ishikawa, Yushi Sato, Daisuke Iwai, and Kosuke Sato, “Sound Image Presentation to a Projected Virtual Hand Using a Directionally Controllable Super Directional Loudspeake,” In *Proceedings of the 68th Institute of Systems, Control and Information Engineers (ISCIE)*, pp. 967–970, Osaka, May 2024.
- Yuto Takeuchi, Yushi Sato, Daisuke Iwai, and Kosuke Sato, “Wrist-mounted augmented hand projection system using MEMS scanner,” In *Proceedings of the 68th Institute of Systems, Control and Information Engineers (ISCIE)*, pp. 965–966, Osaka, May 2024.
- Yuto Takeuchi, Yushi Sato, Daisuke Iwai, and Kosuke Sato, “Wrist-mounted augmented hand projection system using edge deep learning,” In *Proceedings of the General Conference of the Institute of Electronics, Information and Communication Engineers (IEICE)*, p. H-3-03, Hiroshima, March 2024.
- Ato Hitomi, Yushi Sato, Daisuke Iwai, and Kosuke Sato, “Sensory Addition onto Projected ExtendedHand Using Signage with Display Transition Features,” In *Proceedings of the General Conference of the Institute of Electronics, Information and Communication Engineers (IEICE)*, p. H-3-03, Hiroshima, March 2024.
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- Shun Hanai, Takuya Uchida, Yushi Sato, Daisuke Iwai, and Kosuke Sato, “Robust Virtual Hand Projection for Body Movement from Small-Size Shoulder-Mounted System,” In *Proceedings of the 67th Annual Conference of the Institute of Systems, Control and Information Engineers (ISCIE)*, pp. 332–334, Kyoto, May 2023.
- Yoshihiro Okamoto, Yushi Sato, Daisuke Iwai, and Kosuke Sato, “Remote Tactile Extension Using Event Camera-Based Laser Speckle Vibration Measurement (*),” In *Proceedings of INTERACTION 2023 of the Information Processing Society of Japan (IPSJ)*, pp. 857–859, Tokyo, March 2023.

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- Yushi Sato, Daisuke Iwai, and Kosuke Sato, "Provision of Auditory Feedback to a Projected Arm Extension Interface (*)," In *Proceedings of the 27th Annual Conference of the Virtual Reality Society of Japan (VRSJ)*, pp. 3D3-2:1–3, Hokkaido, September 2022.
- Takuya Uchida, Yushi Sato, Daisuke Iwai, and Kosuke Sato, "Information Transmission Based on Minor Movement Discrepancies Between Projected Extended Hands and Real Hands (*)," In *Proceedings of the 27th Annual Conference of the Virtual Reality Society of Japan (VRSJ)*, pp. 1D3-2:1–3, Hokkaido, September 2022.
- Ato Hitomi, Yushi Sato, Takuya Uchida, Daisuke Iwai, and Kosuke Sato, "A Study on Sensory Addition onto Projected Extended Hand in Multimodal Stimuli Environment," In *Proceedings of the 66th Annual Conference of the Institute of Systems, Control and Information Engineers (ISCIE)*, pp. 247–250, Kyoto, May 2022.
- Yushi Sato, Naoya Yoshimura, Yuta Kageyama, Jun Murao, Satoshi Yagi, and Parinya Punpongsanon, "Development of a Hug-Interaction Robot with a Tensegrity Structure (*)," *The 29th Workshop on Interactive Systems and Software (WISS)*, Demo-Poster Presentation (No. 2-A09), Shizuoka, December 2021.
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- Yushi Sato, Naruki Tanabe, Kohei Morita, Parinya Punpongsanon, Haruka Matsukura, Daisuke Iwai, and Kosuke Sato, "Touch Sensation in Projected Virtual Hand by Providing Pseudo-Haptic Feedback," In *Proceedings of the 63th Annual Conference of the Institute of Systems, Control and Information Engineers (ISCIE)*, pp. 1367–1374, Osaka, May 2019.
- Kohei Morita, Naruki Tanabe, Yushi Sato, Parinya Punpongsanon, Haruka Matsukura, Daisuke Iwai, and Kosuke Sato, "Extension of Operation Range in Extended Virtual Hand Projection Using Head Direction," In *Proceedings of the 63th Annual Conference of the Institute of Systems, Control and Information Engineers (ISCIE)*, pp. 1375–1381, Osaka, May 2019.
- Yushi Sato, "Presentation Material Sensations Through Pseudo-Haptic Feedback for Virtual Hand (*)," In *Proceedings of the 8th Science Intercollege*, p. 53, Tokyo, March 2019.