Survey of Pseudo-haptics: Haptic Feedback Design and Application Proposals

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Abstract—In the last two decades, the design of pseudo-haptics as a haptic presentation method that does not require a mechanical feedback device has been proposed in various research papers. Moreover, applications using pseudo-haptics have been proposed and evaluated in various contexts. However, the findings from these studies have not yet been comprehensively organized in a survey paper in the recent times. In this paper, findings from a series of individual prior studies were summarized from the design through to the application proposals. First, we summarize visual stimuli designs based on the target haptic object properties to induce pseudo-haptics. Second, we summarize two special issues when designing pseudo-haptics; (1) workaround design for the visualized mismatch of visual stimuli and user input and (2) the combination design of pseudo-haptics and physical stimuli. Third, application proposals that use pseudo-haptics for training, assistance, and entertainment are presented. This survey paper would help not only researchers in academia but also application developers who intend to use pseudo-haptics as a haptic presentation method.

Index Terms—Haptics, Pseudo-haptics, Design, Application

1 Introduction

Haptics allow humans to perform various exploration and manipulation tasks in the real world [1]. Without haptics, it is difficult to grasp and manipulate objects, and material and surface properties cannot be determined. In desktop, virtual reality (VR), augmented reality, or touch-screen applications, artificially reproduced haptic properties can induce various effects such as realism and improved human performance [2]. Currently, some commercial applications support limited haptics via vibrotactile channels on devices such as smartphones [3]. It is believed that future applications will support a wide variety of haptic feedback, and these applications will be developed actively. However, the development of haptic display design faces several challenges such as creating a rich haptic sensation that meets the requirements of applications.

The straightforward design of a haptic display involves providing physical stimuli to the body of a user using force feedback devices [4], [5], [6]. Owing to technological advancements, it has become possible to present users with a highly realistic tactile experience. However, it is not possible to apply these devices to all cases because of hardware size or cost limitations. Wearable haptic displays, which have been actively researched in recent years, address this issue [7]. However, these require small actuators or batteries, and are not accessible in all cases. For example, there are not these devices in all the ordinary home and the haptic feedback with physical stimuli is sometimes not accessible in home-use applications.

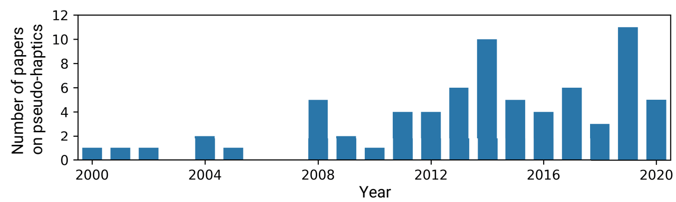

Fig. 1. Number of published papers on pseudo-haptics.

Another approach is to focus on illusional haptic perceptions evoked by human vision. Pseudo-haptics [8] can induce the haptic illusions even in situations where there is no mechanical haptic interfaces. In this paper, we define pseudo-haptics as the phenomenon when users experience haptic feedback by observing a visual stimulus that is designed to distort based on user input. Thus far, many studies have proposed pseudo-haptic designs for inducing various haptic properties, and the effects of pseudo-haptics have been evaluated in some application contexts. Survey papers on pseudo-haptics [8] and [9] were published in 2009 and 2011, respectively. On the other hand, Fig. 1 shows the number of papers on pseudo-haptics published per year considering the keyword "pseudo-haptic" on Google Scholar; the figure indicates that pseudo-haptics has been researched more actively in recent years. The number of papers published in the last decade was approximately 50 and much more than before, but there is no survey paper that comprehensively summarizes these papers on pseudo-haptics over the past decade.

A comprehensive literature search was performed between February and June 2020. First, general search in the databases of Google Scholar using the keyword "pseudo-haptic" was performed. Additional literature was retrieved through the reference lists of the acquired papers. The abstracts of the articles were read to verify whether the

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publications were related to pseudo-haptics.

We conducted a comprehensive literature search in the databases of Google Scholar using the keyword "pseudo-haptic" between February and June 2020. and, as a result, retrieved a total of 74 papers. We summarize the knowledge on the design of pseudo-haptics and application proposals by analyzing those papers.

The rest of this paper is organized into five sections. In section 2, we summarize how to design visual stimuli to present the haptic properties of the objects. In section 3, we summarize two special issues when designing pseudo-haptics; the first one is the workaround design for the visualized mismatch of visual stimuli and user input. the second one is the combination design of pseudo-haptics and physical stimuli. In section 4, we summarize the application proposals. Finally, in the concluding section, we discuss the limitations of the survey and future areas of investigation.

2 Visual Stimuli Design to Present Target Haptic Object Property

2.1 Taxonomy

2.1.1 Taxonomy of Haptic Object Property

The method used to design visual stimuli for presenting each haptic object property is summarized in Table 1. We define the taxonomy of the haptic object property by quoting the existing literature by Jones and Lederman [10] and Okamoto et al. [11]. Thus far, it is known that pseudo-haptic sensations are evoked only when users actively move their bodies; therefore, we quoted the taxonomy from the "active tactile sensing" section of the literature [10]. The taxonomy of object properties comprises material and geometric properties. The material properties include weight, compliance, texture, thermal properties, and material composition; the geometric properties include curvature, orientation and angle, size, shape, contact locations, and attributes of wielded objects. We will proceed with the discussion based on this taxonomy; however, the following points should be noted about the taxonomy.

When we checked object properties covered in the listed pseudo-haptics papers, we found that they were biased toward texture instead of other properties. Therefore, we further classified texture using Okamoto et al. [11]'s classification. This allows application developers to refer to these properties in detail. Texture can be classified based on fine roughness, macro roughness, friction, hardness, and warmth. The surface roughness is referred to as coarse or macroscopic roughness [11] when the surface width of two neighboring dots or ridges is larger than the range of few hundreds of micrometers to 1 mm. Macro roughness is associated with expressions such as "uneven," "relief," or "voluminous." A surface roughness with a width value smaller than this range is called fine roughness, and is referred to by the adjective "rough". Among texture compositions, warmth overlaps thermal properties. Further, hardness overlaps with compliance. Therefore, we excluded warmth and hardness from the texture dimension to avoid redundancy.

There are methods to change geometric perceptions such as position [12], [13], [14], [15] or shape [16]; these methods are similar to that described in Table 1. A few examples of these methods [16], [17], [18] have been proposed within the context of pseudo-haptics. However, they are referred to as "retargeting" or "redirection," methods, and therefore, we removed geometric properties from the scope of pseudo-haptics. If an application developer wants to present geometric properties, we recommend reading these references.

There are some existing papers that cannot be categorized into the taxonomy defined in this paper. For these papers, we set the category as "other."

The final version of the taxonomy is indicated by the first and second columns in Table 1. The sub-properties are presented in the second column. If there is a sub-property among papers that belongs to the target haptic property, there is a description of the sub-property.

2.1.2 Taxonomy of Visual Stimuli and User Input

In addition to haptic object properties, there exist user inputs, visual stimuli, and references, as indicated in the columns in Table 1. User input indicates the action of the user that is essentially the input information to the system. Visual stimuli are the visual information provided to the user as visual feedback based on the user's action. Although items for haptic object properties are collectively exhaustive, the items for user input such as visual stimuli are filled empirically as reported in existing papers. Each row in the table indicates the existing combination of visual stimuli and user input for each target property.

Here, we show three types of "user input" collected from existing papers: displacement, force, and pressing duration (as shown in Fig. 2).

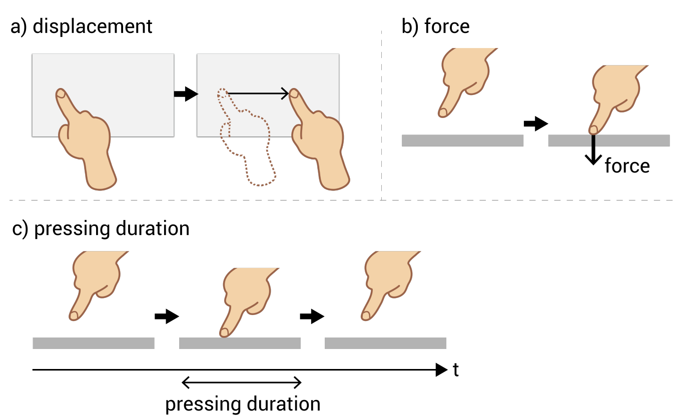

Fig. 2. Three types of user inputs.

- When users move their bodies (such as fingers or hands) or input tools (such as mice or touch pens), the system senses and uses displacement as input, and the user input is considered as displacement (Fig. 2(a)).
- When the user's body or input tools apply a force on something and the system senses and uses the amount of force as input, that specific user input is considered as force (Fig. 2(b)).
- When the user's body or input tools press something for a certain duration and the system senses and uses the duration as input, that user input is considered as pressing duration (Fig. 2(c)).

TABLE 1
Combination of user input and visual stimuli for presenting target haptic properties using pseudo-haptics.

Target haptic property	Sub-property (if present)	User input	Visual stimuli	Reference
Weight	-	Displacement D Applied force F	Displacement D' (e.g., $D' = \alpha D$)	[19], [20], [21], [22]
Weight	-	Displacement D	Displacement D' (e.g., $D' = \alpha D$)	[23], [24], [25]
Weight	-	Angular displacement θ	Angular displacement θ' (e.g., $\theta' = \alpha\theta$)	[26], [27]
Weight	-	Angular displacement θ	Displacement D' (e.g., $D' = \alpha \int \theta dt$)	[28]
Compliance	-	Displacement D Applied force F	Displacement D' (e.g., $D' = \alpha D$)	[29], [30], [31], [32] [33], [34], [35], [36] [37], [38], [39], [40]
Compliance	-	Displacement D	Displacement D' (e.g., $D' = \alpha D$)	[41]
Compliance	-	Applied force F	Displacement D' (e.g., $D' = \alpha F$)	[42], [43], [44]
Compliance	-	Applied force F	Surface deformation $d(F)$	[45], [46], [47], [48]
Compliance	-	Press duration Δt	Surface deformation $d(\Delta t)$	[49], [50]
Compliance	-	Displacement D	Surface deformation $d(D)$	[46], [51], [52], [53]
Compliance	-	Press duration Δt	Cursor color $c(\Delta t)$	[49]
Compliance	-	Applied force F	Skin color $c(F)$	[33], [45]
Compliance	-	Angular displacement θ Applied force F	Angular displacement θ' ($\theta' = \alpha\theta$)	[54]
Friction	Kinetic friction	Applied force F	Displacement D' ($D' = \alpha F$)	[29]
Friction	Kinetic friction	Displacement D	Displacement D' ($D' = \alpha D$)	[24], [55], [56], [57] [58], [59], [60]
Friction	Static friction	Displacement D	Displacement D'	[60], [61]
Friction	Viscosity	Displacement D	Displacement D'	[60], [62], [63]
Fine roughness	-	Displacement D	Perturbed Displacement D'	[60], [63], [64]
Macro roughness	-	Displacement D	Displacement D'	[65], [66], [67], [68] [69], [70], [71]
Macro roughness	-	Displacement D	Pointer size s	[60], [63], [68]
Thermal property	-	-	-	
Material	-	Displacement D	Displacement D'	[72]
Other	Force	Displacement D	Displacement D'	[73], [74], [75], [76] [77], [78], [79], [80] [81], [82], [83], [84] [85]
Other	Force	-	Displacement D' (of background image)	[86]
Other	-	Displacement D	Displacement D'	[87]

We show four "visual stimuli" collected from existing papers. The four types are displacement, surface deformation, color, and size (shown in Fig. 3).

- When the translation or rotational movement of something such as a virtual body part or pointer is presented to users as visual information, that visual stimulus is considered as displacement (Fig. 3(a)).
- When the surface deformation of something is pre-

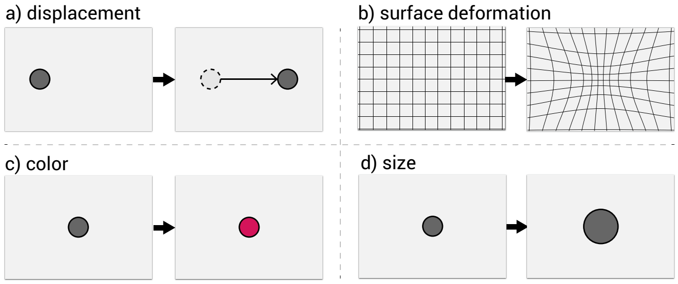

Fig. 3. Four types of visual stimuli.

sented to users as visual information, that specific visual stimulus is considered as surface deformation (Fig. 3(b)).

- When the color change of something is presented to users as visual information, that visual stimulus is considered as color (Fig. 3(c)).
- When the size change of something is presented to users as visual information, that visual stimulus is considered as size (Fig. 3(d)).

2.2 Weight

To change weight perception while we are grasping and moving the object around, all previous studies adopted a method of distorting the ratio α of user input displacement D (shown in Fig. 2(a)) and visualized displacement D' (shown in Fig. 3(a)), i.e., $\alpha = D'/D$. If α is smaller than 1, the users will perceive the object as heavier; if α is larger than 1, the users will perceive the object as lighter. The ratio α is sometimes called the control/display ratio (C/D ratio) in the context of pseudo-haptics. However, the meaning of the "C/D ratio" was different from person to person. Some research (e.g., [21]) regarded the C/D ratio as the output gain with regard to the input. In that case, when the C/D ratio is large, the visualized displacement is larger than the user input displacement. In contrast, other research (e.g., [67]) regarded the C/D ratio as a fraction of Control and Display. In that case, when the C/D ratio is large, the visualized displacement is smaller than the user input displacement. In order to prevent readers to be confused, the term C/D ratio is not used in this study.

Some studies [19], [20], [21], [22] combined the distorted displacement with physical haptic stimuli. Dominjon et al. [19] reported that a larger displacement D' of visual feedback with respect to the users' input displacement D can make users feel that the object is lighter than its actual weight. In their psychophysical experiment, the users lifted a ball the mass of which was simulated by the PHANToM [4]; they experienced the gravitational force and the visual displacement of the hand. The result indicated that all users felt the object was lighter. When α was five, i.e., the visual displacement D' was five times larger than the actual hand displacement D, the object weighing 110 g was evaluated to be lighter than 100 g with a 50 % probability; the assessments from five out of ten users were completely inverted. That is, the heavier objects were perceived as lighter than the objects that were indeed lighter. The other five users were not completely misled; however, they were significantly disturbed. Samad et al. [21] applied a similar method for virtual spaces. Users lifted an object of 185 g, and the experiment showed that ± 5 g can be modified using visual feedback.

In contrast to the studies stated above, studies by [23], [24], [25] only used the visual feedback without the actual physical weight cues that were present. Rietzler et al. [25] proposed visualizing the offset between real hand position and virtual hand position which suggested the weight cue. The lifting of heavier objects results in a larger offset. This is a similar approach with studies mentioned above such as [19]. Rietzler et al. [25] focused also on the inertial properties of the virtual object. They designed heavier objects such that they required more time to accelerate and slow down. Their experiment showed that users could associate the designed visual stimuli with the weight property and accept them as part of the virtual world. Yu and Bowman [26] proposed a method to change the perception of weight by scaling rotational motion. They changed the rotational angle to be smaller when users had the object configured to be heavier. Further, they changed the angle to be larger when the users had the object configured to be lighter. Their psychophysical experiment showed that users felt the object was heavier by more than 80 % with their proposed method than without the method. Issartel et al. [27] proposed a similar method to change the perception of the real object pushed by the real effector held by users. They visualized the virtual clone of the effector and decoupled the position and orientation of the virtual effector from the real one in accordance with the reaction force. Hirao et al. [28] tested controller-based user input to change weight perception. They made users tilt the analogue stick of a VR controller to move a virtual object. The object moved at a speed that was in proportion to both the angular displacement θ of the stick and the static configuration α. The visualized displacement of the object was calculated as $D' = \alpha \int \theta dt$.

2.3 Compliance

There are three different visual stimuli for presenting the compliance property: distortion in displacement (Fig. 3(a)), surface deformation (Fig. 3(b)), and color (Fig. 3(c)).

2.3.1 Displacement

The first approach visualizes the distorted displacement of user input D' (Fig. 2(a)) [29], [30], [31], [32], [33], [34], [36], [37], [38], [39], [40], [88].

Lécuyer et al. [29] asked users to push their thumb on a piston mounted on a passive spring, and they viewed the distorted thumb displacements D' on the display. They computed D' as $D' = F/K$ based on the applied force F and the target compliance of the virtual spring K. Then, they conducted a compliance discrimination experiment between two virtual springs using their proposed method. The Weber fraction for the compliance discrimination between the two virtual springs was 6 %. Instead of a spring, Tatezono et al. [31] used PHANToM [4] and pseudo-haptic feedback to provide compliance. Further, they adopted the same approach as Lécuyer et al. [29] and changed the visual feedback. They showed that the presence of the pseudo-haptic feedback could provide an additional perceived force of 0.2–0.4 N with a physical force feedback greater than when only physical force feedback was provided. Unlike aforementioned studies, Kumar et al. [41] proposed a pseudo-haptic compliance feedback without any haptic physical stimuli. They made users move mouse and provided visual feedback of virtual spring displacement. With an assumption of equal work done in the mouse movement and the virtual spring movement, the relationship between the displacement of the mouse and virtual spring was derived. They experimentally validated their method. In touchscreen environments, Ridzuan et al. [42] proposed a technique of pseudo-compliance feedback inside the screen. They allowed users to interact with the virtual object inside the pressure-sensitive screen using a virtual finger as if the finger of the user could penetrate through the screen surface. The visual deformation depth of the virtual object and finger displacement was controlled when users touched the virtual object inside the screen. By changing the visual feedback, users felt different compliance properties related to the surface of the object.

Paljic et al. [54] proposed a pseudo-haptic technique for simulating torque feedback. When users rotate torsion springs with torque T and the virtual angular displacement θ' is visually presented to users, virtual compliance C can be simulated. They conducted an experiment using real springs to evaluate the JND. The JND value for the compliance of the virtual torsion spring was 9.1 % when using a real spring of the torsion constant, which was 2.05×10^{-2} Nm/rad and an elastic input device.

2.3.2 Surface Deformation

The second approach presents users with simulated surface deformation (Fig. 3 (b)) as visual stimuli [45], [46], [46], [47], [48], [49], [51], [52], [53].

Punpongsanon et al. [45] presented a visual simulated deformation of the cushion surface by projection mapping when the user pressed it with their fingers. They evaluated whether the proposed augmented deformation affects the user's perception of softness. Their analysis showed that their surface deformation method was effective in the softening direction, but there was no significant effect in the hardening direction.

Yabe et al. [48] proposed changing the visual surface deformation of virtual objects displayed on a mobile display. When users pushed the side of the mobile display, the object deformed with respect to the applied force F. The compliance can be modified by changing the relationship between the deformation and applied force. Argelaguet et al. [49] proposed a technique similar to using the mouse and cursor in typical desktop environments. Instead of measuring force, they used the pressing duration Δt of the mouse as the user input. Simulating the deformation d of images based on the pressing duration Δt results in the perceived different compliance of images. Fleureau et al. [50] applied the same technique to a digital tablet with an additional audio feedback to simulate roughness. Kawabe et al. [51] simulated compliance perception when pulling a virtual surface with fingers in mid-air. They clarified that the magnitude of the object deformation with respect to the finger displacement D could change compliance perception. Further, they indicated that Poisson's ratio contributes to the perception of softness. Ban et al. [52] controlled not only the surface deformation of the virtual object but also the posture of the fingers grasping a virtual object to enhance the effect of pseudo-haptics. They confirmed that distorting the virtual fingers' posture to fit the virtual deformation of an object significantly modified the compliance perception in the task of pinching an elastic object with the thumb and forefinger. Argelaguet et al. [53] assumed a collaborative scenario wherein two users interacted with a deformable object. They proposed a pseudo-haptic method considering the input of both users. Their results indicated that users could determine the the compliance of the virtual object with pseudo-haptic feedback.

2.3.3 Color

The third approach changes the color (Fig. 3(c)) of the user's skin [34], [45] or cursor [49].

Note that there are studies that regarded the color change method as a sensory substitution of some haptic properties [89], [90]. Such studies did not investigate how haptic perception was modulated by the color-changing method. In contrast to such studies, the studies presented below verified that the haptic perception was modulated by the color-changing method and we regard such methods as one of the pseudo-haptic methods.

Punpongsanon et al. [45] proposed four coloring methods using projection mapping to change the perception of softness when users press a virtual finger on a cushion: coloring the fingernail of the finger used to press the cushion, coloring the skin of this finger, coloring the skin of this finger gradually from the fingertip to the base, and coloring the blood vessels of this finger. Their experimental results indicated that only the method of coloring the skin of the finger provided a greater perception of softness. Argelaguet et al. [49] proposed a similar method: changing the color of a hand-shaped mouse cursor in a desktop environment from white to red when a user clicked on an image.

Achibet et al. [33] proposed that changing the color of a virtual hand alters the perception of the softness of an elastic handheld device in 3D VR space. They proposed two different visual feedbacks to expose the amount of force exerted on the hand graphically: "Boolean feedback" and "progressive feedback." For Boolean feedback, the appearance of the hand was unchanged until the compression ratio reached the threshold; when it reached the threshold, the appearance changed to a different color. By contrast, with progressive feedback, the appearance of the hand changed continuously. In the experiment for assessing the compliance of the device, progressive feedback provided a better performance.

2.4 Friction

2.4.1 Kinetic Friction

For presenting kinetic friction, all studies visually manipulated the displacements of objects (Fig. 3(a)); however, they adopted different user inputs: force input [29] (Fig. 2(b)) or finger displacement input [24], [55], [56], [57], [58], [59] (Fig. 2(a)).

The first approach uses force as the user input and provides users with displacement feedback. Lécuyer et al. [29] allowed users to move a cube in a virtual environment with a constant velocity. An isometric user interface was used to control the velocity of the cube, v, which was calculated from the user's input force F and the friction coefficient μ_k of the virtual environment. When reaching the area with higher friction, the cube was slowed down with a constant input force. The user was asked to maintain the velocity of the cube, and therefore, the user tended to increase his/her interaction force F. The change in the user's excitation force combined with the visual feedback of the cube's velocity made the user feel differences in friction.

The second approach uses finger displacement as the user input and provides users with a distorted displacement feedback. Narumi et al. [55] proposed a method of changing the displacement ratio α between the finger D and background image scroll D' on a touchscreen ($\alpha = D'/D$). When the ratio α was smaller than one, users felt a resistive frictional feeling. Their psychophysical experiments clarified that when the ratio was 0.34, users succeeded in recognizing the frictional feeling at 75 % probability. Hashimoto et al. [56] adopted the same method on a touchscreen and evaluated the effect on a visual memory task. Ujitoko et al. [57] applied the method for a locomotion interface using a finger as if they were walking on snowy virtual ground on a touchscreen.

2.4.2 Static Friction

Static frictional properties can be induced using distorted displacement (Fig. 3(a)). The work by [60], [61] focused on the stick-slip phenomenon.

Ujitoko et al. [61] focused on the stick-slip phenomenon while users explored surfaces with an input device such as a stylus. During the stick phase, users watched a virtual contact point being stuck at the contact point on the screen while users freely moved the input device. They used the Coulomb friction model and provided users with finger displacement D based on the user's input displacement D', and the static friction coefficient μ_s. Their method succeeded in providing users with a pseudo-haptic static friction property at more than 90 % probability. The method made users feel that the amount of frictional intensity of the virtual surface was changed by 23 % at the maximum through magnitude estimation. Costes et al. [60] focused on stick-slips following Coulomb's law, and they proposed a similar method on the touchscreen. In the stick phase, the cursor on touchscreens stretched as if one of its extremities was fixed to the start position, whereas the other one followed the finger. When a given amount of deformation was reached, the effect entered the sliding phase, wherein the cursor followed the finger without any alteration. Stickiness was represented by the deformation limit between the sticking and sliding phases.

2.4.3 Viscosity

An approach to simulate the visual displacement D' is used to present viscosity (Fig. 3(a)). Fukushima et al. [62] made users watch the visual displacement of a cursor D', which was updated based on the viscous resistance model. Their model assumed that the cursor received viscous resistance $F = 6\pi r\eta V$, where r, η, and V denote the cursor size, fluid viscosity, and uniform stream of velocity, respectively. Costes et al. [60] and Watanabe et al. [63] applied a similar method to simulate fluid viscosity.

2.5 Fine Roughness

To modulate fine roughness, studies [63], [64] perturbed the visual finger displacement D' (Fig. 3(a)) when exploring the virtual surfaces. Watanabe et al. [64] applied visual perturbation while users explored the surface with a mouse and cursor in a desktop environment. Though they did not conduct the experiment, they claimed that users experienced the roughness property even without haptic information. Ujitoko et al. [63] combined the same method with vibrotactile feedback to enhance the roughness sensation represented by the vibration. They had users explore the stylus-based vibrotactile input device on the touchpad and watch the visual perturbation of the cursor on the display monitor. The experiment showed that users could feel the vibrotactile surface become rougher at approximately 80% with visual perturbation. Further, they clarified that the amount of change in the perceived roughness of vibrotactile texture was larger when a larger visual perturbation was presented. Costes et al. [60] applied the same technique to touchscreens.

2.6 Macro Roughness

There are two different approaches for presenting visual stimuli: distortion in the finger displacement (Fig. 3(a)) or of the finger size (Fig. 3(d)).

The first approach changes the visually displayed finger displacement D' with respect to the actual finger displacement D [65], [66], [67], [68], [69], [70], [71]. Mensvoort et al. [69] proposed a method to evoke the perception of bumps or holes with only the distorted cursor displacement D'. If the cursor moved over a hole, the displacement of the cursor became larger and appeared as if the cursor was dragged toward the center. When the cursor rolled over the bump, the cursor appeared to be pushed away from the center. Lécuyer et al. [67] used the same method and clarified that different height profiles of bumps can be simulated. They simulated three profiles: Gaussian, polynomial, and linear ones. Users could draw these different profiles of bumps correctly.

The second approach changes the size of the mouse cursor based on the height profile of the bumps or the depth of the holes [63], [68]. Lécuyer et al. [68] proposed varying the size of the cursor according to the local height of the texture displayed on the screen; they refer to this technique as the "size technique." Their experimental results confirmed that the size technique enabled users to identify bumps and holes successfully. Further, they conducted an experiment wherein they compared the effectiveness of the size technique and the technique of distorted finger displacement. The comparison results indicated that the users' answers were more influenced by the size technique.

2.7 Material

Hachisu et al. [72] combined vibrotactile stiffness and pseudo-haptics to simulate the material properties of instruments while users played with chromatic percussion. Users moved a real stick and watched the virtual stick's vibration on a display when they tapped on the chromatic percussion. The visual vibration was modeled using Okamura et al.'s decaying sinusoidal waveform: $D' = A(v)e^{-Bt}\sin(2\pi ft)$. The displacement D' depended on amplitude A as a function of the instrument impact velocity v, the decay rate of sinusoid B, and the sinusoid frequency f, where A, B, and f were dependent on the type of material. The appropriate configuration of the visual and actual vibrations successfully allowed users to recognize materials such as "wood" or "metal."

2.8 Other Properties

There are papers that proposed using pseudo-haptics for properties that cannot be categorized according to our taxonomy. We introduced these papers as "other properties." Though most of the papers used pseudo-haptic techniques to present force, which are described next subsection, one paper [87] is different. The paper used pseudo-haptic technique to present the defined cost distribution in the two-dimensional images during cursor movement for navigation.

2.8.1 Force

Some papers used pseudo-haptic techniques to present force for various applications.

Nomoto et al. [73] proposed a pseudo-haptic force to support users in tracking a precise path during manual handling tasks (please see details in subsection 4.3.1). Li et al. [75] developed a rehabilitation system by creating a virtual force using pseudo-haptics. They altered the pointer speed and provided motion assistance or resistance to arm movement. Rietzler et al. [76] used a similar method that simulated virtual forces; they combined the pseudo-haptic feedback with muscle exertion. Kang et al. [77] simulated drag force during swimming using pseudo-haptic force feedback. Tada et al. [78] proposed a pseudo-haptic force feedback evoked by rotating the viewpoint of a user in the virtual world. When users moved a hand in the real world at displacement D, the virtual viewpoint rotated, and users felt as if the virtual hand displaced D'. They confirmed that their method could provide pseudo-haptic force. Kashihara et al. [79], [80], [81], [82] used a similar method for educational support. Weng et al. [83] also used a similar method for manipulation of knot diagram interfaces. Baglioni et al. [84] presented users with a virtual inertial force when scrolling on a touchscreen for navigation.

Watanabe et al. [86] provided the sensation of force at the time of collision. In contrast to the studies stated above, they reported that the pseudo-haptic sensation can be produced by modulating the speeds of background visual images, without changing the movement of the pointer itself.

2.9 Discussion

2.9.1 Different Haptic Properties can be Expressed even with the Same Combination of Visual Stimuli and User Input

Here, we focus on the findings that even the same combination of visual stimuli and user input can represent different haptic object properties. For example, when we present the distorted visual finger displacement D' with respect to the real finger displacement D, we can present the sense of weight [23], [24], [25], compliance [29], [30], [31], [32], [33], [34], [35], kinetic friction [24], [55], [56], [57], [58], [59], [60], or macro roughness [65], [66], [67], [68], [69], [70], [71]. To provide users with specific target haptic properties, visual stimuli applied with respect to the interaction with the environment are key. For example, altering the displacement of the entire hand when the user grasps and moves a virtual object can elicit a sensation of increased/decreased weight. Further, altering the displacement of the fingers when probing a surface can elicit the sensation of increased/reduced compliance.

2.9.2 Missing Area

Table 1 indicates that the thermal property is not implemented using pseudo-haptics. In our opinion, it is possible to present or modulate the thermal property using pseudo-haptics. For example, previous studies showed that color-temperature correspondences can affect people's feelings of warmth and coldness [91]. However, previous studies tested thermal perception without synchronizing user input. We are interested in thermal perceptions when the skin color of the user changes to red at the time of touch.

3 Design Tips

3.1 Visual Stimuli Design when User Input is Visible

3.1.1 Problem: Visualized Mismatch

Based on the analysis results from the previous section (summarized in Table 1), there are only four visual stimuli being used in the literature for rendering pseudo-haptic sensations: 1) displacement, 2) surface deformation, 3) color, and 4) size.

For displacement, among these, there is a positional or rotational mismatch between the actual user's input and the visual stimuli. The mismatch of positions cannot cause problems in presentation environments where the user input is invisible to users. Examples include the use of visual presentation devices such as VR HMDs.

By contrast, the mismatch can cause problems in environments where the user input is visible. Examples include the use of visual presentation devices such as touchscreens and optical see-through HMDs. When user input and visual stimuli are co-visualized, the mismatch is directly seen by the users [55], [57], [60] (shown in Fig. 4). The mismatch between the visual stimuli and user input makes the users feel that something is "odd" in the cross-modal feedback [9]. This makes it difficult to induce pseudo-haptics because of the noticeable mismatch in the movement between a user input and a visual stimuli [46].

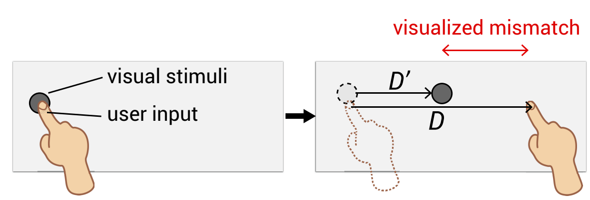

Fig. 4. Visualized mismatch in touchscreen, AR, and projection environments.

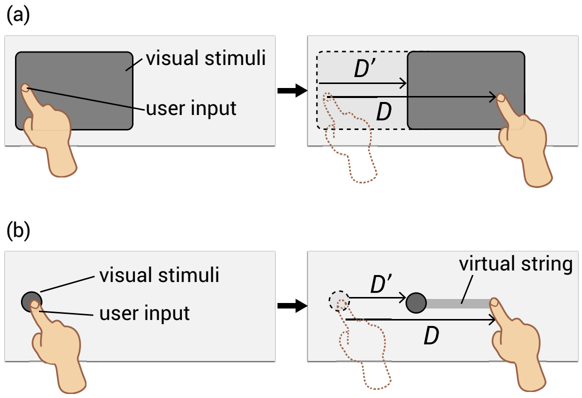

Fig. 5. Top (a): Larger-sized visual stimuli prevent the visualization of mismatch. Bottom (b): Visualized virtual string between user and visual stimuli bridges the mismatch.

3.1.2 Workaround Techniques

Two techniques have been proposed to solve this problem.

The first technique uses larger-sized visual stimuli that reflects user input so that the real body of the user is in the range of the visual stimuli even when there is a displacement mismatch (shown in Fig. 5 (a)). Ujitoko et al. [57] proposed scrolling a background image with various distorted displacement ratios α to induce frictional sensations. The ratio α represents the ratio of displacements between the finger of the user and the background image. Even if the ratio α is large or small, the finger of the user on the touchscreen touches the background image, and therefore, there is no mismatch. Costes et al. [60] used a large cursor on the touchscreen following the same approach. Because the cursor is large to some extent, even if α is small, it seems as if the finger and cursor are in contact with each other.

The second technique [24], [61] uses a virtual visual string that shows a connection between the finger and the object (shown in Fig. 5 (b)). Ban et al. [24] implemented the virtual string on the swipe interaction of the touchscreen. When the users touched and swiped the object with their finger, the displacements between them were caused by the configured displacement ratio of α. The string appeared when the position of the input finger and object moved away while dragging. Further, the users could drag the object via the string even if the finger and object were separated on the screen. The string disappeared when the finger was lifted off the screen. User studies showed that the presence of the virtual string was effective in invoking pseudo-haptics [24].

3.2 Combination Design of Pseudo-haptics with Physical Stimuli

Thus far, there have been studies in which the combination of pseudo-haptics and physical stimuli has been implemented, and the effect of the combination has been confirmed. Here, we introduce phenomena that have been found for two cases, where haptic properties presented by pseudo-haptics and the one presented by physical stimuli are different or the same.

3.2.1 Complementation between Haptic Object Properties

One objective is to complement the different haptic properties by delivering multisensory feedback. For example, Pezent et al. [92] developed a wristband-type multisensory haptic display. This display presents compliance properties using pseudo-haptics, and the different compliance levels are presented by changing the ratio of displacement of the user's real and virtual hands. Further, the wristband-type display can deliver an additional squeeze force and vibrotactile feedback using physical stimuli.

3.2.2 Modulation within Haptic Object Property

The other objective is the modulation of the specific haptic property. The specific property is presented with physical stimuli, and pseudo-haptics is used to modulate the same property.

Tatezono et al. [31] combined a force feedback device with pseudo-haptics to provide compliance effectively. They showed that the pseudo-haptic presence can provide an additional force of 0.2-0.4 N with a force feedback compared to when only the force feedback was provided.

Ujitoko et al. [64] combined real vibration and visual perturbation on a cursor on a display to modulate the perceived roughness. They showed that vibrotactile roughness could be perceived to be rougher with a visual perturbation. Hachisu et al. [72] combined vibrotactile feedback and pseudo-haptics to simulate the material properties of instruments while users played chromatic percussions. Users watched the vibration of a virtual stick on a display when tapping on the chromatic percussion. The proper configuration of the visual vibration and actual vibration allowed users to successfully recognize different materials. Hachisu et al. [71] suggested that the combination of the visual distortion of the displacement and patterned vibration can enable users to recognize macro bumps or holes. In their implementation, the speed of the cursor decreased when there was a positive slope, which was conveyed to the user through visual (cursor moves slower) and vibrotactile cues (frequency decreases).

As suggested by the above studies, the sensation felt by the user can be modulated using pseudo-haptics. Thus, the target sensation should be evaluated after integration if real physical stimuli are present.

3.2.3 Missing Area

Research has been conducted to present different haptic properties with pseudo-haptics and physical stimuli. Further, research has also been conducted to modulate a certain haptic property presented by the physical stimuli with pseudo-haptics.

In previous studies, the methods of physical stimulation and target haptic object properties were both limited. It is expected that more comprehensive verification of the effect of the combination with more diverse physical stimulations and haptic object properties will be conducted in the future.

Further, there is no clarity on how different haptic properties affect each other. For example, when considering complementation, which presents a feeling of friction with pseudo-haptics and a feeling of roughness with vibration, it is unclear if the effects are completely independent of each

TABLE 2
We frame the existing papers into three application categories and extract the context and haptic object property presented by pseudo-haptics.

Application category	Application context	Haptic object property presented by pseudo-haptics	Reference
Training	Surgical training	Compliance	[36], [38], [88]
Assistance	Manual operation	Force	[73]
Assistance	Manual operation	Compliance	[43], [44]
Assistance	Navigation	Friction	[56], [58]
Assistance	Navigation	Force	[74], [83], [84]
Assistance	Navigation	-	[87]
Assistance	Workout	Weight	[20], [22]
Assistance	Workout	Force	[75]
Assistance	Education	Force	[79], [80], [81], [82]
Entertainment	Bowling	Weight	[26]
Entertainment	Swimming	Force	[77]
Entertainment	Walking	Friction	[57], [59]

other. It is important to know the dependency because we need to control the effects on both properties in some cases.

4 Proposed Applications

4.1 Taxonomy of Application

We quote the taxonomy of applications for each objective introduced in [93] as follows:

> *Three categories are presented: training, assistance, and entertainment. The category of training is based on the application of haptic systems in virtual environments as tools or strategies for acquiring knowledge about a specific task/topic. By contrast, the category of assistance focuses on applications created to help during activities wherein the user already has the knowledge and experience, but the system is expected to enhance performance. The final category presented is entertainment. The entertainment industry has played an important role in the development of haptic systems and virtual environments because they have the same objective: immersion of the final user.*

We categorized the existing papers based on the above-mentioned taxonomy. Among the existing studies, those that proposed only a potential application but did not evaluate the effect of pseudo-haptics in the application context were not considered. Further, we extracted the context and haptic object property presented by pseudo-haptics for each application. The results are listed in Table 2.

4.2 Training

Li et al. [36], [38], [88] proposed a surgical training system that used pseudo-haptics for tumor identification during palpation. They proposed presenting the hardness of the tumor using pseudo-haptics on soft tissue surfaces.

They combined pseudo-haptics with actual force feedback to reduce the time required for nodule detection during palpation. Compared to sole pseudo-haptic feedback or force feedback, the proposed combined feedback technique enabled participants to detect hard nodules in soft tissue more quickly. However, the effect on actual tumor identification performance after training with their proposed system remains unclear and is considered a research direction for a future study.

4.3 Assistance

We found that previously proposed applications for this category can be grouped into several subcategories such as manual operation, navigation, workout, and educational support.

4.3.1 Manual Operation

Nomoto et al. [73] presented a force using pseudo-haptics to support users who are tracking a precise path during manual handling tasks. They presented a virtual force when users deviated from the target path. Their results indicated that manual handling accuracy improved by 50 % when using pseudo-haptics. However, the duration required to track a path increased when the expansion rate was large. Neupert et al. [43], [44] used pseudo-haptic feedback to present the compliance property instead of using a kinesthetic feedback device in robot teleoperation. Their proposed system returns the pseudo-haptic feedback of the operation at the end-effector of the remote robot to facilitate the operation. They clarified that users can recognize the compliance of remote materials using pseudo-haptic feedback, and they suggested a use case for pseudo-haptics in the remote operation.

4.3.2 Navigation

Pseudo-haptics can be used to perform navigation on touchscreen interfaces. Kim et al. [58] proposed a content-aware kinetic scrolling technique that presents pseudo-haptic kinetic friction around the points of high interest on a page. This allows users to identify interesting content quickly while exploring the page without further cluttering the limited visual space. Their results indicated that users focused on items with kinetic scrolling feedback during the search, recognition, and skimming tasks. Hashimoto et al. [56] investigated the effect of the kinetic frictional property presented by pseudo-haptics during touchscreen browsing. They used this method to evaluate the performances of the visual memory task. The results showed that figures around higher frictional areas significantly remained in memory. Further, the participants showed the best performance for the visual memory task when using interactive scrolling with the dynamic kinetic friction modification. Baglioni et al. [84] presented users with virtual inertial force using pseudo-haptics when scrolling on a touchscreen for navigation. When users touched the screen during background scrolling, the scrolling speed did not become zero but decelerated slowly. The results of their target acquisition experiment indicated that the number of scrolling times decreased when this technique was applied. In desktop environments, Schoor et al. [87] used pseudo-haptics as a navigation technique for segmenting large biological image data. Though they did not clarify what type of haptic object property was represented by the pseudo-haptic feedback, they modified the visual cursor displacement with respect to input displacement based on the image content. Further, they found that the addition of the pseudo-haptic techniques improved the overall performance of the segmentation in terms of both accuracy and task completion time. Weng et al. [83] proposed a knot manipulation interface with pseudo-haptics for intuitive exploration of mathematical knot diagrams. Their experimental results showed that the pseudo-haptic force cues had the potential to redirect the user ' s eye-gaze onto the designated path and geometric features in mathematical visualization of knot. Gaucher et al. [74] highlighted relevant items in a 3D carousel-based interaction. They presented a frictional and magnetic force using pseudo-haptics and attracted the user towards these specific items when interacting with the carousel.

4.3.3 Workout

The possibility of changing the weight property of an object is illustrated using pseudo-haptics. Taima et al. [20] conducted an experiment wherein they visually altered the movement of a dumbbell to ensure that the dumbbell felt lighter than its actual weight. The results of the user experiments indicated that it was possible to reduce fatigue in subjects and increase the number of repetitions by 9.0 %. These results suggested that the pseudo-haptic effect may affect physiological responses in addition to the perception of the user. Jauregui et al. [22] used a similar approach to make the dumbbell lighter. In their task, the user lifted a virtual dumbbell by mapping gestures in real time onto a self-animated avatar. The avatar showed different visual efforts based on the weight of each virtual dumbbell. Pseudo-haptics has been proposed for use in rehabilitation. Li et al. [75] used pseudo-haptics to add motion assistance or resistance to virtual reality-based upper-limb rehabilitation. The participants were asked to control the cursor with the upper-limb and perform the path following task. The results revealed that the motion assistance mode was more time-efficient and easier compared to the motion resistance mode. It suggested that the difficulty of the path following task could be modulated by the pseudo-haptics.

4.3.4 Education

An illusory force represented by pseudo-haptics has been considered for use in educational support on tablets [79], [80], [81], [82]. Kashihara et al. [79] proposed an illusory force presented using pseudo-haptics to promote knowledge acquisition. They developed a tablet system wherein users can link nodes to construct systematic knowledge. When users link two nodes that were incorrect, users are presented with a repulsive force; when they link nodes with an important relationship, they are presented with an attractive force. Their experimental results indicated that pseudo-haptics can positively influence the memorization of important knowledge.

4.4 Entertainment

Realism in the virtual world is improved when appropriate haptic feedback is presented in addition to visual or auditory feedback [94]. The following studies investigated whether pseudo-haptics, which can be realized using inexpensive devices instead of physical stimuli, can be used to improve realism in entertainment applications.

Rietzler et al. [25] showed that simulating weight by pseudo-haptics provided users with higher levels of presence, immersion, and enjoyment in a virtual bowling scene. Kang et al. [77] proposed the reproduction of drag forces in a virtual underwater environment using pseudo-haptics. Their results indicated that their method could effectively reproduce the sense of being immersed in water. Ujitoko et al. [57], [59] proposed a touchscreen system wherein users can walk in a snowy environment using their fingers. By changing the ratio between the displacement of the finger and the amount of scroll of the visual ground, users can be provided with pseudo-haptic feedback to present the sensation of the difficulty in moving forward because of the snow. A user study showed that users felt a significant amount of difficulty when moving forward while using pseudo-haptics.

4.5 Discussion

Table 2 indicates that the number of research studies on applications for training is lower than that for assistance or entertainment. This is attributed to the following reasons: To use the haptic display to present a virtual haptic object property for training applications, the property should be comparable to the actual property. However, a haptic object property presented by pseudo-haptics is considered to provide only an illusory feeling, and it cannot substitute physical stimuli. Therefore, even if training is performed with a system that presents the haptic object property using pseudo-haptics, it is difficult to guarantee the effect of training in the actual work. In fact, the research proposing surgical training [43], [44] was unable to successfully verify the effectiveness of the training. Therefore, it is considered difficult to use pseudo-haptic feedback for training applications.

By contrast, the effectiveness of pseudo-haptics in assistance or entertainment applications has been demonstrated. Further, it is expected that an increasing number of applications will be developed for these categories. As of November 2020, COVID-19 has become a global threat. Under these circumstances, pseudo-haptics can help support the requirement to touch an object remotely without requiring special equipment. Two targets can be touched by an end user: an object and a human (social touch) [95], [96]. Scenarios where the end user touches an object have been evaluated in many previous studies [95], [96]. However, studies where pseudo-haptics is used for human-to-human touch experience or social touch are lacking. Therefore, the use of pseudo-haptics for social touch is considered a promising scenario.

A comparison between Tables 1 and 2 indicates that some object properties have not been proposed or evaluated in practical application contexts even though the properties can be presented with pseudo-haptics. For example, roughness is a property that has been actively studied; however, its practical application has not been considered yet. This is because the implementation indicates that roughness can be presented using the physical stimulus (e.g., by vibrotactile actuator) in a relatively simple and inexpensive manner. Thus, because these properties can be presented using such an inexpensive and simple competing method, it is necessary to consider the application context carefully.

5 Conclusion

In this study, findings from individual studies on pseudo-haptics were investigated comprehensively and organized from the design through to the application proposal.

- First, we summarized the visual stimuli and user input required for presenting each target haptic property. The summary showed that only four visual stimuli and three user inputs were considered in the existing papers. Although there have been studies addressing the thermal property using cross-modal visual-haptic or audio-haptic effects, we found that this property has not been addressed using pseudo-haptics. It may be possible to present or modulate this property based on the concept of pseudo-haptics.
- Second, we summarized the two supecial issues when designing pseudo-haptics. We introduced the problem and the visual stimuli design as the workaround techniques when the user input could be observed by the users. The restrictions on the presentation environment in which pseudo-haptics can be applied were relaxed using these techniques. Also, we summarized the effects of the combination of pseudo-haptics and other physical stimuli. We introduced the complementation between haptic properties and modulation within the haptic property. However, we could not verify how different haptic properties presented with physical stimuli and pseudo-haptics affect each other. Therefore, it is important to determine the dependency because we need to control the effects on both properties in some cases.
- Finally, we summarized the applications using pseudo-haptics that have been proposed for training, assistance, and entertainment. This clarified the application contexts in which pseudo-haptics has been shown to be effective and what haptic object properties are presented. We found that the number of proposed applications for training is lower than those for assistance or entertainment. This can be attributed to the lack of clarity related to whether training using pseudo-haptics is effective for actual work using real haptic feedback after training.

One of the limitations of this survey paper is that the effects of the proposed pseudo-haptics cannot be compared and evaluated between individual papers. For example, several visual stimuli that change the compliance property of objects have been proposed (shown in Table 1), but it is not possible to make a comparative evaluation of which of these was best in terms of robustness or resolution. This paper summarizes the content of individual papers and simply presents readers with design options.

In our opinion, there exist two future challenges. Firstly, pseudo-haptics is yet to be incorporated into applications used by the public. Though researchers have evaluated pseudo-haptics in various application contexts in the academic world, it is still unknown how it is applicable to real-world issues outside laboratories. When applying pseudo-haptics in the real world, we recognize the gap. Thus, we hope that haptic application developers will have opportunities to conduct experiments with pseudo-haptics outside the lab. Secondly, we need to identify the perceptual basis of pseudo-haptics to facilitate the design. The key challenge will be identifying the visual stimuli design such that the effect of pseudo-haptics is robust across users.

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