This article has been accepted for publication in IEEE Transactions on Haptics. 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/TOH.2023.3269016

Specifying Visual Parameters for Haptic-visual Sequential Matching of Material Softness

Yusuke Ujitoko, and Takahiro Kawabe

***Abstract*—When shopping online, a customer cannot directly touch the products but may sometimes make judgments about the haptic properties of a product based only on visual information, before making a purchase decision. In this scenario, a customer may be dissatisfied if there is an inconsistency in the judgment of the product's haptic properties they made before purchasing, and their actual experience of those haptic properties once they have received the product. Thus, it is necessary for online sellers to appropriately optimize visual information for materials so that perceived softness is consistent between haptic and visual modalities presented in different locations and at different moments in time. Focusing on visual indentation depth and speed, we examined the visual parameters used to sequentially match haptic and visual softness from haptic and visual information made available in different locations and at different times. Participants performed a two-alternative forced choice task to determine which of two video clips contained an elastic material with a softness impression most similar to the haptic softness of an actual material that the participants indented with their index finger. Based on a sequence of 25 repeated judgments for each material, our algorithm optimized each visual parameter based on a Gaussian process. The optimized visual indentation depth varied consistently with material compliance, while the optimized visual indentation speed did not, suggesting that visual indentation depth was critical for softness matching. The optimized visual indentation depth was highly correlated with the haptic indentation depth. Subjective rating scores for the softness matching increased significantly after the optimization process. The results indicate that participants were able to successfully match the haptic and visual softness of materials by checking the relationship between indentation depths detected haptically, and those detected visually.**

***Index Terms*—Material Softness, Sequential Matching, Visual Softness, Haptic Softness.**

I. Introduction

Haptic experiences are an essential aspect of purchasing behaviors. For example, it is known that some individuals purchase a product only after they have experienced some kind of direct haptic interaction with it [1]. Meanwhile, in some purchase contexts, purchase decisions need to be made without direct haptic experience of a product. One representative example is online shopping. Online shopping volumes have grown with each passing year [2] and are expected to continue to do so even after COVID-19 [3]. Although online customers do not directly touch a product before purchasing, they may predict certain haptic properties of a product based on visual information.

One of the haptic properties that can be judged visually is softness [4]. Softness is the subjective impression of the physical compressibility and deformability of materials as described in the introduction of the book [5]. Touching soft materials gives people a pleasant sensation [6], [7], and soft materials sometimes invite hedonic touch [8]. To properly communicate vision-based softness to online customers, it is important for online sellers to devise ways to make visual softness approximate as closely as possible to the actual haptic softness of their products. Consumers may be dissatisfied if there is a major discrepancy between their judgment of the softness of a product made based on visual information before buying, and the softness of the product perceived haptically once they have received the actual item after purchasing. Therefore, online sellers need to properly optimize visual information relating to product materials so that perceived softness is matched between haptic and visual modalities. The present study focuses on the problem of how to achieve haptic and visual sequential matching of material softness by optimizing visual information.

Sequential matching here refers to the human behavior of evaluating the consistency of haptic and visual softness for haptic-visual stimuli when each is separately presented in different locations and at different times. As yet little is known about how the cognitive system matches material softness between the senses of touch and sight. In the context of multi-modal integration, there have been studies investigating how humans "integrated" stimuli with different presentation timings into a single softness perception [9], [10], [11], [12]. For example, Di Luca et al. have shown that a delay between the presentation of visual and haptic information during indentation decreased the perceived softness of a virtual spring [9]. Lecuyer et al. have shown that participants felt a virtual spring on the screen to be softer when the spring was compressed to a larger extent [10]. Metzger et al have shown that the haptic softness judgment made by their experimental participants was sensitive to the sequential order of presented stimuli [11], suggesting that the judgment depended on the participants' prior experience (or judgment) of softness. Like these studies regarding stimulus presentation timing, Xiao et al. have investigated how tactile and visual information is matched when information for both modalities is given at the same time [13]. In contrast with previous studies, we were interested in situations where, for example, three seconds after an observer haptically confirms the softness of a cushion by pressing it with her/his finger, the same observer visually confirms the softness of "another" cushion by watching another person pressing it and compare the softness of the cushions. In the assumed situation, it is unlikely that the perception of a single object will occur, as has been shown to be the case

Y. Ujitoko and T. Kawabe are with NTT Communication Science Laboratories, 3-1, Morinosato Wakamiya, Atsugi, 243-0033, Kanagawa, Japan
Manuscript received XXXXX XX, 2022

© 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Haptics. 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/TOH.2023.3269016

in previous studies [9], [10], [11], because it does not seem a plausible strategy for the cognitive system to integrate the signals relating to the different cushions to create a mental representation of a single object. None of these studies has investigated how human participants match haptic and visual softness when these modalities are stimulated sequentially in such situations.

The purpose of the present study was to clarify which visual parameters in video clips of materials were used for the haptic-visual sequential matching of material softness. Although it is assumed that people perform softness matching in various contexts in their daily lives, no previous study has clarified which information in the haptic and visual modalities was used for the matching. Once it becomes clear what visual parameters are used for softness matching, we will better understand the mechanism of this situation. Moreover, the elucidation of the visual parameters used in haptic-visual sequential softness matching has some practical value in the context of online shopping. For example, online sellers may be able to optimize visual information relating to the haptic softness of their products. By editing videos of material deformation, visual parameters can be easily manipulated. However, no previous studies have focused on the visual parameters used in the haptic-visual sequential matching of material softness. By optimizing the visual parameters identified in this study, online sellers will be able to effectively convey the haptic softness of their products in their video presentations.

In the present study, we focused on visual parameters which could be expected to vary when a deformable material was being indented from its uppermost surface. While there are different perceptual dimensions for visual and haptic softness [14], [15], we focused on the "deformability" dimension, which corresponds well with material compliance, rather than other dimensions such as viscosity, granularity, or furriness. Also, among the different types of materials that could be rated to be soft and viscous [16], we focused on elastic materials. Some previous studies have consistently reported that visual indentation depth was a critical cue for judgments of the softness of a deformable material [17], [18], [19], [20]. The visual indentation depth here means the visible depth of an indentation into an elastic material surface. It has been demonstrated that a video clip of both a real [17], [19], [20] or a computer-rendered material [18] with a deeper indentation produced greater impressions of material softness. In addition, a previous study [19] has also shown that, besides the visual indentation depth, the visual indentation speed significantly contributes to the judgment of visual softness. The visual indentation speed here means the visible speed of an indentation being made into the surface of an elastic material. The study just cited found that a higher indentation speed resulted in higher softness rating scores. The authors of the study also reported that in a comparison between visual indentation speed and visual indentation depth, the latter had a greater influence on the judgment of softness.

We regarded visual indentation depth and speed as potential contributors to the haptic-visual sequential matching of material softness, since they are also haptically discernable when a participant makes an indentation in a real object with their own finger. By establishing the relationship between haptic and visual indentation depths, or haptic and visual indentation speeds, we expected that participants may be able to achieve haptic-visual softness matching. It is a focus of our interest to determine how these visual parameters were actually used for the haptic-visual sequential matching of material softness.

To clarify this main focus of our study, we conducted an experiment in which participants performed sequential matching of softness between haptic and visual stimuli. Specifically, our experimental participants watched a pair of video clips of a material being indented three seconds either before or after they themselves haptically indented a real material. Participants were not allowed to observe the clips during the haptic indentation, nor were they allowed to haptically perform the indentation during the visual observation of the clips. The participants judged which of the clips contained a material whose softness was most similar to the material they were haptically indenting. The participants' judgments on the softness similarity were used to optimize the visual parameters — visual indentation depth and speed —, through a human-in-the-loop optimization process. This was done by using Bayesian optimization with a Gaussian process, which updated the model (that describes the relationship between the participants' judgments and the visual parameters) iteratively based on the participants' judgments. Specifically, in the optimization procedure, the algorithm took the visual parameters which the participants chose in the current trial as its input. Next, the algorithm updated the objective function with a Gaussian process. Finally, the algorithm searched for and proposed a new set of visual parameters that would likely induce a preferential choice by the participants in the subsequent trial, on the basis of a preference learning algorithm featuring exploitation (choosing points near a previously observed optimum) and exploration (choosing points in areas that have not been well explored). Thus, as the optimized values were determined on the basis of the visual parameters that the participants preferentially chose, it followed that we could conclude that the optimized value of the visual parameters was related to the participants' preferential judgment for the haptic-visual softness matching.

II. Method

A. Participants

Twelve people (7 males and 5 females, all right-handed) with a mean age of 27.4 (SD: 7.0) participated. They were not informed about the specific purpose of the experiments. They reported that they had normal or corrected-to-normal visual acuity. They were recruited from outside the laboratory by a Japanese hiring agency and were paid for their participation. Ethical approval for the present study was obtained from the ethics committee at Nippon Telegraph and Telephone Corporation (Approval number: R02-002 by NTT Communication Science Laboratories Ethics Committee). The experiments were conducted in accordance with the 2008 Declaration of Helsinki. Written informed consent was obtained from all participants.

© 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Haptics. 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/TOH.2023.3269016

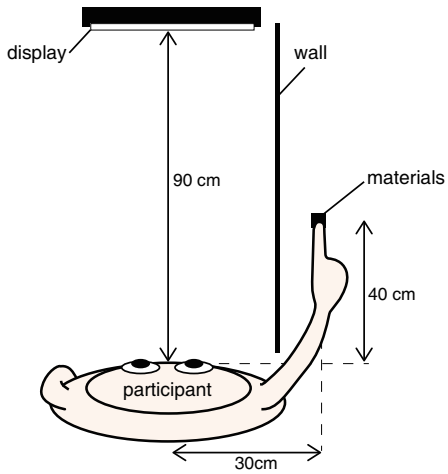

Fig. 1. Experimental environment. Participants indented the material's upper surface without being able to look at it.

TABLE I
TWO SIZES OF HOLE, R SQUARED VALUE OF FITTED LINEAR MODEL (BETWEEN FORCE AND DISPLACEMENT), AND MATERIAL COMPLIANCE FOR EACH MATERIAL.

Material	Diameter of first hole [mm]	Diameter of second hole [mm]	R squared value of fitted linear model	Compliance [mm/N]
A	0.6	0.5	0.993	0.235
B	1.2	0.65	0.988	0.271
C	1.45	0.5	0.985	0.358
D	1.4	0.95	0.986	0.572
E	0.5	1.8	0.993	0.759
F	1.75	0.8	0.917	2.473

B. Apparatus

Figure 1 shows the experimental environment. Participants were seated comfortably on a chair and placed their right index finger on the upper surface of a material positioned in front of their right hand. To prevent them from receiving any visual information about the materials, a barrier was set up between the participants and the materials. A display (VIEWPixx; VPixx Technologies Inc., Canada) with a 1920 × 1200 resolution at 120Hz was positioned in front of the participants at a distance of 90 cm.

1) Haptic Stimuli: We attempted to replicate the six cubic metamaterials introduced in a previous study [21] by using identical types of material (TangoBlackPlus [22]) and a 3D printer (Stratasys Obje500). See supplementary Note 1 for how we selected the specific six materials used for this study from the 12 used in the previous study just referenced. Figures 2(a) and (b) respectively show photographs of the materials and their force-displacement curves. Each side of the material was 42 mm long and the shape contained 169 cylindrical holes. There were two sizes of holes in each material, which differed between the six materials as shown in the first and second columns in Table I. There was a 3.00 mm gap between the holes. These configurations were identical to those used in a previous study [21].

To characterize the properties of each material, we performed uniaxial load testing. An increasing force was applied to the cubes' upper surface to give a displacement at a constant speed of 1 mm / 6 seconds, and the corresponding force was recorded using a force tester (MCT-2150, A&D Co., Ltd.). Figure 2(b) shows the measured force-displacement curves.

To check the linearity of the deformation of the six materials, we fitted the data with linear models to regress the force with displacement for each material. The R squared values of the fitness ranged from 0.917 to 0.993 (see the R squared values for each material in the third column in Table I). Thus, we regarded the force-displacement relationship as linear and defined the compliance according to the values in the fourth column of Table I. The compliance value for each material used for analysis is shown in Figure 2(c).

2) Visual Stimuli: The visual stimuli in our experiment were video clips that showed the upper surface of an elastic material being pushed down by an indenter (a cylinder with a diameter of 1.3 cm). The video resolution was 288 x 288 pixels at 29.97 frames per second. We filmed the videos from a camera position diagonally above the materials so that the upper surface pushed by the indenter could be clearly seen. The horizontal distance between the camera and the materials was 40 cm and the height of the camera above the materials was 17 cm. The elevation angle of the camera was approximately 23 °. The camera lens was oriented towards the material.

The raw video recorded the indenter pressing into the materials at a constant speed of 1 mm/6 seconds. The raw videos started from a point when the indenter was stationary and in contact with the material's upper surface. They showed the indenter pushing the material down to a depth of 18 mm and immediately returning to its starting position (see Figure 3). We exported all the frames from the videos and, by manipulating which frames were presented in each stimulus video, we were able to control the visual indentation depth and the visual indentation speed as they appeared in the videos. See some example video clips in the Supplementary Videos.

The visual indentation depth refers to the depth of the indentation made by the indenter into the material's upper surface. The visual indentation speed refers to the speed at which the indenter pressed into the material's upper surface. In this experiment, these two visual parameters in the video clips were optimized on the basis of the participants' responses. The presented visual indentation depth could vary from 1.0 mm to 18.0 mm. The presented visual indentation speed could vary from 2.0 mm/s to 15.0 mm/s. The details of our optimization algorithm are described in the "II. D. Optimization Algorithm" section.

3) Tracking Participant's Finger Position: The participant's index finger position was monitored with an optical tracking system (Optitrack, V120 Trio). The marker for the tracking system was attached to the nail of the participant's index finger. The mean tracking system refresh rate across all trials was 190.4 captures per second.

C. Task

There were two tasks in this experiment: a visual-haptic task and a haptic-visual task. The tasks differed in the order

© 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Haptics. 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/TOH.2023.3269016

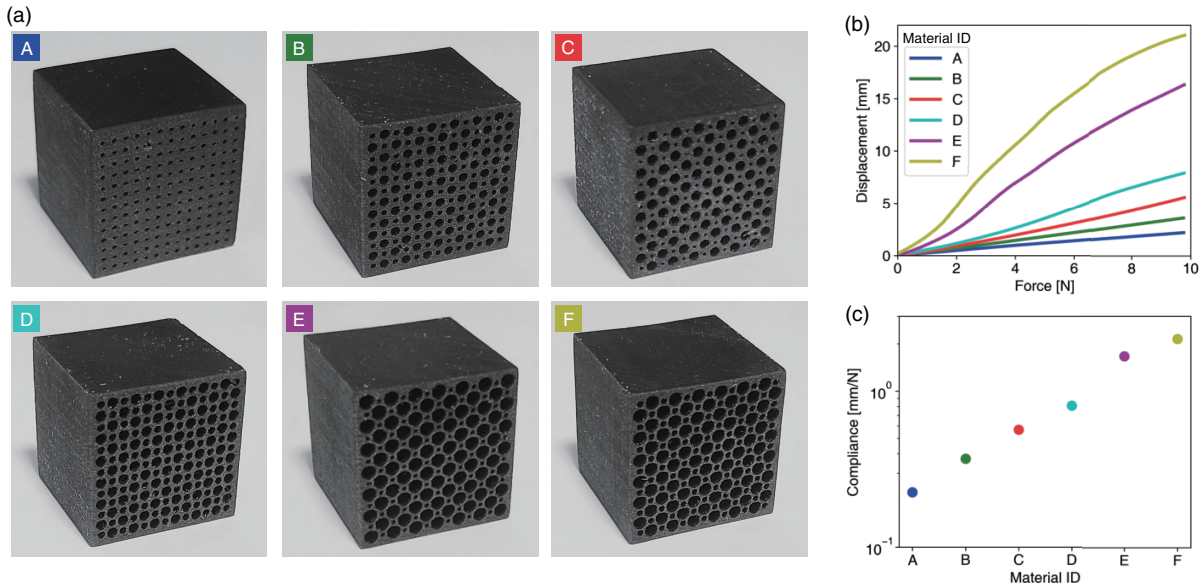

Fig. 2. (a) Appearance of materials. (b) Force-displacement relationships of materials. (c) Compliance of each material.

of presentation of the visual and haptic stimuli. In the visual-haptic task, participants were presented with the haptic stimuli first and, three seconds later, with the visual stimuli. In the haptic-visual task, the order of presentation was reversed. Half of the participants performed the visual-haptic task for all materials first, and the haptic-visual task for all materials second. The other half of the participants performed these tasks in reverse order.

The reason why we configured two tasks (the haptic-visual task and the visual-haptic task) was not to investigate the effect of order but rather to cancel it out.

D. Optimization Algorithm

This study adopted a Bayesian framework with a Gaussian Process [23] to optimize visual parameters. A simple way to optimize two parameters is by a grid search, a time-consuming method that allows comprehensive exploration of a two-dimensional space. A Bayesian optimization with a Gaussian process, on the other hand, allows us to specify within a small number of iterations the visual parameters that maximize the participants' judgments of the similarity between haptic and visual softness. In the optimization process, the algorithm takes the visual parameters which the participants chose in the current trial as its input. Next, the algorithm updates the objective function with a Gaussian process. Finally, the algorithm searches for and proposes a new set of visual parameters that is likely to induce the participant's preferential choice in the next trial on the basis of its preference learning features of exploitation (choosing points near a previously observed optimum) and exploration (choosing points in areas that have not been well explored) [24]. Thus, as the optimized values were determined on the basis of the visual parameters that the participants preferentially chose, it followed that we could conclude that the optimized value of the visual parameters was related to the participant's preferential judgment for the haptic-visual softness matching. The objective function was iteratively updated based on the parameters the participants chose. Note that the algorithm used in our study could simultaneously optimize both visual parameters (indentation depth and speed), without being specialized to either one of them. The optimization procedure was implemented using preference learning with a Gaussian process in the Python GPro library [25].

E. Procedure

The experiment was programmed using PsychoPy [26]. In each trial, one material was positioned in front of the participant's right hand so that a smooth surface of the material was uppermost. The exact same type of material was used for both the haptic and visual stimuli. For the haptic stimulus presentation, participants were allowed to compress the top surface of the material with their index finger once only. To prevent them accurately assessing the indentation depth of their finger press, participants were not allowed to repeatedly touch the materials.

For the visual stimuli, two video clips were shown in which each material was indented, and the participants watched them. One of the clips in each trial was the same clip that the participant had selected in the preceding trial. The other clip was a video newly created by our algorithm on the basis of the clip selected in the preceding trial. In each clip, the material was indented to a certain depth at a certain speed. The clips were looped.

After the presentation of the haptic and visual stimuli, participants were asked to report their judgment as to which of the two video clips contained a material whose softness was most similar to the material they touched with their fingers. After participants had provided their answers, the algorithm updated the model and suggested new values of indentation depth and speed for the video clip to be presented in the

© 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Haptics. 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/TOH.2023.3269016

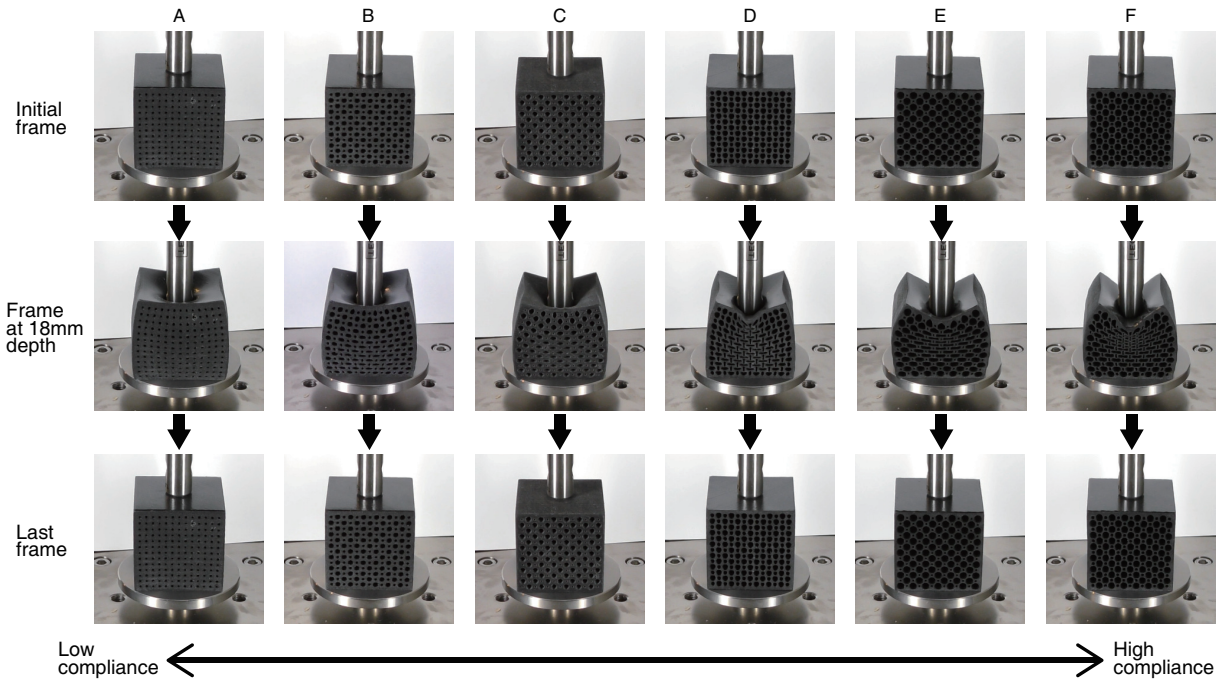

Fig. 3. Snapshots of raw videos of each material.

subsequent trial. The software created a new clip based on the suggested values. As described above, the new clip and the clip selected by the participant in the current trial were presented in the subsequent trial.

There were 25 trials in a set. We set the number of trials at 25 so that the visual indentation depth and speed would converge within one set. On the basis of a preliminary examination, we expected that they would converge within the space of 25 trials. The presented visual indentation depth could vary from 1.0 mm to 18.0 mm. The presented visual indentation speed could vary from 2.0 mm/s to 15.0 mm/s. Based on the author's preliminary observations, the optimized values were expected to be in a range up to 10. Thus, the initial values for indentation depth and speed were randomly sampled from their variation ranges. One task consisted of six sets, corresponding to six materials. The presentation order of the six materials was assigned pseudo-randomly to each participant. There were 2 task types for each participant. Thus, each participant performed 300 trials (=25 trials $\times$ 6 sets $\times$ 2 tasks).

Before the 1st trial and after the 5th, 10th, 15th, 20th, and 25th trials, participants were also asked to provide subjective rating scores of the extent to which the softness of the material in the clip matched the softness of the material they indented. In the 1st trial, participants rated one of two clips made by the experimental software. It was determined at random which clip was rated. In the 5th, 10th, 15th, 20th, and 25th trials, participants rated the clip they selected in the respective trials. Participants reported the degree of consistency between haptic and visual softness as a consequence of the sequential haptic-visual matching on a seven-point scale with 1 for "do not match at all", 2 for "do not match", 3 for "don't match very much", 4 for "neutral", 5 for "somewhat match", 6 for "match", and 7 for "match perfectly".

III. Results

This section is laid out as follows. First, we investigate whether the visual indentation depth and/or visual indentation speed after optimization vary with the material compliance. Second, we examine the relationship of indentation depth between touch and vision. Finally, we check the improvement in the subjective rating for softness matching arising from the optimization since it is still unclear whether the evolution and variation of the optimized visual parameter cause the improvement in the subjective rating for softness matching. We report only the statistical results critical to interpreting the experimental results.

A. Optimization of Visual Parameters

Figures 4(a) and (b) show the evolution of visual indentation depth and indentation speed. It appears that, while there were wide differences in the visual indentation depth among the materials, there were only small differences in the visual indentation speed.

Generally, it is assumed that the optimized value in the later trials is more reliable. Thus, we focused on the visual parameters chosen for the last trial (see Figure 4(c)) and investigated whether the visual parameters were statistically different between the materials. If the participant successfully optimized the visual parameter so that the visual softness matched the material compliance, the visual parameter should correspond to the material compliance. Since the materials used in this experiment had different levels of compliance,

© 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Haptics. 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/TOH.2023.3269016

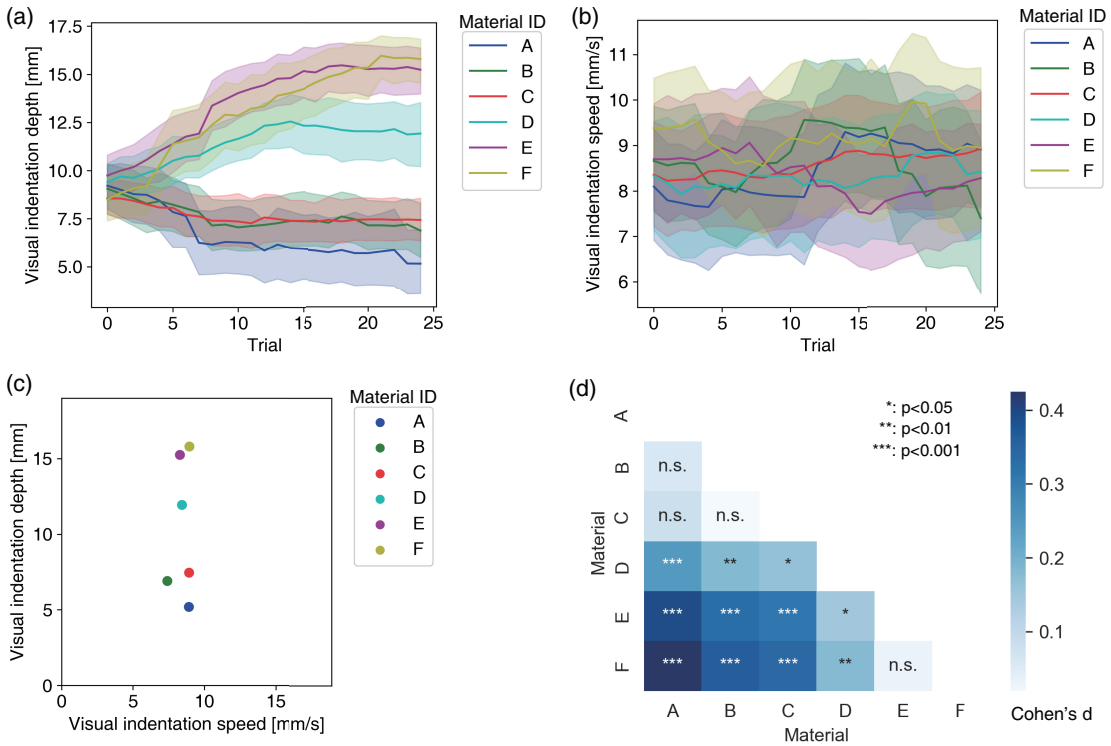

Fig. 4. (a) Evolution of visual indentation depth. (b) Evolution of visual indentation speed. The shadowed area shows 95 %C.I. (c) Optimized visual indentation depth and speed after the last trial. (d) Result of multiple comparisons between material pairs for optimized visual indentation depth after the last trial. The color of the cell denotes Cohen's d value, and the asterisk denotes the significance of the difference. Bonferroni corrected p-value was used for significance judgment.

the optimized visual parameter should also differ between materials if the visual parameter was in fact relevant to the haptic-visual sequential matching of softness.

1) Optimization of Visual Indentation Depth: We conducted a one-way repeated measures ANOVA using material as a fixed factor on visual indentation depth. Note that we averaged the data of the two tasks (visual-haptic and haptic-visual tasks) per participant. There was a significant main effect of material [$F(5, 64) = 27.41, p < 0.001, \eta_p^2 = 0.68$]. In post-hoc test, we conducted multiple comparisons with Bonferroni correction for the significant main effects of materials. There were significant differences only between the following material pairs: A-D, A-E, A-F, B-D, B-E, B-F, C-D, C-E, C-F, D-E, and D-F ($p < 0.05$). See Cohen's d for each of the differences in Figure 4(d).

Our results showed that the optimized values of the visual indentation depth depended on the materials, indicating that the optimization was successfully achieved in accordance with the participants' judgment for the haptic and visual sequential matching of material softness.

2) Optimization of Visual Indentation Speed: We also conducted a one-way repeated measures ANOVA on visual indentation speed. There was no significant main effect of material [$F(5, 64) = 0.35$, $p = 0.88$, $\eta_p^2 = 0.026$, observed power = 0.66]. This showed that the optimized values of the visual indentation speed did not depend on the materials, indicating that the visual indentation speed was not used for the sequential matching of material softness.

One might suspect that the difference in the optimization outcomes between visual parameters was due to the specialization of the algorithm to one of the parameters. That is, there was a possibility that the algorithm tried to preferentially optimize one parameter over the other. To assess this possibility, we checked the value obtained by dividing the standard deviation of the suggested values by the range of each visual parameter. If the values differed between the two parameters, we would have been able to conclude that the algorithm treated them differently. The value obtained for visual indentation depth was 0.294 and that for visual indentation speed was 0.290. The values were thus almost identical. These results indicate that the algorithm treated the two parameters without specialization to either one of them.

3) Correlation between Visual Indentation Depth and Haptic Indentation Depth: As described in the previous sections, we found that the visual indentation depth was used for softness matching. It is clear that indentation depth was haptically recognizable during the indentation the participant made in the real material with their finger. There is a possibility that the participants were able to evaluate the similarity between haptic and visual softness by linking the haptic indentation depth with the visual one. To explore this possibility, during the experiment, the participant's finger position was tracked and analyzed. Using the data from the tracked finger positions, we sought to clarify the relationship between visual and haptic indentation depth.

We averaged the optimized values of the visual indentation

© 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Haptics. 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/TOH.2023.3269016

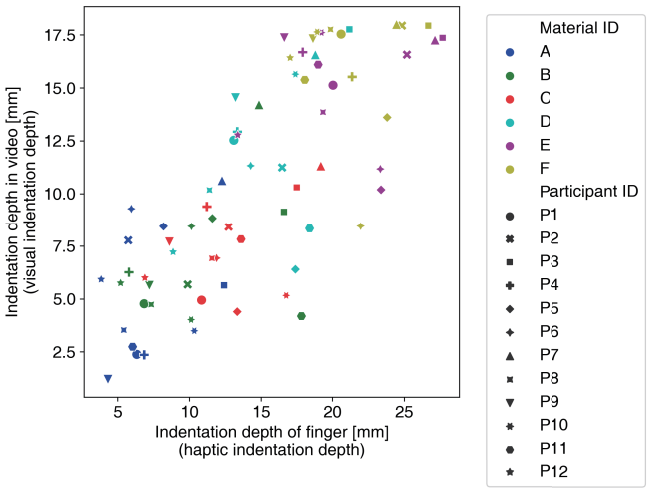

Fig. 5. Relationship between indentation depth in the video clips (visual indentation depth) and depth of the indentation made by the participant's finger (haptic indentation depth).

depth for each combination of participant and material. We also averaged the indentation depth applied by each participant's finger (haptic indentation depth) using the data for tracked finger positions during all trials. The relationship between them is shown in Figure 5. The Pearson correlation coefficient was 0.77 ($p < 0.001$). The results of the correlation analysis indicate that the variation of the optimized values of the visual indentation depth was positively related to the variation of the haptic indentation depth (i.e., the indentation made by the participant's finger). The strong correlation suggests that the participants were able to evaluate the consistency of haptic and visual softness by linking the haptic indentation depth with the visual indentation depth. The results shed light on a new cross-modal matching mechanism that likely operates in scenarios where participants are not allowed to evaluate simultaneously the information given to each haptic and visual modality, but are required to judge the consistency of haptic and visual softness sequentially.

B. Subjective Rating for the Matching between Haptic and Visual Softness

In the previous section, we found that visual indentation depth was optimized depending on the material to match its softness. Still, it was unclear if this optimization actually caused the improvement in subjective ratings for softness matching.

Figure 6(a) shows rating scores for the matching between haptic and visual softness for each material. To clarify whether the evolution of optimized visual indentation depth caused the change in subjective rating for softness matching, we first applied an Aligned Rank Transform (ART) [27], [28] to the data. In general, the rating scores were not normally distributed, and thus, it was not deemed appropriate to parametrically analyze the raw scores. ART is a procedure developed to perform the ANOVA with non-normally distributed data, wherein the rating score is first "aligned" for each of main effects and interactions, and then ranked. The obtained rank can then be the subject of an ANOVA. Unlike other nonparametric statistical tests such as the Kruskal-Wallis test, ANOVA with the use of ART enables analysis using multiple factors with appropriate Type I error rates and suitable powers. We used trials and material as fixed factors in the ART. The main effect of trials was significant [$F(5, 396) = 18.0$, $p < 0.001$, $\eta_p^2 = 0.19$], as was the main effect of material [$F(5, 396) = 4.5$, $p < 0.001$, $\eta_p^2 = 0.05$]. The interaction effect was not significant [$F(25, 396) = 1.0$, $p = 0.44$, $\eta_p^2 = 0.061$].

As post-hoc tests of the significant main effects, we conducted multiple comparisons with Bonferroni correction for each of the significant main effects using the Aligned Rank Transform Contrasts (ART-C) procedure [29]. ART-C is an additional align-and-rank procedure to facilitate post-hoc pairwise comparisons without inflating Type I error rates. Regarding the main effect of trials, there were significant differences between the following trial pairs: 1st-5th, 1st-10th, 1st-15th, 1st-20th, 1st-25th, 5th-15th, 5th-20th, and 5th-25th ($p < 0.05$) (see Figure 6(b)). Regarding the results of the multiple comparisons due to the main effect of materials, please see Figure 6(c).

In addition, to clarify whether the subjective rating for softness matching was significantly improved after optimization, we calculated the 95% confidence interval (CI) of the subjective rating scores in the last trial for each material based on 10,000 bootstrap samples [30]. If the Bonferroni-corrected 95% CI did not overlap four (i.e., "neutral"), we could conclude that the subjective rating was significantly improved over neutral. This analysis showed that the 95% CIs of subjective rating for all materials were significantly larger than four.

Consequently, the optimization for the visual indentation depth improved subjective rating scores for softness matching up to the 10th trial. Moreover, the rating scores with the ultimate optimization value were significantly higher than the "neutral" criterion. The results indicate that the optimization of visual indentation depth significantly improves the subjective consistency of material softness between touch and vision.

IV. Discussion

The present study for the first time investigated which visual parameters were used for the sequential matching of material softness. We discovered that visual indentation depth, rather than visual indentation speed, was used for optimization in haptic-visual sequential matching (see Figure 4). One of our previous studies [19] has shown that both indentation depth and speed significantly contributed to the "visual" judgment of material softness. That study also showed that visual indentation depth had stronger effects on the judgment of softness than visual indentation speed. The present study has reported that only indentation depth was used by the perceptual system to match the material softness between haptic and visual modalities. Thus, it is our conclusion that participants utilized only visual indentation depth, which has been reported to have a pronounced influence on visual softness, in the context of the sequential matching of haptic-visual softness.

© 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Haptics. 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/TOH.2023.3269016

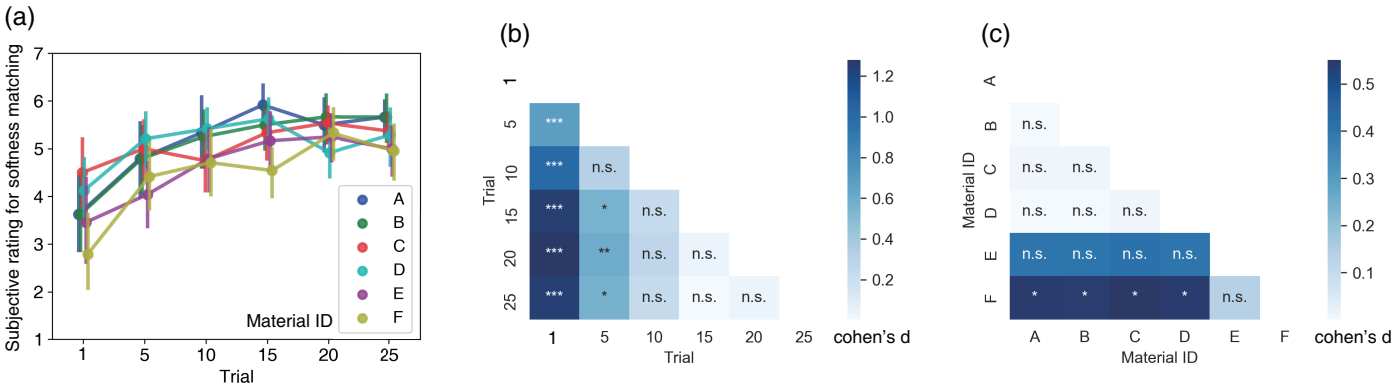

Fig. 6. (a) Evolution of subjective rating for softness matching for each material. Error bars denote 95 %C.I. (b) Result of multiple comparisons between trials as a post-hoc test for the main effect of trial on the subjective rating for softness matching. (c) Result of multiple comparisons between materials as a post-hoc test for the main effect of material on the subjective rating for softness matching.

One thing we should pay attention to is the range of the indentation speed in our experimental settings. The range was limited to between 2 mm/s and 15 mm/s. If the speed could be manipulated beyond this range, the effect of indentation speed might be found to have an effect on perceived softness.

Our results showed that visual indentation depth was highly correlated with haptic indentation depth. We speculate that the participants might imagine ideal values for visual indentation depth based on the indentation depth of their own finger and use this to judge the similarity of the softness. This finding contributes to our understanding of how the perceptual system judges the consistency of haptic and visual softness in contexts where participants are not allowed to evaluate the information given to each sensory modality at the same time.

As for the degree to which haptic-visual sequential matching of material softness is achieved as a result of optimization, the subjective rating scores were significantly higher than 4 (i.e., "neutral"). Furthermore, the subjective rating scores reached 5 (i.e., "visual and haptic softness somewhat match") or 6 (i.e., "visual and haptic softness match") on average for all materials. This subjectively high satisfaction regarding the sequential matching indicates that optimization was carried out successfully. The present study might provide helpful information for haptic-visual sequential matching design. As a real-world problem, there are many cases where a designer wants to match visual softness with haptic softness. For example, if online sellers want to sell soft cushions online, it would be helpful if they could match the visual information in the cushions' photos/video clips on their website with the actual haptic softness of the cushions. The methods used in this study are promising for online sellers who want to ensure the subjective matching of haptic and visual softness of a cushion, or other product; the method does not require much time investment, with the entire process often being completed in less than about ten minutes.

The pattern of convergence of subjective rating scores for the consistency between haptic and visual softness was dependent on the type of material (see Supplementary Table 2). Specifically, rating scores for the stiffer materials (A, B, C, and D) were higher than those for the softer materials (E and F). The present study configured the initial values in optimization for visual indentation depth and visual indentation speeds to be common across the materials. We suggest that the optimal value of the visual indentation depth for the stiffer materials might be nearer to the initial values than the optimal value for the softer materials, and that this caused the difference in the pattern of convergence of the consistency rating scores among the materials. It may be possible to moderate the difference in the rating scores among the materials by appropriately configuring the initial values in optimization and shortening the time to convergence.

The potential impact of demand characteristics on participants' subjective rating scores should be noted. The participant's task was to select the video clips for a certain material that gave a similar softness impression to the softness of the haptic stimuli. Thus, there was a possibility that the participants noticed the purpose of the study and tried to rate the consistency of haptic-visual softness in accordance with the experimenter's expectations. Still, if the demand characteristic was a unitary cause of the improvement of the rating scores, one would be required to explain why the rating scores did not improve after the 10th trial. It is natural to interpret this to mean that the optimization was completed to produce a sufficient level of subjective consistency by the 10th trial. Still, there is also a possibility that the current task is contaminated with a demand characteristic, and thus, future studies need to examine this issue with an improved protocol whereby, for example, the influence of demand characteristics is reduced by mixing trials in multiple sets or including additional trials with unrelated stimuli.

The type of material used in our experiment was limited to a specific rubber-like material. Hence, the generalizability of the conclusion to other categories of elastic materials, such as soft plastics or hard rubbers, is probably promising, but has not been confirmed yet. Further research is needed to determine the extent to which the findings can be generalized to different categories of elastic materials.

In our experiment, participants were required to indent a material with their finger. We decided to ask them to do so because it is known from exploratory procedure studies that people judge the softness of materials mainly by pushing [31]. We expect that even if the participants were allowed to touch

© 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Haptics. 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/TOH.2023.3269016

the material freely, the softness judgment would be performed by indenting the material with their finger and/or palm. The previous study just cited has also suggested that different modes of touch, such as rubbing or lifting, provide information about the roughness or weight of a material, rather than about its softness. Thus, if a different mode of touch than indenting was required, it would not be easy for participants to make an assessment of material softness. As a result, the optimization of visual indentation depth and speed would not proceed as intended.

Our study successfully identified the visual parameter that supports haptic-visual softness matching. Due to the ease with which visual indentation depth can be manipulated and presented in the video clips showing object deformation, our findings will be useful in a number of application scenarios. On the other hand, there is a risk of some ambiguity in the visual indentation cue due to the camera angle and/or the distance between the camera and the material. Even in that case, we suggest that other visual features may contribute to the inference of indentation depth, and thus, visual softness. For example, it is known that texture deformation serves as a cue to softness perception even when the visual indentation depth is not explicitly displayed [32], [33]. Moreover, other haptic and even auditory parameters may also play a part in the determination of material softness perception. Hence, to establish the consistency of haptic-visual softness in a real-world setting wherein more parameters are involved in the determination of perceptual softness, it may be necessary to consider optimizations in a higher dimensional space than the two-dimensional space that the present study assumed. The exploration of this as yet unknown information providing effective cues for haptic-visual softness matching is left as an open issue for future research.

REFERENCES

[1] J. Peck and T. L. Childers, "Individual differences in haptic information processing: The "need for touch" scale," *Journal of Consumer Research*, vol. 30, no. 3, pp. 430–442, 2003.

[2] Statista, "Retail e-commerce sales worldwide from 2014 to 2026," https://www.statista.com/statistics/379046/worldwide-retail-e-commerce-sales/#statisticContainer, (Accessed on 30/01/2023).

[3] UNCTAD, "Covid-19 has changed online shopping forever, survey shows," https://unctad.org/news/covid-19-has-changed-online-shopping-forever-survey-shows, (Accessed on 30/01/2023).

[4] E. C. Hirschman and M. B. Holbrook, "Hedonic consumption: emerging concepts, methods and propositions," *Journal of marketing*, vol. 46, no. 3, pp. 92–101, 1982.

[5] M. D. Luca, *Multisensory Softness, Perceived Compliance from Multiple Sources of Information*, ser. Springer Series on Touch and Haptic Systems, 2014.

[6] A. Pasqualotto, M. Ng, Z. Y. Tan, and R. Kitada, "Tactile perception of pleasantness in relation to perceived softness," *Scientific reports*, vol. 10, no. 1, pp. 1–10, 2020.

[7] R. Kitada, M. Ng, Z. Y. Tan, X. E. Lee, and T. Kochiyama, "Physical correlates of human-like softness elicit high tactile pleasantness," *Scientific reports*, vol. 11, no. 1, pp. 1–10, 2021.

[8] R. L. Klatzky and J. Peck, "Please touch: Object properties that invite touch," *IEEE Transactions on Haptics*, vol. 5, no. 2, pp. 139–147, 2011.

[9] M. Di Luca, B. Knörlein, M. O. Ernst, and M. Harders, "Effects of visual–haptic asynchronies and loading–unloading movements on compliance perception," *Brain research bulletin*, vol. 85, no. 5, pp. 245–259, 2011.

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

[11] A. Metzger, A. Lezkan, and K. Drewing, "Integration of serial sensory information in haptic perception of softness." *Journal of Experimental Psychology: Human Perception and Performance*, vol. 44, no. 4, p. 551, 2018.

[12] C. Cellini, L. Kaim, and K. Drewing, "Visual and haptic integration in the estimation of softness of deformable objects," *i-Perception*, vol. 4, no. 8, pp. 516–531, 2013.

[13] B. Xiao, W. Bi, X. Jia, H. Wei, and E. H. Adelson, "Can you see what you feel? color and folding properties affect visual–tactile material discrimination of fabrics," *Journal of vision*, vol. 16, no. 3, pp. 34–34, 2016.

[14] M. Cavdan, K. Drewing, and K. Doerschner, "The look and feel of soft are similar across different softness dimensions," *Journal of vision*, vol. 21, no. 10, pp. 20–20, 2021.

[15] M. Cavdan, K. Doerschner, and K. Drewing, "Task and material properties interactively affect softness explorations along different dimensions," *IEEE Transactions on Haptics*, vol. 14, no. 3, pp. 603–614, 2021.

[16] O. Caldiran, H. Z. Tan, and C. Basdogan, "Visuo-haptic discrimination of viscoelastic materials," *IEEE Transactions on Haptics*, vol. 12, no. 4, pp. 438–450, 2019.

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

[18] V. C. Paulun, F. Schmidt, J. J. R. van Assen, and R. W. Fleming, "Shape, motion, and optical cues to stiffness of elastic objects," *Journal of vision*, vol. 17, no. 1:20, pp. 1–22, 2017.

[19] Y. Ujitoko and T. Kawabe, "Perceptual judgments for the softness of materials under indentation," *Scientific reports*, vol. 12, no. 1, pp. 1–11, 2022.

[20] Y. Ujitoko and T. Kawabe, "Visual estimation of the force applied by another person," *Scientific reports*, vol. 12, no. 1, pp. 1–9, 2022.

[21] M. Piovarči, D. I. Levin, J. Rebello, D. Chen, R. Ďurikovič, H. Pfister, W. Matusik, and P. Didyk, "An interaction-aware, perceptual model for non-linear elastic objects," *ACM Transactions on Graphics (TOG)*, vol. 35, no. 4, pp. 1–13, 2016.

[22] S. S. Center, "Tango (rubberlike)," https://support.stratasys.com/en/materials/polyjet/tango, (Accessed on 30/01/2023).

[23] W. Chu and Z. Ghahramani, "Preference learning with gaussian processes," in *Proceedings of the 22nd international conference on Machine learning*, 2005, pp. 137–144.

[24] E. Brochu, V. M. Cora, and N. De Freitas, "A tutorial on bayesian optimization of expensive cost functions, with application to active user modeling and hierarchical reinforcement learning," *arXiv preprint arXiv:1012.2599*, 2010.

[25] C. Alkhassim, "Gpro," https://github.com/chariff/GPro, 2021, (Accessed on 14/11/2021).

[26] J. W. Peirce, "Psychopy—psychophysics software in python," *Journal of neuroscience methods*, vol. 162, no. 1-2, pp. 8–13, 2007.

[27] J. Higgins, R. Blair, and S. Tashtoush, "The aligned rank transform procedure," in *Proceedings of the Conference on applied statistics in agriculture (USA)*, 1990.

[28] J. O. Wobbrock, L. Findlater, D. Gergle, and J. J. Higgins, "The aligned rank transform for nonparametric factorial analyses using only anova procedures," in *Proceedings of the SIGCHI conference on human factors in computing systems*, 2011, pp. 143–146.

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

[30] B. Efron and R. J. Tibshirani, *An introduction to the bootstrap*. CRC press, 1994.

[31] S. J. Lederman and R. L. Klatzky, "Hand movements: A window into haptic object recognition," *Cognitive psychology*, vol. 19, no. 3, pp. 342–368, 1987.

[32] F. Argelaguet, D. A. G. Jáuregui, M. Marchal, and A. Lecuyer, "Elastic images: Perceiving local elasticity of images through a novel pseudo-haptic deformation effect," *ACM Transactions on Applied Perception (TAP)*, vol. 10, no. 3, pp. 1–14, 2013.

[33] P. Punpongsanon, D. Iwai, and K. Sato, "Softar: Visually manipulating haptic softness perception in spatial augmented reality," *IEEE transactions on visualization and computer graphics*, vol. 21, no. 11, pp. 1279–1288, 2015.

© 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Haptics. 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/TOH.2023.3269016

V. Biography Section

Yusuke Ujitoko 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 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.

Takahiro Kawabe is a senior distinguished researcher, 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.

© 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.