This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2023.3254522

Softness Perception of Visual Objects Controlled by Touchless Inputs: The Role of Effective Distance of Hand Movements

Takahiro Kawabe, *Member, IEEE,* Yusuke Ujitoko, *Member, IEEE,*

Abstract—Feedback on the material properties of a visual object is essential in enhancing the users' perceptual experience of the object when users control the object with touchless inputs. Focusing on the softness perception of the object, we examined how the effective distance of hand movements influenced the degree of the object's softness perceived by users. In the experiments, participants moved their right hand in front of a camera which tracked their hand position. A textured 2D or 3D object on display deformed depending on the participant's hand position. In addition to establishing a ratio of deformation magnitude to the distance of hand movements, we altered the effective distance of hand movement, within which the hand movement could deform the object. Participants rated the strength of perceived softness (Experiments 1 and 2) and other perceptual impressions (Experiment 3). A longer effective distance produced a softer impression of the 2D and 3D objects. The saturation speed of object deformation due to the effective distance was not a critical determinant. The effective distance also modulated other perceptual impressions than softness. The role of the effective distance of hand movements on perceptual impressions of objects under touchless control is discussed.

Index Terms—Material perception, Pseudo-haptics, Touchless inputs, Softness

1 Introduction

Perceiving material properties is an essential experience in our daily lives. For example, by stretching a cloth fabric, we can perceptually judge whether the fabric is soft or hard, whether the fabric feels good or not, and so on. Similar kinds of interaction between users' actions and visual objects likely enhance the perceptual understanding of material properties in virtual and augmented reality scenes [1], [2], [3]. By controlling visual objects' motion direction and speed as visual feedback of user's actions, it is possible to give users the impression of various material properties such as weight/mass [4], [5], [6], [7], [8], [9], stiffness/softness [10], [11], [12], surface roughness [13], [14], and so forth. To understand what kind of visual presentation method gives the desired impression of material properties effectively, it is necessary to closely examine the relationships between users' actions, the type of visual feedback, and the impressions of material properties that are obtained.

Recently, the manipulation of visual objects through touchless inputs has attracted attention [15], [16]. Some interfaces, for example, cars' dashboard interfaces [17], [18], KIOSK [19], and digital signage [20] employ touchless inputs. In order to achieve rich interaction between users and a visual object through touchless inputs, it is necessary to examine in detail what kind of visual feedback of the inputs is effective in providing the user with an appropriate impression of the material properties of the object. Some previous studies [12], [21] have shown that the physics-based manipulation of visual feedback can enrich the perception of three-dimensional carousels [21], object heaviness [22], and elastic materials [12] controlled by touchless gesture inputs.

One drawback of touchless input systems is that touchless gestures do not serve as practical inputs for controlling the appearance of visual feedback if not properly captured by sensing devices such as a camera. In such cases, the visual feedback is not updated, and thus, only static images are provided to the user. Let us consider the case where users pull a deformable virtual object laterally and generate its deformation on the basis of touchless gesture inputs. When the camera no longer captures the user's pulling gestures due to occlusion which is something blocking the path of view, or the limits of the effective angle of view, the object stops deforming. It was unclear how this unexpected cessation of deformation would affect the user's perception of the material. While it is possible to employ additional methods such as electromyography [23], electromagnetic interfaces [24], air-pressure sensors [25], and Radio Frequency Identification [26] to detect users' gestures which are not captured by a camera, this study focuses on the case where the only method for detecting gestures is the camera. Cameras as sensing devices are widespread, often attached to notebook PCs, and their implementation is low-cost. On the other hand, specialized sensing devices such as those mentioned above are not yet common and are expensive. For these reasons, it is worth focusing only on situations where gestures are detected by a camera.

The purpose of this study was to elucidate whether and how the cessation of object deformation during touchless gestures affected the perception of object softness and other object properties. The cessation of object deformation likely causes the change of motion speed. It is known that the change in motion speed can create the impression of friction, gravity, or viscosity [11], resistance [27], and collision [28],

- *E-mail: takkawabe@gmail.com*
- *T. Kawabe and Y. Ujitoko are with NTT Communication Science Laboratories, Nippon Telegraph and Telephone Corporation, Atsugi, Kanagawa, 243-0198, Japan.*

Manuscript received April 19, 2005; revised August 26, 2015.

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2023.3254522

[29], [30], [31]. On the other hand, it was still unclear whether the change in motion speed, which was caused by the cessation of object deformation, was a factor to modulate perceived softness. Thus, in Experiment 1, we explore whether the perceived softness of the object is altered when the object stopped deforming at some point with touchless gestures. Specifically, we manipulate the effective distance of hand movement within which the virtual object could deform in response to hand movement and examined whether the effective distance of hand movements could modulate the perceived softness of the object. In Experiment 2, we examine whether the saturation speed of object deformation during touchless inputs, which is varied with the effective distance of hand movements, can modulate the level of the perceived softness of the object. To further gain insights into the effect of the cessation of object deformation on perceptual impression, in Experiment 3, we examine how the cessation of the object deformation during touchless inputs can change the perceptual impression of objects other than softness. Based on the results, we speculate the mechanism underlying the change in perceptual softness by the cessation of object deformation during touchless inputs.

In the second section of this article, we describe the previous literature relevant to the present study. In the third section, we specify the issue we treat in this study. In the fourth and fifth sections, we describe the two experiments we conducted. In the sixth section, we discuss the significance, another interpretation, and limitations of the present study.

2 Related Studies

2.1 Softness Perception in Vision

Visual perception of material properties is one of the recent hot topics in vision science [32], [33]. Most studies on the material properties have focused on optical (or surface) properties such as texture and glossiness. In addition, users can perceive mechanical properties of materials [34], and several previous studies have investigated the mechanism for the perception of the mechanical properties such as elasticity [35], [36], [37], viscosity [38], [39], [40], [41], and fabric stiffness [42], [43], [44].

Above all, the visual perception of softness (or relatedly, stiffness) has attracted the attention of scientists. The most promising cue to the visual softness perception for a material that is indented by an external body is the indentation depth [45], [46] or the deformation magnitude [47]. Specifically, a greater magnitude of indentation depth generates a larger magnitude of deformation in the image, producing an impression of greater softness for the indented material. In addition, the speed of indentation plays an effective cue in the perception of the softness of material. A faster indentation generates a faster deformation in the image, which produces the impression of a greater softness of the material [35], [47]. However, analyzing image motion in stimulus video clips, the previous study [47] reported that deformation magnitudes were stronger cues to the perception of the softness of a material than the deformation speed.

2.2 Softness Perception of Objects Deformed under User's Manual Control

The perception of the softness of an elastic object has been examined in a situation wherein users controlled the appearance of the object displayed on a monitor by manipulating real objects and/or input devices. A previous study [48] has shown that the judgment of the stiffness of real spring devices could be significantly influenced by the visual feedback of the spring. Another previous study [11] has found that users could discriminate stiffness between a real spring that was controlled in the real world and a visual spring that was controlled by using an isometric device. Similarly, a recent study [49] also showed that when users controlled the deformation of a rectangle on a smartphone monitor by applying force to the side of the smartphone, the rectangle's deformation could generate the impression of stiffness of the rectangle which was comparable with the stiffness of the real object. In a video see-through system, a previous study [50] showed that the perceptual judgment of an object's softness was strongly altered by the combination of the appearance of users' pinching gestures as well as the one of a real elastic object. Although the previous study was related to the judgment of object softness in augmented reality, a more recent study [51] has reported that a visual object under the user's manual control was judged to be softer in augmented reality than in virtual reality settings.

2.3 Softness/stiffness Perception of Objects in Touchless Controls

It has also been examined how the user's touchless gesture to control a visual object could contribute to the generation of the stiffness sensation of the object. There are several previous studies proposing an AR system that gives users a pseudo-softness of an object [12], [52] and a pseudo-contact to an object [53] while the user makes a gesture of controlling the object with a bare hand. Hereinafter, we describe one of the previous studies in detail. The previous study [12] instructed experimental participants to make a gesture to pull a visual object displayed on the monitor laterally. A camera-based hand tracker was used to track the position of the participant's hands. The magnitude of deformation applied to the visual object was changed in accordance with the tracked position of the hands. The participants were asked to report the stiffness of the object on a 5-point scale. The results of that study showed that the reported stiffness was dependent on the magnitude of horizontal deformation of the visual object in relation to the distance of hand movements. Specifically, the stiffness increased in accordance with the ratio of the deformation to the distance of the hand movements. The previous study also found that not only the horizontal deformation but also the vertical one also contributed significantly to the stiffness perception, consistent with the idea that the sensory system in users internalizes the physical characteristics called the Poisson effect [54], [55] and uses the internalized representation of the Poisson effect to judge the stiffness of the visual object.

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2023.3254522

2.4 Contribution of The Present Study to Softness Perception Research

Although the previous studies have clarified the visual parameters to determine perceived softness, it is still unclear how the change in object motion speed, which is likely caused by the cease of object deformation during touchless inputs, can influence softness perception. Examining the effect of the change in object motion speed on the softness perception will help us to understand the mechanism of softness perception better and to determine the parameters when implementing soft objects in touchless inputs.

3 Research Issue in the Present Study

Figure 1 shows a schematic description of the relationships between the angle of the camera view, a user's right hand position, and an occluder, that is something that blocks the camera view. In the angle of camera view (Figure 1 (a)), a camera captures images of a user's right hand (Figure 1 (b)), and based on the images, a computer calculates the position of the hand as being at certain coordinates and modifies the appearance of visual objects as feedback. The user's right hand, when outside the angle of the camera view, will not be captured (Figure 1 (c)). In addition, as shown in Figure 1 (d), if another object occludes the hand, the images of the user's hand will not be captured by the camera. When the image of the user's hand is not captured, the position of the user's hand is not updated. Consequently, the modification of the appearance of the visual object ceases. It was unclear how users perceived the material properties of the object when the modification of the object's appearance ceased during the manipulation by touchless input.

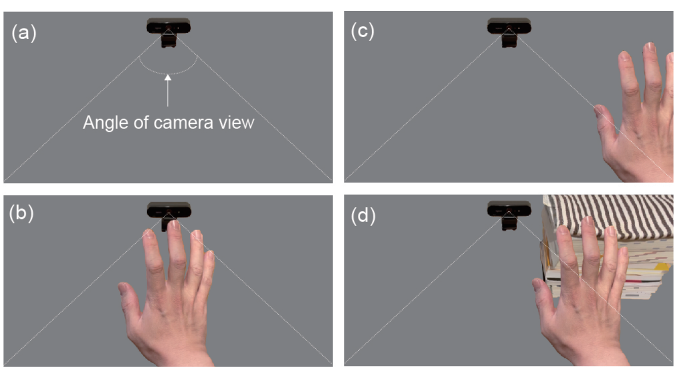

Fig. 1. Graphical explanations of the relationships between the angle of camera view, the position of a user's right hand, and an occluder. Panel (a) shows the angle of the camera view. Panel (b) shows the situation wherein the user's right hand falls into the angle of the camera view. Panel (c) shows the situation wherein the hand is outside of the angle of the camera view. Panel (d) shows the situation in which the hand is not captured by the camera due to the existence of an occluder even though the hand falls within the angle of camera view.

4 Experiment 1: The Role of Effective Distance of Hand Movement

4.1 Purpose

The purpose of this experiment was to explore whether the cessation of visual object deformation during the manipulation of the object influenced the participant's judgment

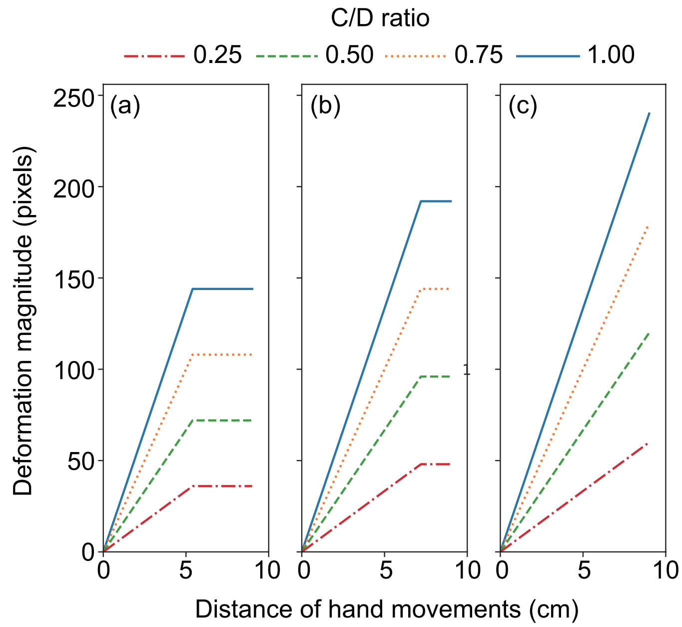

Fig. 2. Variation of deformation magnitudes with the effective distance of hand movements of (a) 5.4, (b) 7.2, and (c) 9.0 cm. Different lines indicate the deformation magnitudes for different C/D ratio conditions.

of the object's softness. The participants moved their right hand in front of a camera which was used to track the hand's position, while watching a visual object on the monitor. We manipulated the effective distance of hand movements within which the hand movement caused the object deformation (Figure 2). When the effective distance of hand movements was shorter, the deformation ceased earlier on the path of the hand movement. In other words, the longer the effective distance of hand movements, the larger the magnitude of the object deformation. It was predicted that the rating scores of the softness would increase with the effective distance of hand movement because the larger magnitude of the object deformation likely triggered a stronger softness impression of the object. We also tested the effect of the ratio of the distance of hand movement to the object deformation magnitude. Hereinafter, we call the ratio the C(Control)/D(Display) ratio after the previous studies [56]. Although the definition of the C/D ratio varies depending on studies [3], in the present study, the larger the C/D ratio caused the larger deformation with the smaller hand movements. It was expected that the larger the C/D ratio, the greater the rating scores for the object's softness. We also checked the interaction between the effective distance of hand movements and the C/D ratio.

4.2 Method

4.2.1 *Participants*

Eighty-four (42 female and 42 male) people participated in this experiment. The participants' mean age was 40.38 (SD: 12.11). The participants' ages ranged from 20 to 59, and the numbers of participants in the 20's, 30's, 40's, and 50's age generations were 21, 20, 21, and 22, respectively. We did not ask about the handedness of the participants. All of the participants were unaware of the specific purpose of the experiment. The participants in this study were recruited by

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2023.3254522

a Japanese online survey company and paid for their participation. Ethical approval for this study was obtained from the ethics committee at Nippon Telegraph and Telephone Corporation (Approval number: R02-009 by NTT Communication Science Laboratories Ethics Committee). The experiments were conducted according to principles originating in the 2008 Helsinki Declaration. Written informed consent was obtained from all participants in this study.

4.2.2 Apparatus

This experiment was conducted online. Stimuli were presented on the monitor of the personal computer that the participants normally used. The position of the participant's hand was tracked by using the web camera which was available in the participant's environment. The position of the participant's hand was calculated using the coordinates of the camera image by using (handsfree.js https://handsfreejs.netlify.app/). The measured mean sampling rate of the hand tracking was 30.747 Hz (SD: 13.223 Hz).

4.2.3 Stimuli

Stimuli, consisting of a horizontal arrow and a two-dimensional rectangle against a black background, were presented in the upper part of the monitor (see Figure 3). The arrow indicated the range within which the participants were required to move their right hand. In front of the arrow, the participants moved their hand from left to right or right to left. The horizontal length of the arrow was 9 cm (the corresponding pixel distance varied with the participant's environment). The left side of the arrow was located at the horizontal center of the monitor and at 256 pixels above the vertical center of the monitor. While the system detected the participant's hand in front of the arrow, the arrow's color was green. Otherwise, its color was gray. By the color change, we encouraged the participant to set and move their hand position in front of the arrow. The color change unlikely influenced the results of the experiment. The center of the rectangle was located 384 pixels to the left and 256 pixels above the center of the monitor. The rectangle initially subtended 128 (height) $\times$ 128 (width) pixels. The rectangle had gray-scale two-dimensional 16 $\times$ 16 random noise as texture. The noise intensity ranged from 0 to 255 in the RGB values. The rectangle with the texture was horizontally deformed in accordance with the participant's hand position. In an incompressible material, when an elastic material is stretched horizontally, it is naturally compressed vertically, wherein the magnitude of vertical deformation is smaller than that of horizontal deformation. The ratio of the vertical to horizontal deformations is called the Poisson's ratio [57]. Based on the physical characteristics of the deformation of an elastic material, vertical deformation was added to the rectangle so that the deformation had Poisson's ratio of 0.25. We chose the value (0.25) of the Poisson's ratio because the value fell in the range of the Poisson's ratio supporting the natural impression of the Poisson effect in human observers [54]. Moreover, we used the two-dimensional rather than the three-dimensional stimuli because the previous studies [54], [55] have mainly used the two-dimensional stimuli to assess the perception of object deformation with the Poisson effect. We experimentally tested the following two factors. The first factor was a C/D ratio controlled in the following four levels (0.25, 0.5, 0.75, and 1). The second factor was an effective distance of hand movements defined as the spatial distance between the left terminator of the arrow and the hand position. The effective distance of hand movements was controlled in the following three levels (5.4, 7.2, and 9 cm). When the distance exceeded 9 cm, the deformation ceased. Moreover, the deformation was also stopped when the camera temporally lost the participant's hand. We chose the maximum value (9 cm) of the effective distance for the following reason. We assumed an ideal situation whereby the participant's hand was always separated by 30 cm from the camera with a 60 deg angle of view. In this case, approximately 9 cm was the maximum hand movement distance the camera could capture. Considering that the angle of view in the usual Laptop PC was expected to be more than, or equal to, 60 deg, it was reasonable to use 9 cm as a maximum value of the effective distance. 5.4 and 7.2 cm were arbitrarily chosen as the 60 and 80 % of the maximum value (9 cm). For each trial, the maximum deformation magnitude of the rectangle was determined depending on the C/D ratio and effective distance of hand movement as shown in Table 1. Figure 2 shows how the magnitude of object deformation changes with the two factors. As shown in Figure 4, the appearance of the rectangle drastically changed with the magnitude of object deformation applied to it.

TABLE 1
Maximum magnitude of object deformation which varies depending on C/D ratio and effective distance of hand movements.

C/D ratio	Effective distance of hand movements (cm)	Maximum magnitude of object deformation (pixels)
0.25	5.4	36
0.25	7.2	48
0.25	9.0	60
0.50	5.4	72
0.50	7.2	96
0.50	9.0	120
0.75	5.4	108
0.75	7.2	144
0.75	9.0	180
1.00	5.4	144
1.00	7.2	192
1.00	9.0	240

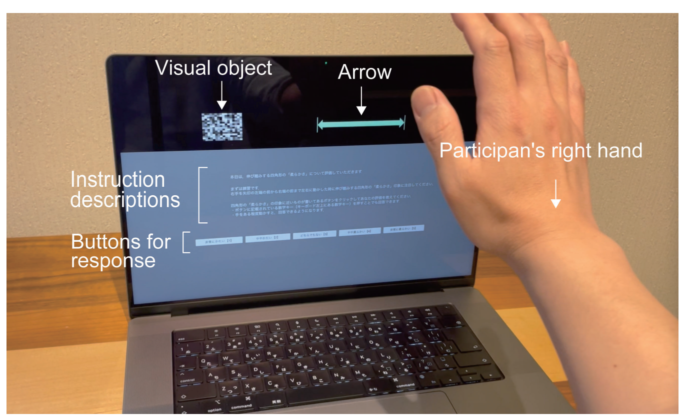

Fig. 3. A snapshot of a representative experimental setup.

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2023.3254522

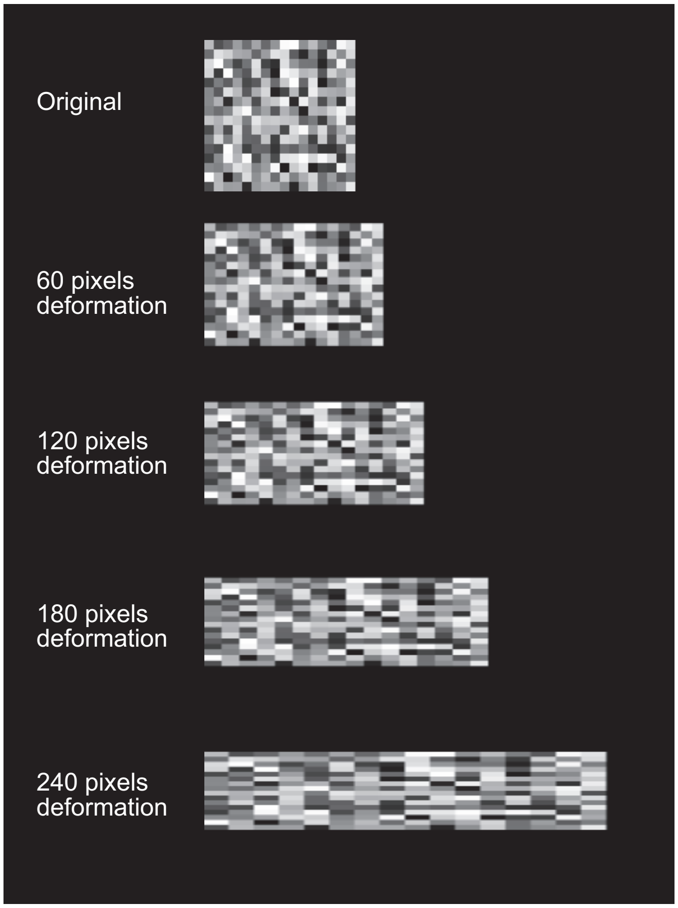

Fig. 4. The change in the appearance of object deformation with different levels of deformation magnitude. The object deforms in both the vertical and horizontal dimensions.

4.2.4 Procedure

Based on the previous study [58], before starting an experimental session, the participant was asked to adjust the size of a rectangle presented on the monitor so that the rectangle had an identical size to a credit card (or a card of equal size) which the participant possessed. This matching was essential to determine the real scale (i.e., in cm) which depends on the pixel size of the monitor the participant was using for the experiment. After determining the real scale for the pixel size, we set the length of the arrow at 9 cm. The length setting was important because we wanted to control the travel distance of the participant's hand movement in the main tasks by the length of the arrow. Then, the participants were asked to move their right hand in front of the arrow. After the system successfully detected that the participants moved their hand in front of the arrow, the participant moved to the practice and main trials in this order. In each trial, the participants were instructed to place their right hand approximately 30 cm from the camera and move their hand in front of the arrow while maintaining the 30 cm distance from the camera (see Supplementary Video 1 for experimental scenes). Preliminary examinations with several cameras confirmed that moving the hand laterally for 9 cm at 30 cm from the camera (having approximately a 60 deg angle of camera view) produced camera images in which the hand was moved by roughly 1/4 of the width of the camera image. When the participants moved their hand by more than a critical value (approximately 1/4 of the width of the camera image, that is, 9 cm from the horizontal center of the monitor) from the left terminator of the arrow, the five buttons for the input of rating scores appeared. The buttons included the following pairs of a digit and a short description of softness impressions: "1: Very stiff", "2: Moderately stiff", "3: Neither stiff nor soft, "4: Moderately soft", and "5: Very soft". The participants reported the softness judgment of the rectangle by clicking one of the buttons. Alternatively, they were also allowed to report the softness judgment by pressing number keys that corresponded to the digit of the button including the softness description which represented their softness judgment. The practice trials consisted of two trials: the first one had a C/D ratio of 1.0 and an effective distance of hand movements of 0.25 and the second one had a C/D ratio of 1.0 and an effective distance of hand movements of 1. The main trials consisted of twelve trials with the four different C/D ratios (0.25, 0.5, 0.75, and 1.0) and three conditions of the effective distance of hand movements (0.6, 0.8, and 1). The order of the twelve trials was randomized within and across the participants.

4.2.5 Results

Figure 5 shows mean rating scores for the object softness as a function of the effective distance of hand movement for each C/D ratio condition. We reviewed the time it took participants to complete the task and found that they completed it within a reasonable amount of time (median: 0.858 minutes, 95% confidence intervals: [0.38, 2.12]). Only one participant took a relatively long time (6.78 minutes) to complete the task. We checked the data for that participant but found nothing suspicious. Since there was no reason to exclude this participant's data, we used all participants' data for further analysis. First, we checked whether the frame rate of stimulus presentation influenced the softness rating scores. Specifically, we calculated Spearman's correlation between the rating scores of object softness and frame rates (that is, sampling rates). We found that there was no significant correlation between them ($rs = 0.037$, $p = 0.236$). Second, we analyzed how the factors we tested influenced the softness rating scores. The rating scores are not parametric data. Hence, we conducted the aligned rank transform [59] of the rating scores and then a two-way repeated measures of analysis of variance (ANOVA) with the C/D ratio and the effective distance of hand movements as within-participant factors. The results of the ANOVA are shown in Table 2. The main effect of the C/D ratio was significant. The main effect of the effective distance was also significant. Interaction of the two factors was also significant.

TABLE 2
ANOVA table for the rating data in Experiment 1.

Factors	df(df.res)	F value	Pr(>F)	η_p^2
C/D ratio	3(249)	147.729	<.0001	0.640
Effective distance	2(166)	20.360	<.0001	0.197
Interaction	6(498)	3.952	=.0007	0.045

As shown in Table 3, multiple comparison tests (with ART-C proposed by a previous study [60]) showed that each level of the C/D ratio was significantly different from all

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2023.3254522

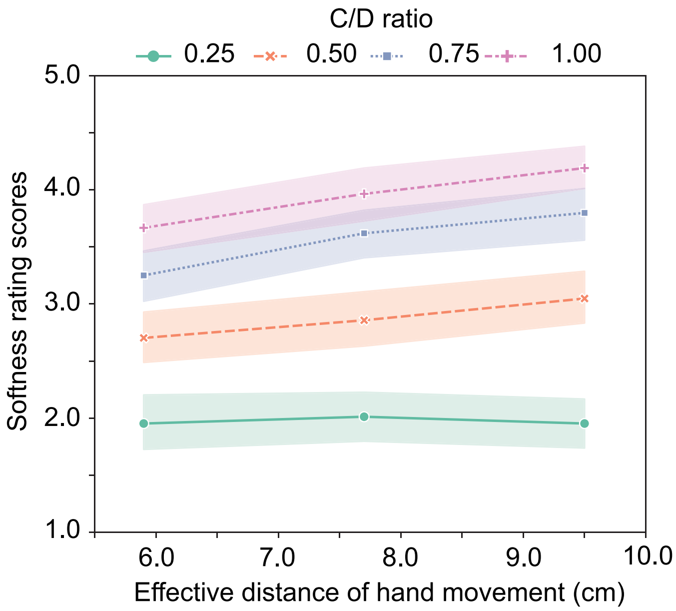

Fig. 5. Ratings scores for object softness in Experiment 1 (N = 84). Error stripes denote 95 % confidence intervals.

TABLE 3
Results of multiple comparison tests for function type in Experiment 1.

contrast	estimate	df	t.ratio	p.value
0.25 - 0.5	-184.4	249	-8.548	<.0001
0.25 - 0.75	-335.6	249	-15.556	<.0001
0.25 - 1	-422.7	249	-19.594	<.0001
0.5 - 0.75	-151.2	249	-7.007	<.0001
0.5 - 1	-238.3	249	-11.046	<.0001
0.75 - 1	-87.1	249	-4.038	=0.0004

other levels of the C/D ratio. The results support the results in the previous study [12] showing that the C/D ratio was a critical parameter in determining the stiffness of the visual object under user's touchless control.

Table 4 shows the results of the multiple comparison tests for the effective distance of hand movements. The rating scores were significantly different between 5.4 and 7.2 cm, and 5.4 and 9.0 cm, of the effective distance. The difference of the rating scores between 7.2 and 9.0 cm of the effective distance was marginally significant.

We also assessed the simple effect of the significant interaction. The simple effect of the C/D ratio (Table 7) was significant for all effective distance conditions. The multiple comparison tests of the simple effect (Table 8) showed that the rating score in a certain C/D condition was significantly different from other conditions except a pair of the 0.75 and 1.0 C/D ratios for the 7.2 cm effective distance condition. The simple effect of the effective distance (Table 5) was also significant when the C/D ratio was more than 0.25. The multiple comparison tests of the simple effect (Table 6) showed that when the C/D ratio was 0.5 or more, the rating scores in the 5.4 cm effective distance condition were significantly lower than those in the 9.0 cm effective distance condition. Moreover, when the C/D ratio was 0.75 or more, the rating scores in the 5.4 cm effective distance condition were significantly lower than those in the 7.2 and 9.0 cm effective distance condition.

TABLE 4
Results of multiple comparison tests for the effective distance of hand movement in Experiment 1.

contrast	estimate	df	t.ratio	p.value
5.4 - 7.2	-69.8	166	-3.962	=0.0003
5.4 - 9.0	-111.3	166	-6.313	<.0001
7.2 - 9.0	-41.4	166	-2.351	=0.0597

TABLE 5
Simple effect of effective distance in Experiment 1.

C/D ratio	df(df.res)	F value	Pr(>F)	η_p^2
0.25	2(166)	0.3531	=0.703	0.004
0.50	2(166)	3.148	0.046	0.037
0.75	2(166)	9.493	0.0001	0.103
1.00	2(166)	11.876	<0.001	0.125

4.2.6 Discussion

The effective distance of the participant's hand affected the softness perception of an object under the participant's touchless control. In other words, an earlier cessation of object deformation gave the impression of a less soft object. This finding suggests the necessity of taking the cessation of object deformation into account in giving users the intended softness impression of the object under the user's touchless control.

5 Experiment 2: The Role of Saturation Speed of Object Deformation

5.1 Purpose

The purpose of the experiment was to confirm whether the saturation speed of object deformation during touchless inputs was the source of the decrease in the softness rating scores. In Experiment 1, when the effective distance was applied to the hand movement, the deformation ceased; that is, the magnitude of object deformation was discontinuously saturated at the middle of the hand trajectory (see Figure 2). Moreover, depending on the level of the effective distance of hand movements, the saturation speed changed. A smaller effective distance caused earlier saturation of object deformation. Hence, there was a possibility that the source of the effect of the effective distance on the softness rating scores was the saturation of object deformation during touchless inputs. In Experiment 2, we systematically manipulated the temporal pattern of object deformation so that the pattern had a saturation function in several degrees (see Figure 6) while the overall magnitude of object deformation was kept constant. Moreover, we also explored how the growth (not the saturation) of object deformation could infleunce the softness perception. We again instructed the participants to rate the object's softness.

5.1.1 Participants

82 (41 female and 41 male) people, who had not participated in the previous experiment, participated. Their mean age was 39.63 (SD: 11.40). The participants' ages ranged from 20 to 59, and the numbers of participants in the 20's, 30's, 40's, and 50's age generations were 20, 20, 20, and 22, respectively All of the participants were unaware of the specific purpose of the experiment.

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2023.3254522

TABLE 6
Multiple comparisons for the simple effect of effective distance in Experiment 1.

contrast	estimate	df	t.ratio	p.value
0.5 C/D ratio				
5.4cm - 7.2cm	-9.36	166	-1.058	=0.875
5.4cm - 9.0cm	-22.12	166	-2.500	=0.040
7.2cm - 9.0cm	-12.76	166	-1.441	=0.454
0.75 C/D ratio				
5.4cm - 7.2cm	-23.1	166	-2.662	=0.026
5.4cm - 9.0cm	-37.5	166	-4.319	=0.001
7.2cm - 9.0cm	-14.4	166	-1.657	=0.299
1.00 C/D ratio				
5.4cm - 7.2cm	-26	166	-3.259	=0.004
5.4cm - 9.0cm	-38	166	-4.768	<0.0001
7.2cm - 9.0cm	-12	166	-1.508	=0.400

TABLE 7
Simple effect of the C/D ratio in Experiment 1.

Effective distance	df(df.res)	F value	Pr(>F)	η_p^2
5.4cm	3(249)	61.687	<0.0001	0.426
7.2cm	3(249)	74.169	<0.0001	0.472
9.0cm	3(249)	99.486	<0.0001	0.545

5.1.2 Apparatus

The apparatus for this experiment was identical to that used in the previous experiment. The mean sampling rate of the hand tracking in this experiment was 29.946 Hz (SD: 13.169 Hz).

5.1.3 Stimuli

The stimuli were identical to those used in Experiment 1 except for the following points. The effective distance of hand movement was kept constant at 9.0 cm. The C/D ratio was controlled in the following three levels: 0.25, 0.5, and 1.0. At each C/D ratio level, we manipulated the type of functions in the following five levels: Type 1: Early saturation, Type 2: Late saturation, Type 3: Linear, Type 4: Early growth, and Type 5: Late growth (Figure 6).

To generate stimuli having the saturation/growth of object deformation, we used an exponential function D defined by using the following formula,

$$D = \exp(-s \times h).$$

For the functions of Type 1 and Type 5, s was set at 0.1. For the functions of Type 2 and Type 4, s was set at 0.05. h was the distance of hand movements.

Then, we normalized the D into D_{norm} so that the value of the D_{norm} distributed in the range between 0 and 1 in the following way,

$$D_{norm} = \frac{D - D_{min}}{D_{max} - D_{min}},$$

wherein D_{min} and D_{max} are the minimum and maximum values in the given function D.

The deformation magnitudes D_{final} in Type 1 and Type 2 functions were defined by the following formula,

$$D_{final} = G \times (1 - D_{norm}),$$

TABLE 8
Multiple comparisons for the simple effect of C/D ratio in Experiment 1.

contrast	estimate	df	t.ratio	p.value
5.4cm distance				
0.25 - 0.50	-57.0	249	-5.593	<0.0001
0.25 - 0.75	-99.2	249	-9.741	<.0001
0.25 - 1.00	-130.8	249	-12.835	<.0001
0.50 - 0.75	-42.2	249	-4.147	=0.0003
0.50 - 1.00	-73.8	249	-7.242	<.0001
0.75 - 1.00	-31.5	249	-3.095	=0.0132
7.2cm distance				
0.25 - 0.50	-58.6	249	-5.683	<0.0001
0.25 - 0.75	-115.0	249	-11.140	<0.0001
0.25 - 1.00	-141.5	249	-13.706	<0.0001
0.50 - 0.75	-56.3	249	-5.457	<0.0001
0.50 - 1.00	-82.8	249	-8.023	<0.0001
0.75 - 1.00	-26.5	249	-2.566	=0.0652
9.0m distance				
0.25 - 0.50	-72.1	249	-7.335	<0.0001
0.25 - 0.75	-127.4	249	-12.958	<0.0001
0.25 - 1.00	-157.9	249	-16.059	<0.0001
0.50 - 0.75	-55.3	249	-5.623	<0.0001
0.50 - 1.00	-85.8	249	-8.723	<0.0001
0.75 - 1.00	-30.5	249	-3.101	=0.0129

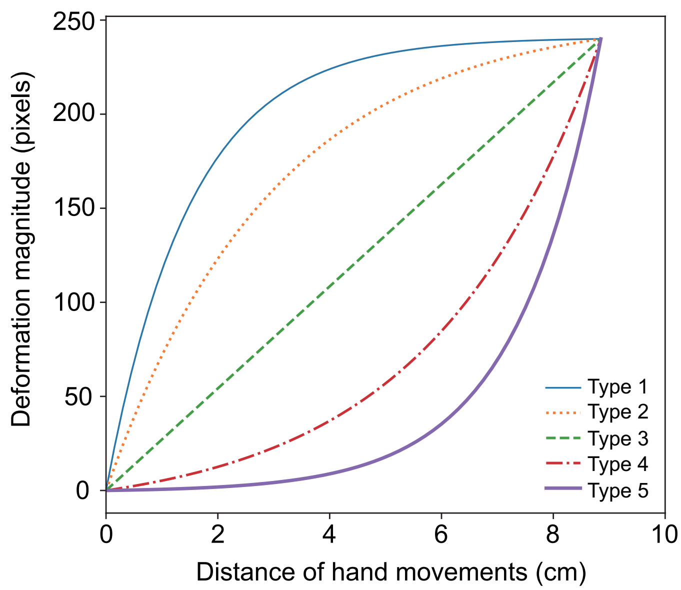

Fig. 6. Saturation/growth of object deformation we employed for each condition of the five function types in Experiment 2, with the C/D ratio of 1.0 (thus, the maximum magnitude of object deformation of 240 pixels).

and the deformation magnitudes D_{final} in Type 4 and Type 5 functions were defined by the following formula,

$$D_{final} = G \times D_{norm},$$

wherein G denotes the maximum deformation magnitude in pixels. When the C/D ratio was 0.25, 0.5, and 1.0, G was 60, 120, and 240 pixels, respectively.

5.1.4 Procedure

The procedure was identical to the one used in Experiment 1 except for the following points. The main trials consisted of fifteen trials with the three conditions of C/D ratios (0.25, 0.5, and 1.0) and five conditions of nonlinear functions (Types 1-5). The order of the fifteen trials was randomized and within and across the participants.

5.1.5 Prediction of Results in Terms of the saturation speed of Object Deformation

If the results of Experiment 1 were derived from the variation in the saturation speed of object deformation due to the effective distance of hand movements, the softness rating scores should be lower in the Type 1, Type 2, and Type 3 conditions in that order because the object deformation was saturated earlier in that order. In contrast, since the temporal non-linearity of object deformation in the Type 4 and Type 5 conditions was not similar to the one in Experiment 1's stimuli, it was not appropriate to make predictions for the results in the Type 4 and Type 5 conditions on the basis of the results of Experiment 1. Nevertheless, we tested the two conditions because we wanted to explore the role of the growth of object deformation in determining the object's softness. If the growth speed of object deformation was substantial in modulating the perception of object softness, the rating scores would be lower in the Type 5, Type 4 and Type 3 conditions in that order because the growth of object deformation was attenuated in that order.

5.1.6 Results

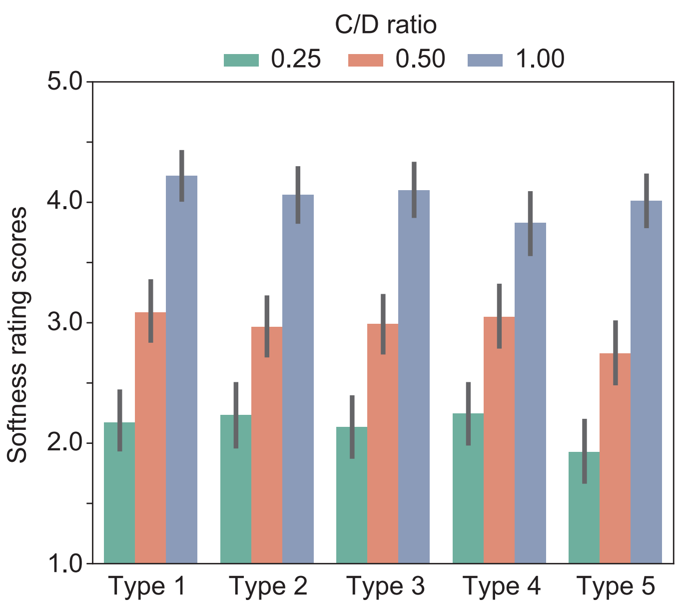

Fig. 7. Softness rating scores for each C/D ratio and function type condition (N = 82). Error bars denote 95% confidence intervals.

As in Experiment 1, we checked whether the frame rate of stimulus presentation influenced the softness rating scores. There was no significant correlation between them ($rs = 0.013$, $p = 0.578$).

We again reviewed the time it took participants to complete the task and found that they completed it within a reasonable amount of time (median: 3.22 minutes, 95% confidence intervals: [1.16, 12.34]). Only one participant took 44 minutes to complete the task. For that participant, only the first trial took a long time, so it was assumed that she/he probably performed the task a while after the first screen was opened. We checked the data for that participant but found nothing suspicious. Since there was no reason to exclude this participant's data, we used all participants' data for further analysis.

Figure 7 shows the rating scores for the object softness for each of the three C/D ratios and five function types. As in Experiment 1, we transformed the rating scores by using the ART and conducted a two-way repeated ANOVA with the C/D ratio and the function types as within-participant factors.

Table 9 shows the ANOVA results for the rating data in Experiment 2. Both the main effects of the C/D ratio and the function type were significant. Interaction between the two factors was also significant. Multiple comparison tests (Table 10) for the main effect of the C/D ratio showed that the rating scores for each C/D ratio condition were significantly different from those in all other C/D ratio conditions. Multiple comparison tests (Table 11) for the main effect of the function type showed that the rating scores in the Type 5 condition were significantly different from those in the Type 1, Type 2, and Type 4 conditions.

We also checked the simple effects of the significant interaction and the outcome of their multiple comparison tests. The simple effect of the function type (Table 12) was significant when the C/D ratios were 0.25 and 1. Multiple comparisons (Table 13) showed that when the C/D ratio was 0.25, the rating scores were significantly different between Type 2 and Type 5, and between Type 4 and Type 5. Also, when the C/D ratio was 1, the rating scores were significantly different between Type 1 and Type 4. The simple effect of the C/D ratios (Table 14) was significant for all function type conditions. Multiple comparisons (Table 15) showed that the rating score in each C/D ratio condition was significantly different from the one in all other C/D ratio conditions.

TABLE 9
ANOVA table for the rating data in Experiment 2.

Factors	df(df.res)	F value	Pr(>F)	η_p^2
C/D ratio	2(162)	158.972	<.0001	0.662
Function type	4(324)	4.524	=.002	0.052
Interaction	8(648)	2.175	=.028	0.026

TABLE 10
Results of multiple comparison tests for C/D ratio in Experiment 2's rating data.

contrast	estimate	df	t.ratio	p.value
0.25 - 0.5	-219	162	-7.702	<.0001
0.25 - 1.00	-506	162	-17.778	<.0001
0.50 - 1.00	-287	162	-10.076	<.0001

5.1.7 Discussion

Although the rating scores significantly varied depending on the function type defining the saturation/growth speed of object deformation during touchless controls, none of the outcomes could account for the results of Experiment 1. Specifically, the rating scores in this experiment did not decrease in the order of the Type 1, Type 2, and Type 3 conditions, which were not consistent with the results of Experiment 1. The results indicate that the saturation speed of object deformation could not explain the effect of the effective distance of hand movements on the object softness judgments in Experiment 1.

TABLE 11
Results of multiple comparison tests for C/D ratio in Experiment 2's rating data.

contrast	estimate	df	t.ratio	p.value
1 - 2	12.35	324	0.512	1.0000
1 - 3	26.72	324	1.108	1.0000
1 - 4	24.28	324	1.007	1.0000
1 - 5	93.34	324	3.872	0.0013
2 - 3	14.37	324	0.596	1.0000
2 - 4	11.93	324	0.495	1.0000
2 - 5	80.99	324	3.360	0.0087
3 - 4	-2.44	324	-0.101	1.0000
3 - 5	66.62	324	2.764	0.0604
4 - 5	69.06	324	2.865	0.0445

TABLE 12
Simple effect of function types in Experiment 2.

C/D ratio	df(df.res)	F value	Pr(>F)	η_p^2
0.25	4(324)	3.340	=0.0106	0.040
0.50	4(324)	1.486	=0.2062	0.018
1.00	4(324)	2.579	=0.0374	0.031

TABLE 13
Multiple comparisons for the simple effect of function types in Experiment 2.

contrast	estimate	df	t.ratio	p.value
0.25 C/D ratio				
1 - 2	-3.74	324	-0.324	=1.0000
1 - 3	7.48	324	0.649	=1.0000
1 - 4	-7.01	324	-0.608	=1.0000
1 - 5	30.24	324	2.623	=0.0913
2 - 3	11.22	324	0.973	=1.0000
2 - 4	-3.27	324	-0.283	=1.0000
2 - 5	33.98	324	2.947	=0.0344
3 - 4	-14.49	324	-1.256	=1.0000
3 - 5	22.76	324	1.974	=0.4923
4 - 5	37.25	324	3.230	=0.0136
1.00 C/D ratio				
1 - 2	14.9	324	1.142	=1.0000
1 - 3	13.8	324	1.058	=1.0000
1 - 4	39.7	324	3.045	=0.0252
1 - 5	25.6	324	1.963	=0.5051
2 - 3	-1.1	324	-0.084	=1.0000
2 - 4	24.8	324	1.903	=0.5792
2 - 5	10.7	324	0.821	=1.0000
3 - 4	25.9	324	1.987	=0.4774
3 - 5	11.8	324	0.905	=1.0000
4 - 5	-14.1	324	-1.082	=1.0000

TABLE 14
Simple effect of C/D ratios in Experiment 2.

Func types	df(df.res)	F value	Pr(>F)	η_p^2
Type 1	2(162)	95.693	<0.0001	0.542
Type 2	2(162)	67.409	<0.0001	0.454
Type 3	2(162)	74.342	<0.0001	0.478
Type 4	2(162)	46.413	<0.0001	0.364
Type 5	2(162)	86.600	<0.0001	0.517

We observed that the softness rating scores in the Type 5 condition were significantly smaller than the scores in the Type 1 and Type 2 conditions. When the participant's hand movement distance exceeded 9 cm and the deformation ceased, the discontinuity of object deformation was caused. In the Type 5 condition with late growth deformation patterns, the discontinuity of object deformation was likely salient in comparison with the Type 1 and Type 2 conditions with saturation deformation patterns. Such discontinuity of object deformation might contribute to the determination of perceived softness during touchless inputs. The salient discontinuity of object deformation might serve as a cue to non-soft materials.

6 Experiment 3: Relationship Between Softness and Other Perceptual Impressions

6.1 Purpose

So far, we have shown that the effective distance of hand movements was a strong determinant of softness matching scores for an object controlled by the participants' touchless inputs. On the other hand, it was still unclear how the sudden cease (that is, the discontinuity) of object deformation affected the softness rating scores. To address the unclear issue, it would be beneficial to focus on not only softness but also other perceptual impressions. As described above, the change in object speed contributes to the change in the impression of friction, gravity, or viscosity [11], resistance [27], and collision [28], [29], [30], [31]. Moreover, in our preliminary observation, the participants informally reported "the sudden change of softness and heaviness" and "something happened to the object". Thus, there was a possibility that the discontinuity of object deformation caused the change in perceptual impressions other than softness. Moreover, as a previous study [61] on haptic devices has shown, other types of haptic impressions, such as warmness, roughness, size, and weight, could be influenced by the discontinuity of object deformation. Checking the relationship between the softness impression and other types of impression may also give us some insights into the underlying psychological mechanism for reducing perceptual softness due to the discontinuity of object deformation. In this experiment, we asked the participants to rate eight items regarding various types of perceptual impressions (please refer to the "Procedure" section for detail). Based on the results, we tried to interpret how the change in softness perception occurred when the object deformation ceased during touchless inputs. Specifically, we analyzed Spearman's correlation coefficients among the rating scores for various perceptual impressions. Moreover, we conducted a factor analysis to explore latent variables underlying the determination of perceptual impressions for object deformation during touchless inputs.

Furthermore, instead of the two-dimensional texture noise used in the previous experiments, we used the three-dimensional object to check whether we could observe the similar effect of the C/D ratio and the effective distance of hand movements on the softness rating scores with the three-dimensional object. In the previous experiment, the object to be deformed was a two-dimensional textured rectangle. In daily life, we often pull and push three-dimensional elastic objects. In this respect, it would be meaningful to check whether the conclusion of the previous experiments could be extended to the case wherein the participants manipulated the three-dimensional object with touchless inputs.

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2023.3254522

TABLE 15
Multiple comparisons for the simple effect of C/D ratio in Experiment 2.

contrast	estimate	df	t.ratio	p.value
Type 1				
0.25 - 0.50	-45.8	162	-5.943	<.0001
0.25 - 1.00	-106.3	162	-13.790	<.0001
0.50 - 1.00	-60.5	162	-7.847	<.0001
Type 2				
0.25 - 0.50	-37.5	162	-4.597	<.0001
0.25 - 1.00	-94.1	162	-11.532	<.0001
0.50 - 1.00	-56.6	162	-6.935	<.0001
Type 3				
0.25 - 0.50	-42.8	8.36	-5.122	<.0001
0.25 - 1.00	-101.5	8.36	-12.144	<.0001
0.50 - 1.00	-58.7	8.36	-7.022	<.0001
Type 4				
0.25 - 0.50	-42.5	8.72	-4.870	<.0001
0.25 - 1.00	-84.0	8.72	-9.634	<.0001
0.50 - 1.00	-41.5	8.72	-4.765	<.0001
Type 5				
0.25 - 0.50	-41.3	162	-5.213	<.0001
0.25 - 1.00	-103.6	162	-13.072	<.0001
0.50 - 1.00	-62.3	162	-7.859	<.0001

6.2 Participants

189 (93 female and 96 male) people, who had not participated in the previous experiments, participated in this experiment. Their mean age was 40.80 (SD: 10.83). The participants' ages ranged from 20 to 59, and the numbers of participants in the 20's, 30's, 40's, and 50's age generations were 36, 51, 52, and 50, respectively. All of the participants were unaware of the specific purpose of the experiment.

6.2.1 Apparatus

The apparatus for this experiment was identical to that used in the previous experiments. The mean sampling rate of the hand tracking in this experiment was 18.859 Hz (SD: 12.352 Hz). The lower frame rate in this experiment might be that rendering the three-dimensional objects in visual stimuli required more computational time than the two-dimensional noises used in Experiments 1 and 2.

6.2.2 Stimuli

The stimuli were identical to those employed in the previous experiments except for the following. While the previous experiments used a two-dimensional object with texture noises as a stimulus, this experiment used a three-dimensional object (a cylinder) as a stimulus. The cylinder was rendered by using Three.js (https://threejs.org/). The surface of the cylinder was textured with the white noise image as used in Experiments 1 and 2. The cylinder was displayed on the left side of the display. The left side of the cylinder was located 3cm to the left of the horizontal center of the display. The cylinder was captured by a camera (in the virtual scene) with a frustum vertical field of view of 45 deg. The camera always looked at the center of the coordinate. To indicate the spatial range for participants to move their right hand, we presented a thick line with 0.3 cm height and 9 cm width, instead of the arrow as used in Experiments 1 and 2. The reason for this change was that we felt that the arrow was not always necessary to indicate the spatial range of hand movements to the participants. The line was centered at the 5.6 cm right of the horizontal center of the display. The background for the cylinder and the line was black.

The initial width and height of the cylinder were 1.4 and 1.6 cm, respectively. As the participant moved their right hand toward the right in front of the line, the cylinder was horizontally elongated toward the right. The maximum width of the cylinder was 2.0 cm, which occurred in the condition with a C/D ratio of 1.0 and an effective distance of 9 cm. The amount of elongation was fairly smaller than the one employed in Experiments 1 and 2. This was because, in the three-dimensional scene, the larger elongation distorted the apparent shape due to the camera's field of view. Specifically, the cylinder distorted in a more periphery visual field. Although we could use a lower value of the field of view to correct the distortion, in that case, the appearance of the cylinder was akin to the two-dimensional noises used in Experiments 1 and 2. Hence, we chose this small magnitude of elongation to present the three-dimensional appearance of the cylinder reliably. In the conditions with the C/D ratio of 0.25, 0.50, 0.75, and 1.00, the maximum magnitude of elongation was 1.55, 1.70, 1.85, and 2.0 cm, respectively. In the conditions with the effective distance of hand distance of 5.4, 7.2, and 9.0 cm, the elongation ceased when the elongation reached $\times 0.6$, $\times 0.8$, and $\times 1.0$ the maximum magnitude of elongation which was determined by the C/D ratio.

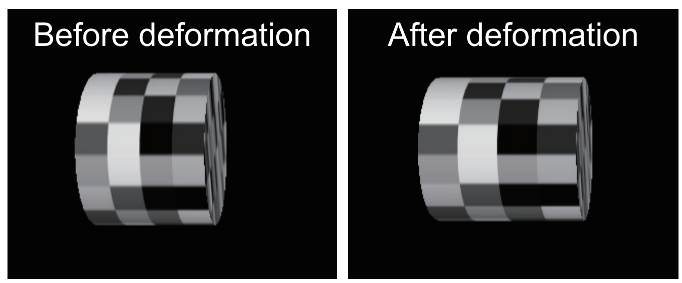

Fig. 8. The appearance of stimuli as used in Experiment 3. The left and right panels show the appearance of stimuli before and after object deformation due to the participant's touchless inputs.

6.2.3 Procedure

In each trial, the participant was asked to move their right hand in front of the line presented on the right side of the display. Despite the effective distance of hand movements, the list of items to which the participant responded appeared after the participants moved their hand by 9 cm. The list of the items consisted of impression words for "Soft-Not soft", "Cold-Warm", "Not viscous-Viscous", "Bumpy-Not bumpy", "Small-Large", "Heavy-Light", "No friction–With friction", and "Collision–No collision." We chose the items on the basis of the previous studies [?], [11], [27], [29], [30], [31], [61]. Each item had seven numbers (1-7) with radio buttons. Participants were instructed to click on the radio button to the left of the number closest to their impression written on either side of each question item. We used a 7-point scale, instead of a 5-point scale as in Experiments 1 and 2 because we assumed that a finer scale than the previous experiments was required for the evaluation of stimuli of this experiment, which had a narrower stimulus

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2023.3254522

deformation range than the stimuli of the previous experiments. The participant could proceed to the next trial only after they responded to all eight items. As in Experiment 1, each participant received 12 trials of 4 conditions of the C/D ratio and 3 conditions of the effective distance of hand movements. The trials were conducted in a random order that varied among participants.

6.2.4 Results

We again reviewed the time it took participants to complete the task and found that they completed it within a reasonable amount of time (median: 3.22 minutes). Only one participant took 44 minutes to complete the task. For that participant, only the first trial took a long time, so it was assumed that she/he probably performed the task a while after the first screen was opened. We checked the data for that participant but found nothing suspicious. Since there was no reason to exclude this participant's data, we used all participants' data for further analysis.

For the item "Soft-Not soft", to make consistency among experiments, we subtracted the rating scores from 7 and treated it as the score of "Not soft-Soft". The median time the participant took to perform the task on each trial was 30.449 seconds (with 95% confidence intervals of [14.203, 119.736]). As in Experiments 1 and 2, we checked whether the frame rate of stimulus presentation influenced the softness rating scores. Different from the previous experiments, there was a significant correlation between them (rs = 0.100, $p < 0.001$). The results indicate that the higher frame rate of stimulus presentation caused the higher softness rating scores. In comparison with Experiments 1 and 2, the mean sampling rate (that is, frame rate) was lower in Experiment 3. As described above, the lower frame rate in this experiment might be that rendering the three-dimensional objects in visual stimuli required more computational time than the two-dimensional objects used in Experiments 1 and 2. The lower frame rate in this experiment might cause lower softness rating scores, and consequently, a significant correlation coefficient might be obtained. On the other hand, the correlation coefficient, while significant, was not very high. Hence, we concluded that the influence of the frame rate on the softness rating scores was not so strong.

Figure 9 shows the rating scores for each item. Each graph shows the scores for each condition of the four levels of C/D ratios and three levels of the effective distance of hand movements. As in Experiment 1, we transformed the rating scores using the ART and conducted a two-way repeated ANOVA with the C/D ratio and effective distance of hand movements as within-participant factors.

Table 16 shows the main effect and interaction of the two factors. The main effect of the C/D ratio was significant for the items "Not soft-Soft", "Cold-Warm", "Small-Large", "Heavy-Light", and "No friction-With friction". The results of the multiple comparison tests for each significant main effect are shown in Table 17. The main effect of the effective distance of hand movements was also significant for the items "Not soft-Soft", "Cold-Warm", "Bumpy-Not bumpy", and "Heavy-Light". The results of the multiple comparison tests for each significant main effect are shown in Table 18. Interaction between the two factors was significant for "Collision-Not collision". The simple effect of the significant interaction reached significance only for the effective distance of hand movement when the C/D ratio was 1.0 ($F_{2,374}$=3.425, p=.0335, η_p^2=0.018). The multiple comparison test for the significant simple effect showed that the rating scores for "Collision-No collision" were significantly higher when the effective distance of hand movements was 5.4 than when it was 9.0 ($t_{374} = 2.466, p = .0423$).

TABLE 16
ANOVA table for the rating scores in Experiment 3.

Factors	df(df.res)	F value	Pr(>F)	η_p^2
Not soft - Soft				
C/D ratio	3(561)	81.675	<.0001	0.304
Effective distance	2(374)	11.359	<.0001	0.057
Interaction	6(1122)	1.827	=.0967	0.009
Cold - Warm				
C/D ratio	3(561)	14.685	<.0001	0.072
Effective distance	2(374)	3.523	=.0305	0.018
Interaction	6(1122)	2.034	=.0584	0.010
Not viscous - Viscous				
C/D ratio	3(561)	0.171	=.9155	0.001
Effective distance	2(374)	0.0245	=.9757	0.0001
Interaction	6(1122)	0.5876	=.7404	0.003
Bumpy - Not bumpy				
C/D ratio	3(561)	1.108	=.3452	0.006
Effective distance	2(374)	11.853	<.0001	0.060
Interaction	6(1122)	0.8066	=.5645	0.004
Small - Large				
C/D ratio	3(561)	3.480	=.0158	0.018
Effective distance	2(374)	0.7819	=.4582	0.004
Interaction	6(1122)	1.718	=.113	0.009
Heavy - Light				
C/D ratio	3(561)	45.852	<.0001	0.197
Effective distance	2(374)	4.6732	=.009	0.024
Interaction	6(1122)	0.6198	=.7145	0.003
No friction - With friction				
C/D ratio	3(561)	24.437	<.0001	0.116
Effective distance	2(374)	2.013	=.1350	0.010
Interaction	6(1122)	0.527	=.7889	0.003
Collision - No collision				
C/D ratio	3(561)	1.817	=.1429	0.009
Effective distance	2(374)	1.6398	=.1954	0.008
Interaction	6(1122)	3.143	=.0046	0.017

To explore the relationship among perceptual impressions that we examined, we calculated Spearman's correlation coefficients among the rating scores of the items. The obtained correlation coefficients and p-values are shown in Figure 10. Softness impression was moderately correlated with the impression of "Heavy-Light". That is, a softer object was judged to be lighter. Interestingly, the softer impression was also moderately correlated with the scores of "Cold-Warm" while the scores of "Cold-Warm" was correlated more strongly with the scores of "Small-Large". The scores of "Not viscous-Viscous" were most correlated with the scores of "Bumpy-Not bumpy" while the scores of "Bumpy-Not bumpy" were most correlated with the scores of "Collision-No collision". The scores of "Heavy-Light" were most correlated with the scores of "Not soft-Soft". The scores of "No friction-Friction" were most correlated with the scores of "Collision-No collision".

The interpretation of the correlation coefficients was not so easy because the rating scores of a single item were correlated with the rating scores of multiple items. To facilitate the interpretation, we conducted a factor analysis and checked what sort of latent factors was involved with

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2023.3254522

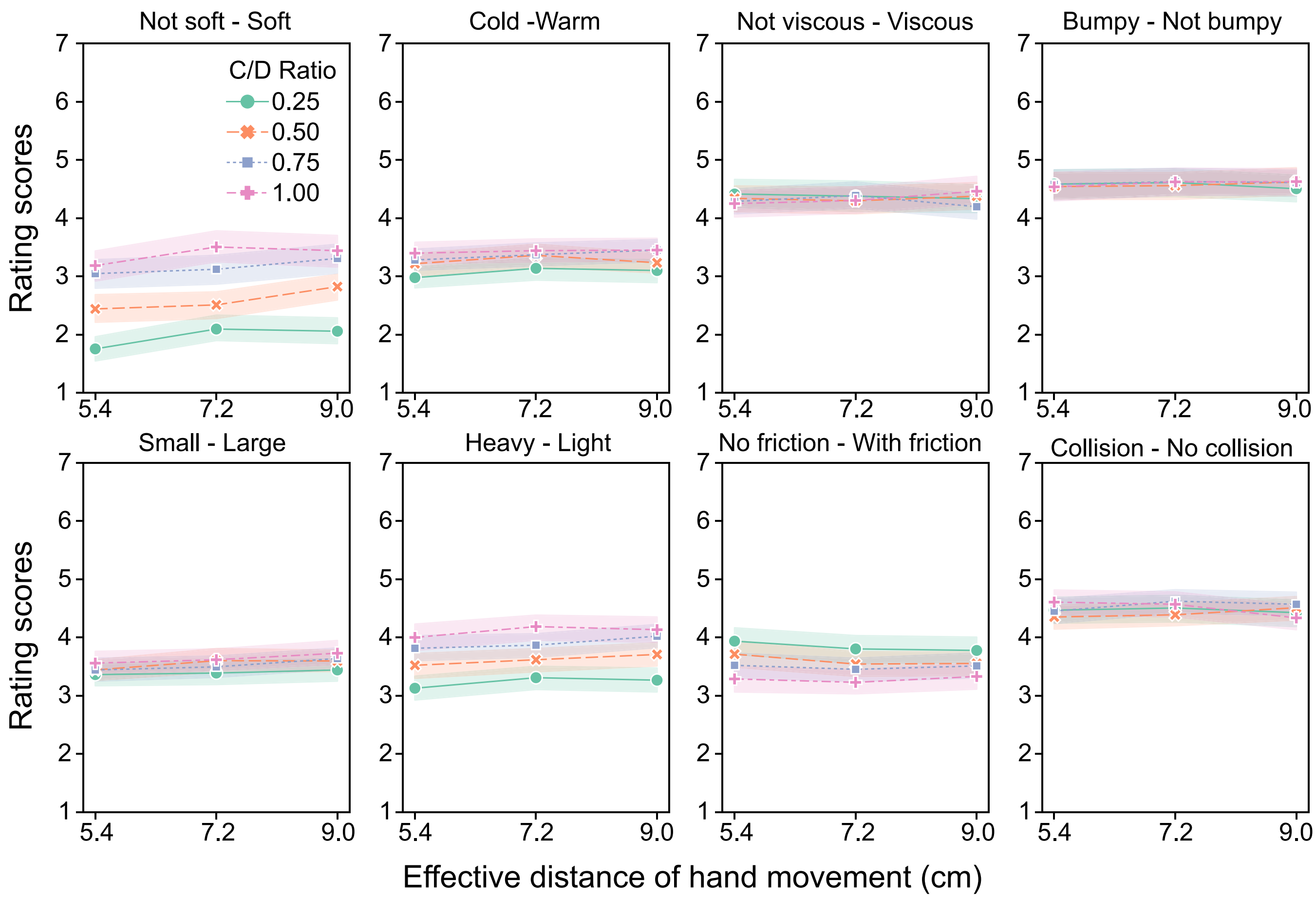

Fig. 9. Rating scores for each condition of C/D ratio and effective distance of hand movements (N = 189) in Experiment 3. Error bars denote 95% confidence intervals.

perceptual impressions for the object deformation during touchless control. To determine the factor count for the factor analysis, we first calculated eigenvalues. As shown in Figure 11, the factor count with the eigenvalues greater than 1 was three. Thus, we conducted the factor analysis with a factor count of three. Table 19 shows the factor score of each item after a varimax rotation. The first factor contained the items of "Cold - Warm", "Small - Large", and "Heavy - Light". The second factor contained "Not soft - Soft". The third factor contained "Not viscous - Viscous", "No friction – With friction", and "Collision – No collision".

6.2.5 Discussion

The results showed that the effective distance of hand movements still significantly influenced the softness rating scores even when the participants were asked to judge other perceptual impressions than softness. The results indicate that the effect of the effective distance of hand movements on the softness rating scores is not the product of bias due to asking the participants to judge softness impressions only.

On the other hand, not only softness but also other perceptual impressions such as "Cold-Warm", "Bumpy-Not bumpy", and "Heavy-Light" were also influenced by the effective distance of hand movements. According to the results of our factor analysis, "Cold-Warm" and "Heavy-Light" stemmed from the first factor, "No soft-Soft" stemmed from the second factor, and "Bumpy-Not bumpy" stemmed from the third factor. Thus, the discontinuity of object deformation, which was caused by the presence of

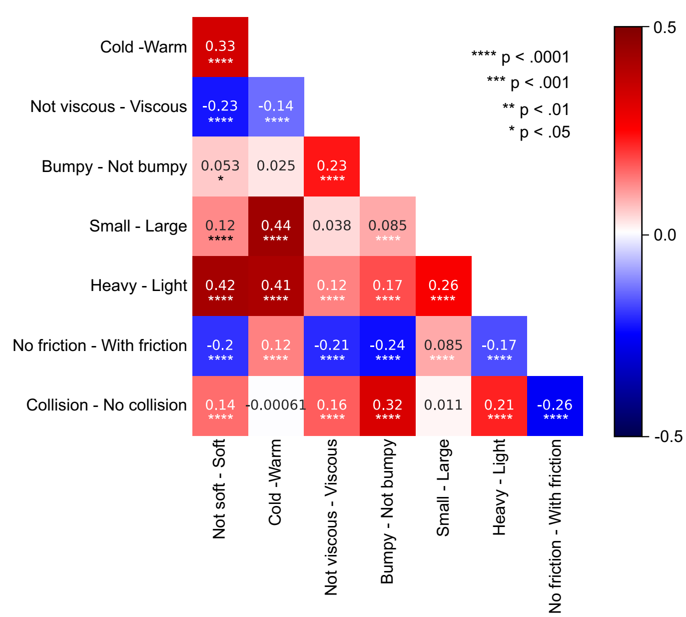

Fig. 10. Correlation matrix among the rating scores in Experiment 3. Annotations are Spearman's correlation coefficients and p-values.

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2023.3254522

TABLE 17
Results of multiple comparison tests of the significant main effect of the C/D ratio in Experiment 3.

contrast	estimate	df	t.ratio	p.value
Not soft - Soft				
0.25 - 0.5	-211.2	561	-5.969	<.0001
0.25 - 0.75	-414.1	561	-11.703	<.0001
0.25 - 1	-508.8	561	-14.377	<.0001
0.5 - 0.75	-202.9	561	-5.734	<.0001
0.5 - 1	-297.5	561	-8.408	<.0001
0.75 - 1	-94.6	561	-2.674	=.0462
Cold - Warm				
0.25 - 0.5	-113.5	561	-4.271	=.0001
0.25 - 0.75	-144.8	561	-5.446	<.0001
0.25 - 1	-158.8	561	-5.971	<.0001
0.5 - 0.75	-31.24	561	-1.175	=1.000
0.5 - 1	-45.2	561	-1.700	=.5375
0.75 - 1	-13.9	561	-0.525	=1.000
Small - Large				
0.25 - 0.5	-66.9	561	-2.403	=.0099
0.25 - 0.75	-53.2	561	-1.908	=.3408
0.25 - 1	-83.5	561	-3.07	=.0134
0.5 - 0.75	-13.7	561	-0.494	=1.000
0.5 - 1	-18.5	561	-0.666	=1.000
0.75 - 1	-32.3	561	-1.161	=1.000
Heavy - Light				
0.25 - 0.5	-143.4	561	-4.235	=.0002
0.25 - 0.75	-264.6	561	-7.812	<.0001
0.25 - 1	-377.7	561	-11.151	<.0001
0.5 - 0.75	-121.1	561	-3.577	=.0022
0.5 - 1	-234.2	561	-6.916	<.0001
0.75 - 1	-113.0	561	-3.338	=.0052
No friction - With friction				
0.25 - 0.5	88.1	561	2.776	=.0034
0.25 - 0.75	184.5	561	5.816	<.0001
0.25 - 1	253.6	561	7.993	<.0001
0.5 - 0.75	96.4	561	3.039	=.0015
0.5 - 1	165.5	561	5.216	<.0001
0.75 - 1	69.0	561	2.1770	=.1793

TABLE 18
Results of multiple comparison tests of the significant main effect of the effective distance of hand movement in Experiment 3.

contrast	estimate	df	t.ratio	p.value
Not soft - Soft				
5.4 - 7.2	-79.6	374	-3.155	=.0051
5.4 - 9.0	-117.8	374	-4.671	<.0001
7.2 - 9.0	-38.2	374	-1.516	=.3910
Cold - Warm				
5.4 - 7.2	-59.0	374	-2.642	=.0257
5.4 - 9.0	-117.8	374	-1.537	=.3751
7.2 - 9.0	-38.2	374	1.105	=.8090
Bumpy - Not bumpy				
5.4 - 7.2	-33.5	374	-1.720	=.2582
5.4 - 9.0	59.9	374	3.083	=.0065
7.2 - 9.0	93.4	374	4.804	<.0001
Heavy - Light				
5.4 - 7.2	-61.8	374	-2.363	=.0558
5.4 - 9.0	74.9	374	-2.861	=.0133
7.2 - 9.0	-13.0	374	-0.497	=1.000

the effective distance of hand movements during touchless inputs, can influence various aspects of perceptual impression.

When the C/D ratio was 1.0, the main effect of the effective distance of hand movements was significant for the rating scores of "Collision - No collision". The results are consistent with the previous studies [28], [29], [30], [31] showing that motion discontinuity served as a cue to

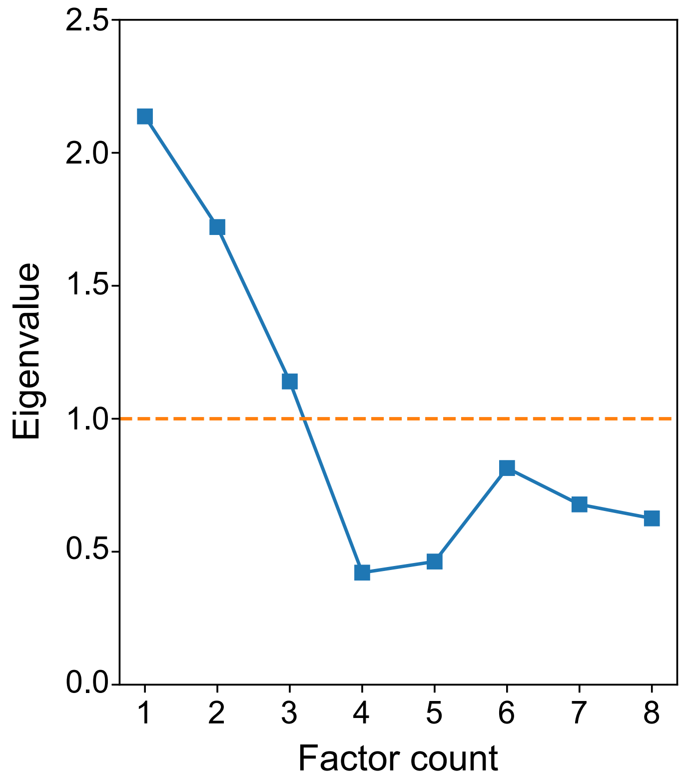

Fig. 11. Eigenvalues as a function of factor counts for the rating scores in Experiment 3. Since the factor count with the eigenvalues greater than 1 was 3, we conducted a factor analysis with the factor count of 3.

TABLE 19
Factor scores for each item and cumulative variance in Experiment 3. Bold-style values indicate maximum factor factors for each item.

Item	factor1	factor2	factor3
Not soft - Soft	0.208337	**0.971814**	0.089918
Cold - Warm	**0.841540**	0.197321	-0.150379
Not viscous - Viscous	0.006472	-0.270443	**0.479372**
Bumpy - Not bumpy	0.125152	-0.020790	**0.493394**
Small - Large	**0.518055**	-0.018932	0.060709
Heavy - Light	**0.482910**	0.294893	0.365981
No friction – With friction	0.108375	-0.190682	**-0.497647**
Collision – No collision	0.030515	0.099745	**0.489601**
Cumulative variance	0.160195	0.309015	0.450130

pseudo-haptic collision.

The factor analysis showed that the three latent variables might underlie the judgment of perceptual impressions for the objects controlled by touchless inputs. The first variable, which influenced "Cold-Warm", "Small-Large", and "Heavy-Light", seemed to be involved with the inference of the object's material properties. The second variable, which influenced "Not soft-Soft", is likely related to the inference of perceptual softness. The third variable, which influenced "Not viscous-Viscous", "No friction–With friction", and "Collision–No collision", is possibly related to the inference of interaction between the user (or user's action) and external objects. Though the list of the latent variable is possibly not a thorough one due to the limited number of items we tested, our results indicate that perceptual impressions that the participants conceive during touchless inputs are multi-facet. To accurately understand the psychological

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2023.3254522

mechanism, it is necessary to use an expanded set of items for perceptual impressions.

There were pros and cons to using the 3D object in this experiment. For pros, we could extend the conclusion with the 2D objects in Experiment 1 to the case with the 3D objects. For cons, it was not possible to check whether the results of Experiment 1 with the 2-D objects could be reproduced by different subjects in a new experiment that also used 2-D objects. Moreover, the difference in stimuli caused the difference in the softness rating scores between Experiments 1 and 3. Compared with Experiment 1, the absolute level of rating scores for perceptual softness was lower in this experiment. This might be because the magnitude of object deformation was smaller in this experiment than in Experiment 1. On the other hand, the effect of the effective distance of hand movements was significant in both experiments. Therefore, the discontinuity of object deformation possibly serves as a cue to perceptual softness relatively independent of the magnitude of object deformation.

7 Conclusion

7.1 Summary of Results

The present study examined how the effective distance of hand movements impacted the softness rating scores of an object under the control of the user's touchless inputs. Experiment 1 showed that in addition to the C/D ratio, the effective distance of hand movements was a critical factor in determining the softness rating scores. Experiment 2 showed that the saturation speed of object deformation, which was inherently triggered by adopting the effective distance of the hand movements, did not account for the variation of the rating scores in Experiment 1. In Experiment 3, we observed that the effective distance of hand movements still significantly influenced the softness rating scores even when the participants were asked to report other perceptual impressions than softness. We also reported that the effective distance of hand movements affected other perceptual impressions than softness.

7.2 Significance of the Present Study

7.2.1 *Scientific Significance*

The present study essentially replicated the previous studies showing that in a passive stimulus viewing, the visual softness of elastic objects increased with the magnitude of the object deformation [45], [46], [47]. As described above, manipulation of the effective distance of hand movements, which significantly affected the softness rating scores, caused the variation of the deformation magnitudes. Thus, the present study showed that the softness rating scores varied with the magnitude of object deformation while users actively controlled the magnitude of deformation via their touchless inputs.

7.2.2 *Technical Significance*

The present study showed that the softness judgment of an object under the control of user's touchless input was altered by the cessation of object deformation during the control. Specifically, an earlier cessation of object deformation in the course of deformation manipulation via touchless control produced a lower softness judgment for the object. Without considering the effect of the effective distance of hand movements, it doesn't seem easy to provide the desired level of object softness to users who controlled the deformation of the object via their touchless control. In presenting the softness of an object that is deformed by users' touchless inputs, the first important thing to keep in mind is the need to adjust the hand position to fall within the angle of camera view, so that the deformation of the object does not stop in the course of the input. In addition, it must be implemented so that any occluder does not block the camera view of the hand. Although the effective distance of hand movements is likely to cause problems such as the one this study demonstrated, the problems can be avoided by using a hand position sensing device other than a camera.

Issues arising from sensing failures (in our case, issues arising from the effective distance of hand movements) are a general problem which can occur when we adopt other touchless sensing devices. For example, a magnetic sensor such as Polhemus tracker [62] has an effective range of sensing. When the user's hand exceeds this range, tracking cannot be performed. Therefore, there is a possibility that the issues examined in our study are common to various sensing methods for touchless input that have an effective range of sensing. In addition, the issues might be common to devices that are not directly related to the sensing of touchless inputs. For example, a touchpad that is embedded within a laptop PC cannot sense finger movements outside the area of the touchpad, and thus there is an effective sensing range. A similar sort of the effect of the effective distance on softness judgment would be observed in the case of the touchpad, although it may be necessary to consider the effect of the actual touch feeling on the softness judgment as well. In this way, in order to mitigate the effect of sensing failures on the softness judgment, it is probably necessary to consider the characteristics of users' perceptions, which likely vary according to each sensing method.

So far, we have considered the effect of effective distance as a negative component for the softness presentation in the touchless input system and have proposed some methods of avoiding it. However, it may be also, possible for us to regard it as a positive component for the presentation of softness impressions. Since the present study showed the significant interaction between the C/D ratio and the effective distance, it may be possible to control the level of object softness in a finer manner with, rather than without, taking the effect of the effective distance into account.

7.3 Limitations and Future Issues

7.3.1 *Another Interpretation of the Present Study*

We attributed the effect of effective distance on hand movements to the changes in the magnitude of deformation with effective distance. However, the results can be interpreted in a different manner from ours. Namely, the results may be interpreted in terms of the C/D ratio only. In our stimuli, when the hand was outside the effective distance of hand movements, any hand movement no longer caused the deformation. The C/D ratio in this situation can be considered to be zero. If the sensory system can integrate and/or average the C/D ratio across time (or along a hand movement trajectory), the perceived C/D ratio is lower in the condition with the smaller effective distance of hand movements. However, there is no previous study to support the proposal for the temporal integration of the C/D ratio across time. Future studies are necessary to support this suggestion.

7.3.2 Spatiotemporal Resolution

The experiment of the present study was conducted online, and thus, the hand-tracking device was limited to the camera which the participants used. The results suggest that the touchless input is effective even in a situation in which users controlled the objects via touchless inputs online. We suggest that the spatiotemporal resolution of the camera was also enough to clarify the basic property of object softness judgments by users. However, using devices with a higher spatiotemporal resolution may enhance users' immersive experiences of the object's softness and/or the sense of agency in controlling the object's deformation via touchless inputs. From a scientific perspective, a device with high temporal resolution may enable us to check how fine temporal structures of hand movements could influence the users' judgment of the object's softness.

Similarly, it is an important limitation of the present study that the frame rate of the stimulus presentation was not controlled. Although no significant correlations were observed between the softness rating scores and frame rate in Experiments 1 and 2, a significant correlation was observed in Experiment 3. The precise control of the frame rate might be beneficial to obtain robust experimental data and/or user experiences in touchless input systems.

7.3.3 Lack of Control of Hand Movement Speed

In the experiments in the present study, we did not control the speed of hand movements. The variation of hand movement speeds led to the variation in the speed of object deformation. Thus, the speed of hand movements might be a potential factor in modulating softness rating scores because it is known that the speed of object deformation is a modulatory factor of perceived softness [47]. Future studies need to carefully evaluate the role of the speed of hand movements in the determination of the perceived softness of objects controlled by touchless inputs.

7.3.4 Insufficient monitoring of Experimental Task

All experiments in this study were conducted online. Therefore, the experimenter could not monitor how participants performed the tasks. As far as the time taken for participants to complete a single trial was monitored, it appeared that participants performed the task within a reasonable amount of time. On the other hand, the other aspects of monitoring, such as how many times the hand tracking failed and in what light and sound environment the task was performed, were unclear. These unmonitored factors could affect the evaluation scores. Experimentation in a controlled environment would reduce this possibility.

7.3.5 Implementation with 3D Objects and XR

We believe that the results of the present study will be useful for implementing interfaces in which users interact with virtual objects in xR. For example, in online shopping using xR, the results of this study will be useful for understanding/configuring situations where users pull the cloth they want to buy and check the softness and appearance of the cloth. Though we used touchless inputs to deform a virtual object, it would be meaningful to examine whether there is a difference in results between using a VR controller to deform an object and using touchless input. Although we used the three-dimensional object in Experiment 3, the relationship between the participant's hand movements and corresponding object deformation could be described in the two-dimensional space. In this respect, it is intriguing to extend the results of the present study to the manipulation in a three-dimensional space and verify whether the effect of the effective distance of hand movements can be observed in the extended situation. Such extension is promising with the touchless inputs because they do not use physical devices, which often restrict users' hand movements.

References

[1] F. Biocca, J. Kim, and Y. Choi, "Visual touch in virtual environments: An exploratory study of presence, multimodal interfaces, and cross-modal sensory illusions," *Presence: Teleoperators and Virtual Environments*, vol. 10, no. 3, p. 247–265, 2001.

[2] A. Lécuyer, "Simulating haptic feedback using vision: A survey of research and applications of pseudo-haptic feedback," *Presence: Teleoperators and Virtual Environments*, vol. 18, no. 1, p. 39–53, 2009.

[3] Y. Ujitoko and Y. Ban, "Survey of pseudo-haptics: Haptic feedback design and application proposals," *IEEE Transactions on Haptics*, vol. 14, no. 4, p. 699–711, 2021.

[4] Y. Ban and Y. Ujitoko, "Enhancing the pseudo-haptic effect on the touch panel using the virtuual string* *research supported by the ministry of education, science, sports and culture." *2018 IEEE Haptics Symposium (HAPTICS)*, p. 278–283, 2018.

[5] L. Dominjon, A. Lecuyer, J. Burkhardt, P. Richard, and S. Richir, "Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments," *Proceedings. VR 2005*, pp. 19–25,, 2005.

[6] Y. Hirao, T. M. Takala, and A. Lécuyer, "Comparing motion-based versus controller-based pseudo-haptic weight sensations in vr," vol. 00, p. 305–310, 2020.

[7] J. Kim, S. Kim, and J. Lee, "The effect of multisensory pseudo-haptic feedback on perception of virtual weight," *IEEE Access*, vol. 10, p. 5129–5140, 2022.

[8] R. Mandryk, M. Hancock, M. Perry, A. Cox, M. Rietzler, F. Geiselhart, J. Gugenheimer, and E. Rukzio, "Breaking the tracking: Enabling weight perception using perceivable tracking offsets," *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, p. 1–12, 2018.

[9] M. Samad, E. Gatti, A. Hermes, H. Benko, and C. Parise, "Pseudo-haptic weight: Changing the perceived weight of virtual objects by manipulating control-display ratio," *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, p. 1–13, 2019.

[10] F. Argelaguet, D. A. G. Jáuregui, M. Marchal, and A. Lécuyer, "Elastic images: Perceiving local elasticity of images through a novel pseudo-haptic deformation effect," *ACM Transactions on Applied Perception (TAP)*, vol. 10, no. 3, p. 17, 2013.

[11] A. Lécuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet, "Pseudo-haptic feedback?: Can isometric input devices simulate force feedback?" *Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048)*, p. 83–90, 2000.

[12] T. Kawabe, "Mid-air action contributes to pseudo-haptic stiffness effects," *IEEE Transactions on Haptics*, vol. 13, no. 1, p. 18–24, 2020.

[13] Y. Ota, Y. Ujitoko, Y. Ban, S. Sakurai, and K. Hirota, "Surface roughness judgment during finger exploration is changeable by visual oscillations," *Lecture Notes in Computer Science*, p. 33–41, 2020.

[14] Y. Ujitoko, Y. Ban, and K. Hirota, "Modulating fine roughness perception of vibrotactile textured surface using pseudo-haptic effect," *IEEE Transactions on Visualization and Computer Graphics*, vol. 25, no. 5, p. 1981–1990, 2019.

[15] P. Habibi and D. Chattopadhyay, "The impact of handedness on user performance in touchless input," *International Journal of Human-Computer Studies*, vol. 149, p. 102600, 2021.

[16] L. T. D. Paolis and V. D. Luca, "The effects of touchless interaction on usability and sense of presence in a virtual environment," *Virtual Reality*, p. 1–21, 2022.

[17] K. Harrington, D. R. Large, G. Burnett, and O. Georgiou, "Exploring the use of mid-air ultrasonic feedback to enhance automotive user interfaces," *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, p. 11–20, 2018.

[18] K. Małecki, A. Nowosielski, and M. Kowalicki, "Gesture-based user interface for vehicle on-board system: a questionnaire and research approach," *Applied Sciences*, vol. 10, no. 18, p. 6620, 2020.

[19] O. Georgiou, H. Limerick, L. Corenthy, M. Perry, M. Maksymenko, S. Frish, J. Müller, M. Bachynskyi, and J. R. Kim, "Mid-air haptic interfaces for interactive digital signage and kiosks," *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, p. 1–9, 2019.

[20] R. Mandryk, M. Hancock, M. Perry, A. Cox, L. Corenthy, M. Giordano, R. Hayden, D. Griffiths, C. Jeffrey, H. Limerick, and et al., "Touchless tactile displays for digital signage," *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, p. 1–4, 2018.

[21] P. Gaucher, F. Argelaguet, J. Royan, and A. Lécuyer, "A novel 3d carousel based on pseudo-haptic feedback and gestural interaction for virtual showcasing," *2013 IEEE Symposium on 3D User Interfaces (3DUI)*, p. 55–58, 2013.

[22] T. Kawabe, Y. Ujitoko, and T. Yokosaka, "The relationship between illusory heaviness sensation and the motion speed of visual feedback in gesture-based touchless inputs," *Frontiers in Psychology*, vol. 13, p. 811881, 2022.

[23] J. McIntosh, C. McNeill, M. Fraser, F. Kerber, M. Löchtefeld, and A. Krüger, "Empress," *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, p. 2332–2342, 2016.

[24] N. Zhao, G. Dublon, N. Gillian, A. Dementyev, and J. A. Paradiso, "Emi spy: Harnessing electromagnetic interference for low-cost, rapid prototyping of proxemic interaction," *2015 IEEE 12th International Conference on Wearable and Implantable Body Sensor Networks (BSN)*, p. 1–6, 2015.

[25] P.-G. Jung, G. Lim, S. Kim, and K. Kong, "A wearable gesture recognition device for detecting muscular activities based on air-pressure sensors," *IEEE Transactions on Industrial Informatics*, vol. 11, no. 2, p. 485–494, 2015.

[26] T. Le, R. A. Bahr, M. M. Tentzeris, B. Song, and C.-p. Wong, "A novel chipless rfid-based stretchable and wearable hand gesture sensor," *2015 European Microwave Conference (EuMC)*, p. 371–374, 2015.

[27] T. Kawabe, Y. Ujitoko, T. Yokosaka, and S. Kuroki, "Sense of resistance for a cursor moved by user's keystrokes," *Frontiers in Psychology*, vol. 12, p. 652781, 2021.

[28] T. Hachisu, G. Cirio, M. Marchal, A. Lécuyer, and H. Kajimoto, "Pseudo-haptic feedback augmented with visual and tactile vibrations," in *2011 IEEE International Symposium on VR Innovation*. IEEE, 2011, pp. 327–328.

[29] ——, "Visual vibrations to simulate taps on different materials," in *Haptic Interaction*. Springer, 2015, pp. 297–303.

[30] ——, "Virtual chromatic percussions simulated by pseudo-haptic and vibrotactile feedback," in *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology*, 2011, pp. 1–5.

[31] J. Watanabe, "Pseudo-haptic sensation elicited by background visual motion," *ITE Transactions on Media Technology and Applications*, vol. 1, no. 2, pp. 199–202, 2013.

[32] R. W. Fleming, "Visual perception of materials and their properties," *Vision Research*, vol. 94, p. 62–75, 2014.

[33] ——, "Material perception," *Annual Review of Vision Science*, vol. 3, no. 1, p. 1–24, 2016.

[34] E. H. Adelson, "On seeing stuff: the perception of materials by humans and machines," *Human Vision and Electronic Imaging VI*, p. 1–12, 2001.

[35] T. Kawabe and S. Nishida, "Seeing jelly: Judging elasticity of a transparent object," *Proceedings of the ACM Symposium on Applied Perception, SAP '16*, p. 121–128, 2016.

[36] V. C. Paulun and R. W. Fleming, "Visually inferring elasticity from the motion trajectory of bouncing cubes," *Journal of Vision*, vol. 20, no. 6, p. 6–6, 2020.

[37] F. Schmidt, V. C. Paulun, J. J. R. v. Assen, and R. W. Fleming, "Inferring the stiffness of unfamiliar objects from optical, shape, and motion cuesschmidt et al." *Journal of Vision*, vol. 17, no. 3, p. 18–18, 2017.

[38] J. J. R. v. Assen, S. Nishida, and R. W. Fleming, "Visual perception of liquids: Insights from deep neural networks," *PLOS Computational Biology*, vol. 16, no. 8, p. e1008018, 2020.

[39] J. J. R. v. Assen, P. Barla, and R. W. Fleming, "Visual features in the perception of liquids," *Current Biology*, vol. 28, no. 3, pp. 452–458.e4, 2018.

[40] T. Kawabe, K. Maruya, R. W. Fleming, and S. Nishida, "Seeing liquids from visual motion," *Vision Research*, vol. 109, p. 125–138, 2015.

[41] V. C. Paulun, T. Kawabe, S. Nishida, and R. W. Fleming, "Seeing liquids from static snapshots," *Vision Research*, vol. 115, no. Pt B, p. 163–174, 2015.

[42] W. Bi, P. Jin, H. Nienborg, and B. Xiao, "Estimating mechanical properties of cloth from videos using dense motion trajectories: Human psychophysics and machine learning," *Journal of Vision*, vol. 18, no. 5, p. 12–12, 2018.

[43] ——, "Manipulating patterns of dynamic deformation elicits the impression of cloth with varying stiffness," *Journal of Vision*, vol. 19, no. 5, p. 18–18, 2019.

[44] W. Bi and B. Xiao, "Perceptual constancy of mechanical properties of cloth under variation of external forces," p. 19–23, 2016.

[45] E. Fakhoury, P. R. Culmer, and B. Henson, "The effect of indentation force and displacement on visual perception of compliance," *2015 IEEE World Haptics Conference (WHC)*, p. 88–93, 2015.

[46] V. C. Paulun, F. Schmidt, J. J. R. v. Assen, and R. W. Fleming, "Shape, motion, and optical cues to stiffness of elastic objects," *Journal of Vision*, vol. 17, no. 1, p. 20–20, 2017.

[47] Y. Ujitoko and T. Kawabe, "Perceptual judgments for the softness of materials under indentation," *Scientific Reports*, vol. 12, no. 1, p. 1761, 2022.

[48] M. Srinivassan, "The impact of visual information on the haptic perception of stiffness in virtual environments," *Proc. ASME Dynamic Systems and Control Div.*, vol. 58, pp. 555–559, 1996.

[49] S.-i. Yabe, T. Kimura, H. Kishino, and T. Nojima, "The effect of visually-induced pseudo-haptic on softness." in *ICAT-EGVE (Posters and Demos)*, 2014.

[50] Y. Ban, T. Narumi, T. Tanikawa, and M. Hirose, "Controlling perceived stiffness of pinched objects using visual feedback of hand deformation," in *2014 IEEE Haptics Symposium (HAPTICS)*. IEEE, 2014, pp. 557–562.

[51] Y. Gaffary, B. Le Gouis, M. Marchal, F. Argelaguet, B. Arnaldi, and A. Lécuyer, "Ar feels "softer" than vr: Haptic perception of stiffness in augmented versus virtual reality," *IEEE transactions on visualization and computer graphics*, vol. 23, no. 11, pp. 2372–2377, 2017.

[52] M. Sato, S. Suzuki, D. Ebihara, S. Kato, and S. Ishigaki, "Pseudo-softness evaluation in grasping a virtual object with a bare hand," in *ACM SIGGRAPH 2016 Posters*, 2016, pp. 1–1.

[53] J. Cauquis, V. R. Mercado, G. Casiez, J.-M. Normand, and A. Lécuyer, ""kapow!": Studying the design of visual feedback for representing contacts in extended reality," in *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology*, 2022, pp. 1–11.

[54] T. Kawabe, "Visual assessment of causality in the poisson effect," *Scientific Reports*, vol. 9, no. 1, pp. 1–10, 2019.

[55] ——, "Perceptual properties of the poisson effect," *Frontiers in Psychology*, p. 4044, 2021.

[56] L. Dominjon, A. Lécuyer, J.-M. Burkhardt, P. Richard, and S. Richir, "Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments," in *IEEE Proceedings. VR 2005. Virtual Reality, 2005.* IEEE, 2005, pp. 19–25.

[57] G. N. Greaves, A. L. Greer, R. S. Lakes, and T. Rouxel, "Poisson's ratio and modern materials," *Nature materials*, vol. 10, no. 11, pp. 823–837, 2011.

[58] Q. Li, S. J. Joo, J. D. Yeatman, and K. Reinecke, "Controlling for participants' viewing distance in large-scale, psychophysical

online experiments using a virtual chinrest," *Scientific Reports*, vol. 10, no. 1, p. 904, 2020.

[59] J. O. Wobbrock, L. Findlater, D. Gergle, and J. J. Higgins, "The aligned rank transform for nonparametric factorial analyses using only anova procedures," *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*, p. 143–146, 2011.

[60] L. A. Elkin, M. Kay, J. J. Higgins, and J. O. Wobbrock, "An aligned rank transform procedure for multifactor contrast tests," *The 34th Annual ACM Symposium on User Interface Software and Technology*, p. 754–768, 2021.

[61] D. Wang, K. Ohnishi, and W. Xu, "Multimodal haptic display for virtual reality: A survey," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 1, pp. 610–623, 2019.

[62] Polhemus, "Human interface guidelines," https://polhemus.com/.

Takahiro Kawabe is a Senior Distinguished Researcher and the leader of Sensory Representation Group, Human Information Science Laboratories, NTT Communication Science Laboratories. He received a Doctor of Psychology from Kyushu University, Fukuoka, in 2005. In 2011, he joined NTT Communication Science Laboratories, where he studies basic and applied aspects of human perception. He received the 2013 JPA Award for International Contributions to Psychology: Award for Distinguished Early and Middle Career Contributions from the Japanese Psychological Association. In 2018, he was also awarded The Young Scientists' Prize of The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology. He is a member of the Vision Sciences Society and the Vision Society of Japan.

Yusuke Ujitoko (Member, IEEE) received the B.E.degree in mechanical engineering and the M.A.E.degree in interdisciplinary information studies from the University of Tokyo, Tokyo, Japan, in 2014 and 2016, respectively, and the Ph.D. degree from The University of Electro-Communications, Chofu, Japan, in 2020. Since 2020, he has been a Distinguished Researcher at NTT Communication Science Laboratory, Atsugi, Japan. From 2016 to 2020, he was a Member of the R&D Group, Hitachi, Ltd., Tokyo, Japan. His research interests include applied haptic perception and haptic interfaces.