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RESEARCH ARTICLE

Effect of Inconsistency in Perceiving Macro-Roughness of Virtual Texture on Real Object

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ABSTRACT When using Augmented Reality (AR) to overlay virtual textures onto real objects, a significant discrepancy between the tactile and visual characteristics of the real objects can cause users to experience dissonance. This study aims to quantitatively determine the acceptable range of differences in surface roughness that do not induce this dissonance. Specifically, it focuses on macro-roughness, characterized by spatial periods of 200 μm or more. The experiment system employed ensures accurate occlusion between the user's finger and virtual textures, a factor often neglected in most conventional studies. Adopting people occlusion in the AR environment reduces the burden on users, while ensuring that the sense of dissonance is not from occlusion rendering. Two materials were used in the experiments: acrylic and medium density fiberboard. The findings indicate that users are more sensitive to dissonance when the real object is rougher than the virtual texture, compared to the opposite case. Additionally, the friction magnitude between the materials and the user's finger was found to be proportional to the finger pressure applied. Based on this study's quantitative analysis of the visual-haptic interaction in AR environments, it provides a basis for further research on multisensory interactions and its applications, such as AR material design.

INDEX TERMS Multi-modal, pseudo haptic (or tactile), sense of dissonance, texture perception.

I. INTRODUCTION

Mixed Reality (MR) technology enables the overlay display of virtual objects in real space. By taking advantage of this characteristic of an overlay displaying different virtual textures on the surface of a real object, it is possible to visually present virtual textures of various materials on a single real object, while still allowing tactile feedback from the real object to be presented. Ohshima et al. have taken advantage of this, to enable multiple interior design considerations from a single car, both visually and haptically [1]. This study utilized multi-modal perception, in which, the interaction of the five senses influence perception, which in turn, provides tactile feedback, as if the user were actually touching the object being viewed. The influence of multi-modal perception in MR environments has been investigated in studies of visual-auditory and visual-olfactory-gustatory interactions [2], [3]. The commercial potential of MR technology has also been discussed in the field of industrial Augmented Reality (AR) [4], [5], [6], [7]. This creates the advantage of reducing the number of prototypes and mockups manufactured, thus reducing manufacturing costs and speeding up the manufacturing cycle. However, if the real object's texture differs significantly from that of the

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TABLE 1. Visual and haptic stimuli and hand occlusion in experiments of directly touching real objects with a finger.

Study	Research target	Visual stimuli	Haptic stimuli	Hand occlusion
Yamaguchi et al. [13]	Acceptable range of macro-roughness of textures	Textures displayed on a smartphone and a mirror	Real objects	No
Kitahara et al. [14]	Impression of textures (different or identical)	Textures displayed on an HMD	Real objects	Yes
Hirano et al. [15]	Sense of hardness	CGI animations displayed on an HMD	Real objects	Yes
Ours	Acceptable range of macro-roughness of textures	Textures displayed on an iPad	Real objects	Yes

virtual texture, the user may perceive a sense of dissonance when touching the real object; so, it is important to investigate the difference between the virtual texture and the acceptable range, at which, people do not perceive dissonance. Therefore, in this study, we investigated the acceptable range of surface roughness, so that users do not perceive dissonance when touching a real object overlaid and displayed with virtual textures.

According to Okamoto et al. [8], the characteristic parameters of an object consist of macro-roughness, micro-roughness, hardness/softness, temperature/cooling, and friction. From the duplex theory of texture perception [9], it is known that micro-roughness is determined by temporal cues, the velocity of vibration when moving a finger on a textured surface. In contrast, macro-roughness is determined by spatial cues, the shape and distribution of a textured surface. It is also known that the perception method differs with a spatial period of approximately 200 μm [10], [11], [12]. Therefore, we should conduct experiments without confusing micro-roughness with macro-roughness. Research has already been conducted on each of these parameters using real and virtual textures [13], [14], [15], [16], [17]. While the positional consistency between real and virtual textures is maintained in the research on micro-roughness, hardness, temperature, and friction [14], [15], [16], [17], it is not maintained in the research on macro-roughness. Therefore, in this research, we have analyzed the acceptable range of macro-roughness, that people perceive as a sense of dissonance, considering the positional consistency.

Few researchers have considered the positional consistency of virtual textures. One of the reasons for this, is the back-and-forth problem in AR technology. Currently, when AR technology is used on mobile devices, such as smartphones, virtual objects are not calculated or rendered in a way that considers the relationship between virtual textures and real objects. Therefore, virtual objects are displayed in front of any real objects. This study used the people occlusion technology to avoid drawing the area where the participants' fingers are overlaid on the virtual texture [18]. This method solves the back-and-forth problem, reduces participants' workload, and measures the acceptable range of roughness that a real object can represent, without causing a sense of dissonance.

This paper is organized as follows. Section II briefly reviews the related work, including methods using tactile devices, virtual hands, and real objects. Section III describes the experimental design and setup. Section IV presents the experimental procedure and results. Section V discusses the implications of the findings. Finally, Section VI concludes the paper and suggests directions for future research.

II. RELATED WORK

A. METHODS USING TACTILE DEVICES OR VIRTUAL HANDS

We considered that developing a method to perceive multiple tactile stimuli, even in the absence of real objects, such as the automobile reported in [1], could further reduce manufacturing costs. Several studies have explored tactile perception without real objects using tactile devices and virtual hands.

Culbertson et al. [19] emphasized the importance of matching physical properties such as friction, hardness, and texture to create realistic haptic virtual surfaces. Osama et al. [20] proposed a method for generating haptic textures using solid noise, simulating tactile sensations without physical objects. Balzarotti et al. [21] investigated the effects of Chai3D texture rendering parameters on texture perception, demonstrating how software parameters influence haptic experiences. Sato et al. [22] explored pseudo-haptic feedback to modify texture perception in a projected virtual hand interface, showcasing how visual and haptic cues can be integrated to enhance the realism of virtual textures without relying on physical surfaces.

Additionally, surface haptics, which provides tactile feedback on touchscreens, has been investigated by many researchers. İşleyen et al. [23] examined tactile roughness perception of virtual gratings through electrovibration, revealing how electrical stimulation can mimic realistic textures. Costes et al. [24] introduced Touchy, a visual method to simulate haptic effects on touchscreens, showing the importance of visual cues in enhancing tactile perception. Otake et al. [25] combined vibrotactile and electrostatic-friction stimuli in a tactile texture display, achieving substantial improvements in perceived realism and moderate effects on user behavior. These studies underscore the potential of integrating multiple sensory inputs to create more immersive and realistic haptic experiences on touchscreens, contributing significantly to the advancement of surface haptics technology [26].

However, these approaches have limitations in making participants perceive detailed shapes. Thus, we used real objects to investigate the acceptable range when participants directly touched them with their fingers.

B. METHODS OF DIRECTLY TOUCHING REAL OBJECTS WITH A FINGER

Yamaguchi et al. [13] investigated the acceptable range, and prepared test pieces with eight different widths of roughness: 0.2 mm, 0.6 mm, 1.0 mm, 1.4 mm, 1.8 mm, 2.2 mm, 2.6 mm, and 3.0 mm. Their experiment, which used a virtual texture displayed on a smartphone and test pieces, to investigate the acceptable range of the difference between visual and tactile perception, reported that the acceptable range was 0.561 mm when the real object had a roughness width of 1.0 mm, and that the acceptable range tended to greatly differ, depending on the real object's roughness width, especially when the virtual texture had an unevenness of 0.6 mm or more. However, in this study, the virtual texture was always displayed in front of the participant's finger because it was displayed on the smartphone screen. Therefore, participants need to consider the positional consistency between their fingers and the virtual texture during the experiment. Furthermore, in Yamaguchi et al.'s experiment, the macro-roughness of the virtual texture overlaid on the real object was changed gradually. Conducting experiments based on the method of limits allows for a clear calculation of the acceptable range. However, since the stimuli are applied only in a consistent direction, biases such as habituation and expectations may be introduced, leading to predictability.

Kitahara et al. [14] investigated how visual and haptic sensory cues interact and influence each other in an MR environment, focusing on the impressions of texture and edge sharpness. They used an MR system to superimpose computer-generated textures onto real objects and conducted subjective evaluations of texture and sharpness using materials such as stone, cork, unglazed tile, steel, and wood. Participants wore thin latex gloves to reduce haptic sensations and viewed computer-generated textures through a high-definition head-mounted display (HMD). The system maintained hand visibility using a skin color matting technique to prevent disruptions in haptic feedback. However, variability in individual sensory perception and the realism of computer-generated textures could affect the consistency and accuracy of subjective evaluations.

Hirano et al. [15] examined how MR visual stimulation affects the perception of hardness in real objects by superimposing computer-generated imagery (CGI) that deform differently from the actual physical deformation. Using an MR system with a video see-through HMD, participants pushed real urethane objects of varying hardness while viewing CGI animations showing different levels of dent deformation. The experiment measured perceived hardness using a 7-point scale and included combinations of real and virtual hardness. The system addressed hand occlusion by using extracting the hand's area from captured images in real-time, preventing the CGI rendering over the hand. However, the CGI deformation influenced the hardness perception rather than the urethane's actual hardness, potentially limiting the study's application to objects with similar properties.

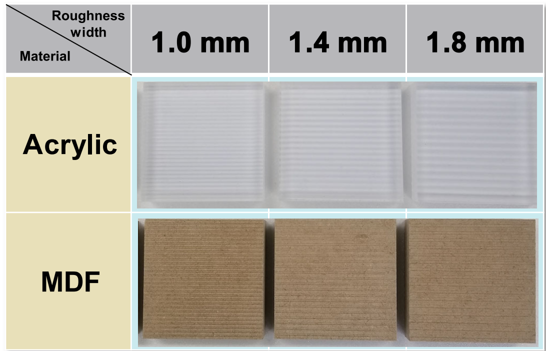

FIGURE 1. Real objects in the experiment.

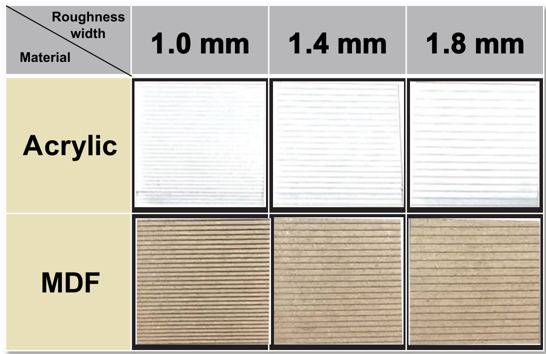

FIGURE 2. Virtual textures in the experiment.

Table 1 summarizes the devices and presence or absence of hand occlusion in studies where virtual textures are overlaid on actual textures to analyze roughness, hardness, etc., by directly touching the actual textures. In this study, to mitigate potential biases in determining the acceptable range, we adopted the method of constant stimuli. We ensure accurate occlusion between the user's finger and virtual textures, addressing a factor often neglected in conventional studies. By adopting people occlusion in the AR environment, we reduce the burden on users and ensure that any sense of dissonance does not arise from occlusion rendering. The specific experimental methodology will be discussed in the subsequent sections.

III. MATERIALS AND METHODS

A. REAL OBJECTS AND VIRTUAL TEXTURES

To investigate the effect of inconsistency in perceiving macro-roughness, this study presented participants with a virtual texture overlaid on a real object, and asked them to answer about their dissonance regarding the texture's macro-roughness when they first saw it, and after touching it. Fig. 1 shows the real objects and Fig. 2 shows the virtual textures.

Acrylic and Medium Density Fiberboard (MDF) were used as the real objects, and investigate the effect of inconsistency in perceiving macro-roughness. As acrylic has been used in related research [13], it was also used in this experiment. Considering the possibility, that differences in the material effect of the inconsistency of macro-roughness, MDF, which has a different texture from acrylic, was also used in these experiments. The surfaces of two types of materials were processed with unevenness of 1.0 mm, 1.4 mm, and 1.8 mm, using a machining center (VM40III, Hitachi Seiki Co., Ltd.), for a total of six different real objects. The differences in height between the concave and convex portions of the real objects were processed to be 0.3 mm. Each test piece's size was 40 mm wide, 40 mm deep, and 15 mm high. The six real objects were photographed from a 45-degree angle of elevation and used as virtual textures.

B. DESIGN

The experiment followed a within-subjects design with the two macro-roughness as levels of the independent variable (real objects and virtual textures). For each macro-roughness three variations are arranged: 1.0 mm, 1.4 mm, 1.8 mm.

C. EXPERIMENTAL ENVIRONMENT

Fig. 3 shows the experimental environment. Fig. 4 shows the experimental system, as seen from the viewpoint of participants. Participants were instructed to view only the virtual texture displayed on a tablet computer, and a wall made of styrofoam was placed, so that the test pieces were not visible. A tablet computer (iPad Air, 3rd generation, 10.5 inches) was used as a tablet computer to overlay the virtual texture on the real objects. The screen brightness was always set to maximum. If the participant was left-handed, the wall in front of the participant in Fig. 3 was inverted to the left and right. The Unity development platform (Version 2020.1.1f1) was used to implement the virtual texture display system.

A load cell (SC616C, Sensor and Control Company Ltd.), which measures the magnitude of force by the value of a strain gauge, was used under the test piece placement to determine how much force the participant applied to the test piece every 0.2 s.

The load cell was calibrated using a weight before each participant's experiment, to ensure that the value was within ±1 g when no force was applied. The microcontroller (Arduino UNO, Arduino) was used to control the load cell, and the A/D converter (HX711, Akizuki Denshi Tsusho Co., Ltd.) was used as an Analog/Digital converter. Given that, the proposed system did not draw the part of the virtual texture, that was overlaid on the participant's finger, there was a possibility that the area would be mistakenly detected as a finger, if a shadow was created between the test piece and finger. Therefore, a light (Dyson Lightcycle desk) was placed 36 cm above the test piece, and a 4600 K 100 lm light was constantly shined toward the test piece.

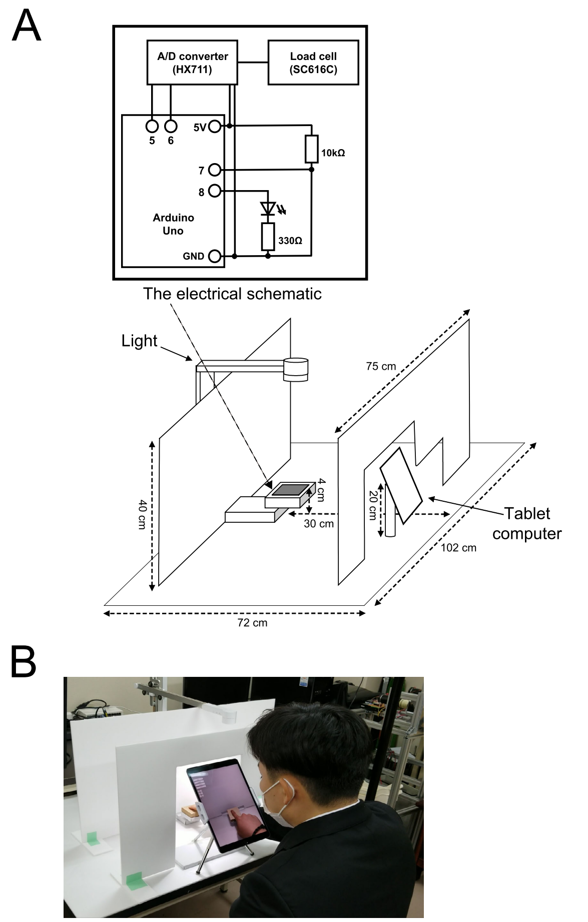

FIGURE 3. Experimental environment. (A) The electrical schematic and the system configuration diagram. (B) The implemented system.

IV. EXPERIMENT

A. PARTICIPANTS

This study involved 30 participants who were college students: 26 males and 4 females. The average age of the participants in the experiment was 19.4 years, with a range from 15 to 22 years. While 26 of them were right-handed, the others were left-handed. All of them had normal or corrected-to-normal vision, a decent physical condition without any upper limbs-related medical history, no experience of similar studies or any relevant measurement devices utilized in this experiment. The participants provided their written consent prior to participation in the research. All the experiments were performed in compliance with relevant guidelines and regulations. The study's protocol was approved by the ethics committee of the National Institute of Technology, Gunma College.

B. PROCEDURE

To measure the acceptable range, this study presented participants with a virtual texture overlaid on a real object, and asked them to answer about their dissonance regarding the texture's macro-roughness when they first saw it, and after touching it.

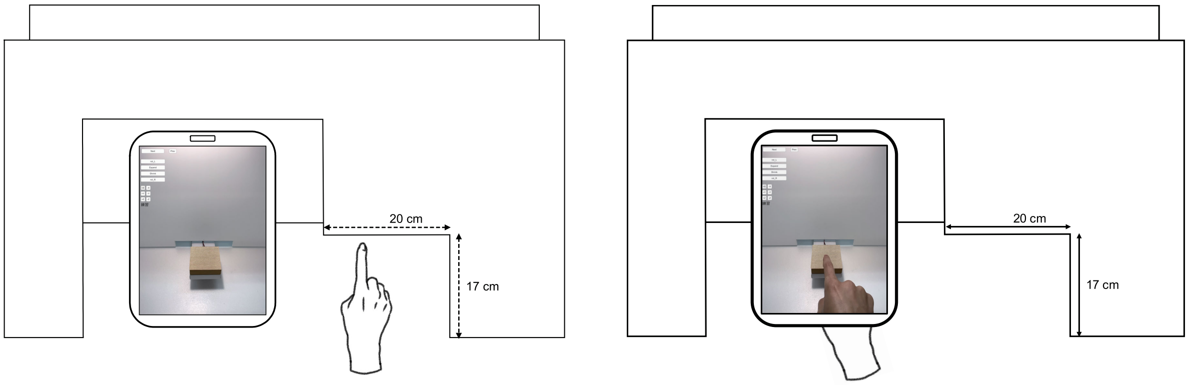

FIGURE 4. Experimental environment as seen by participants.

Prior to the start of the experiment, the participants were briefed about the survey, materials and types of the unevenness of the real object, method of creating the virtual texture, and finger pressure measurement using a load cell. They were then asked to answer a questionnaire, that included the following information: name, gender, age, dominant hand, dominant eye, visual acuity (right eye, left eye, and both eyes), and AR/MR status. Additionally, as a practice session, they were presented with randomly selected combinations of real and virtual textures, and asked to answer questions about their visual and haptic impressions of macro-roughness.

In this experiment, a virtual texture of acrylic was overlaid on the real object if it was acrylic, whereas a virtual texture of MDF was overlaid on the real object if it was MDF, for a total of 18 combinations. The order of the combinations was randomly changed for each participant to maintain a counterbalance. To investigate the acceptable range of macro-roughness, that a real object can represent without causing a sense of dissonance, the participants were asked to touch the center of the test piece from the back to the front with their dominant hand's index finger, and then answer the question about the difference in their tactile and visual impressions of the macro-roughness between the first time they saw the presented texture, and the time they touched it. Their answer method comprised a five-point semantic differential scale, that established whether "same," "almost same," "neither," "almost different," and "different."

Thus, the participants rated on a 5-point scale, the degree of similarity between the virtual and real objects in terms of macro-roughness. At first, we thought that more knowledge could be obtained by asking whether the virtual or real object was perceived as coarser, but as the impression of roughness is multidimensional [27], [28], we realized that it would be a difficult task for participants to answer this question in all the experimental patterns; so, we only collected their answers regarding whether the roughness of the real and virtual textures was the same. Given that, participants were asked to trace the test piece until they were able to answer the question about a sense of dissonance, we did not specify the number of times they were to trace, or set a time limit. With reference to the research by Yoshioka et al. [29], that the perception of roughness is constant when tracing real object's surface by active scans, no restrictions were set on the speed at which the test piece was traced. In addition, the effect of the difference in contact force due to pressing on the perceived roughness was relatively small. The strength of the force used to trace the test piece was not specified in the research by Roberts et al. [30].

After the experiment, participants were asked to answer another questionnaire, in which, they had to describe their dissonance regarding the distance between the tablet device and participant, distance between the tablet device and test piece, dissonance when their fingers were displayed in front of the virtual texture, dissonance regarding the color and unevenness of the virtual textures of acrylic and MDF when compared with the same type of real objects and other free descriptions. For the items that asked about the dissonance, a 5-point Likert scale with "no dissonance," "almost no dissonance," "neither," "almost dissonance," and "dissonance" was used to establish the level of dissonance.

C. RESULTS

1) ANSWERS TO DISSONANCE

Regarding the data analysis methods, IBM SPSS statistics V26 was used to carry out two-way repeated measures analysis of variance (RM ANOVA) tests at three levels; 1.0 mm, 1.4 mm, and 1.8 mm, for both, the virtual texture and real object factors, to numerically analyze the difference between real objects and their virtual texture. Mauchly's sphericity test ($p > 0.05$) was also executed to validate the results of ANOVA. For results, whose sphericity was not assumed ($p < 0.05$), the values corrected with Greenhouse–Geisser tests of within-participants' effects were

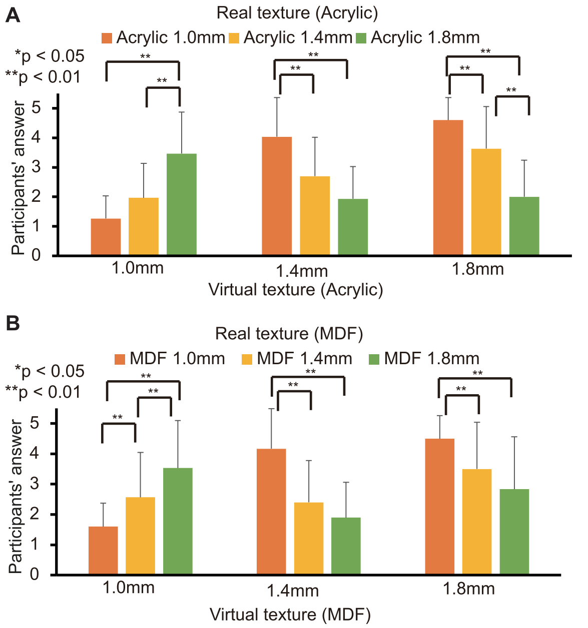

FIGURE 5. Results of analysis of acceptable ranges for the differences of macro-roughness in each test for: (A) Acrylic test pieces, (B) MDF test pieces.

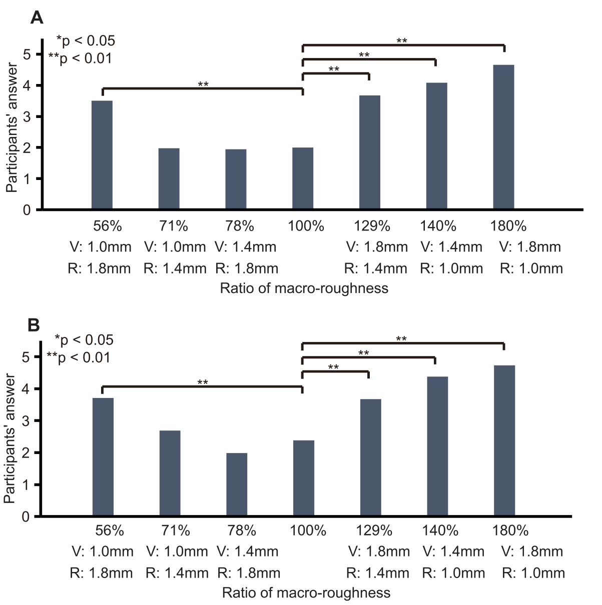

FIGURE 6. Results of analysis of when rearranging Fig. 4 for the ratio of macro-roughness in virtual textures to the macro-roughness of physical objects: (A) Acrylic test pieces, (B) MDF test pieces. The ratio was calculated by dividing virtual textures' macro-roughness by real objects' macro-roughness. "V" represents the macro-roughness of the virtual texture, while "R" indicates the macro-roughness of the real object.

employed. To verify the significance of each condition for real and virtual factors, the post hoc test was performed using the Bonferroni pairwise comparison test ($p < 0.05$).

The results of the two-way RM ANOVA are revealed in Fig. 5 (A). S1 Table shows the results of the statistical analysis for acrylic. Significance was found at the 1% level (Virtual texture: $F(2, 58) = 24.21$, $p < 0.0001$, partial $\eta^2 = 0.46$; real object: $F(2, 58) = 10.94$, $p < 0.0001$, partial $\eta^2 = 0.27$). The interaction between virtual textures and real objects was also significant at the 1% level ($F(3.42, 99.3) = 36.32$, $p < 0.0001$, partial $\eta^2 = 0.56$). These results indicate that the perceived macro-roughness is affected by the difference in the unevenness of the virtual textures and real objects, and the combination of their unevenness also affects the perceived macro-roughness. While the results of the post hoc tests are shown in S3 Table, only the conditions for which there were no significant differences are shown to clearly indicate the acceptable range. When the virtual texture was 1.0 mm, there was no significant difference between the real object of 1.0 mm and 1.4 mm ($p = 0.055$, CI: -1.412 0.012). Similarly, when the virtual texture was 1.4 mm, there was no significant difference between the real object of 1.8 mm ($p = 0.117$, CI: -0.134 1.668).

Next, the results of the two-way RM ANOVA are displayed in Fig. 5 (B). S2 Table shows the results of the statistical analysis for MDF. Significance was found at the 1% level (Virtual texture: $F(2, 58) = 14.57$, $p < 0.0001$, partial $\eta^2 = 0.33$; real object: $F(1.72, 49.87) = 10.94$, $p = 0.005$, partial $\eta^2 = 0.178$). The interaction between the virtual and real objects was also significant at the 1% level ($F(4, 116) = 19.173$, $p < 0.0001$, partial $\eta^2 = 0.40$). These results indicate that the perceived macro-roughness is affected by the difference of roughness between the virtual and real objects, whose combination of unevenness also affects the perceived macro-roughness. The results of the post hoc tests are indicated in S4 Table, but only the conditions for which there were no significant differences are shown, to indicate the acceptable range clearly. When the virtual texture was 1.4 mm, there was no significant difference between the real object of 1.4 mm and 1.8 mm ($p = 0.485$, CI: -0.385 1.385). When the virtual texture was 1.8 mm, there was no significant difference between the real object of 1.4 mm and 1.8 mm ($p = 0.388$, CI: -0.418 1.752). There was no significant difference between acrylic and MDF materials ($F(3.725, 216.053) = 1.589$, $p = 0.182$, partial $\eta^2 = 0.027$).

Fig. 6 show the results of analysis of when rearranging Fig. 5 for the ratio of macro-roughness in virtual textures to the macro-roughness of physical objects: (A) acrylic test pieces, (B) MDF test pieces. Only limited interpretations can be made from the results using three types of macro-roughness test pieces for each texture. We considered that by leveraging Weber's law, it would be possible to discuss the acceptable range for real objects with different macro-roughness based on the ratio of macro-roughness between the virtual textures used in this experiment and the real objects. Therefore, we conducted the analysis shown in Fig. 6. The bar labeled "100%" in the Fig. 6 represents the situation where the macro-roughness of the real object and virtual texture are the same. In this experiment, there are three patterns for each material where the macro-roughness of the real object and virtual texture are 1.0 mm, 1.4 mm, and 1.8 mm, respectively. To facilitate discussion on the acceptable range of macro-roughness in the following

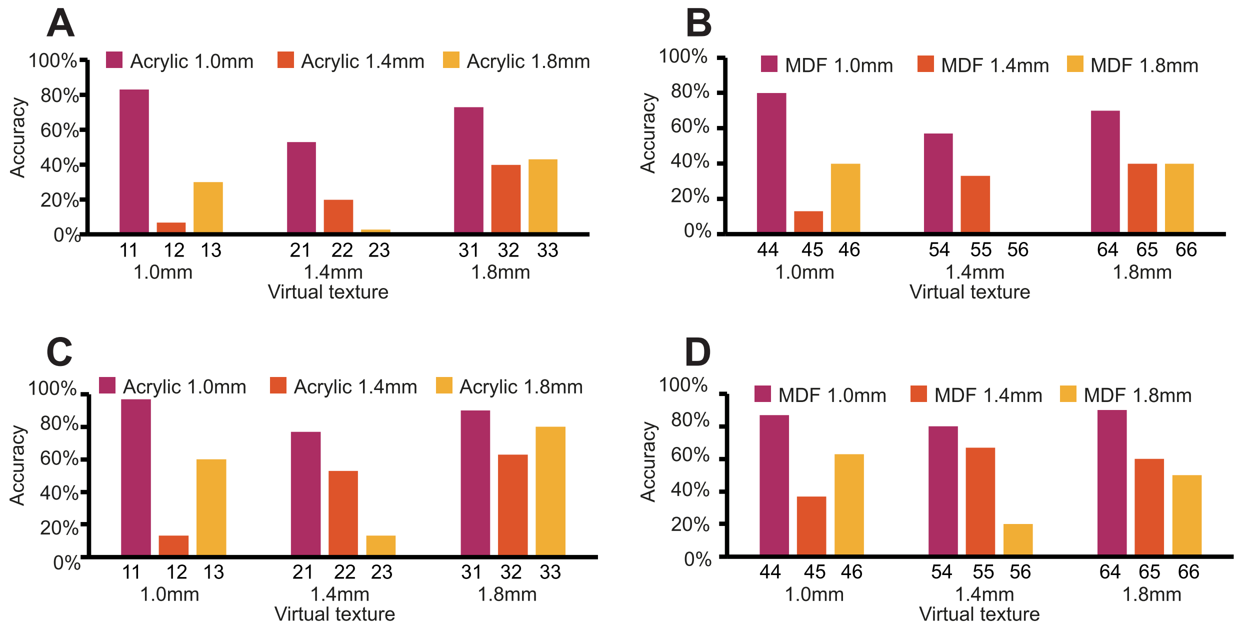

FIGURE 7. Accuracy rates for different unevenness widths across experimental patterns. (A) Accuracy rate 1 for Acrylic. (B) Accuracy rate 1 for MDF. (C) Accuracy rate 2 for Acrylic. (D) Accuracy rate 2 for MDF. The horizontal axis values represent types of virtual textures and real objects. 1: Acrylic (real/virtual) with 1.0 mm width. 2: Acrylic (real/virtual) with 1.4 mm width. 3: Acrylic (real/virtual) with 1.8 mm width. 4: MDF (real/virtual) with 1.0 mm width. 5: MDF (real/virtual) with 1.4 mm width. 6: MDF (real/virtual) with 1.8 mm width.

section, the average of the three patterns is shown as the "100%" bar.

2) PERCENTAGE OF PARTICIPANTS CORRECT

Participants answered on a 5-point Likert scale about their dissonance with the 18 combinations of experimental patterns. We calculated the accuracy rate from the results and correlated them with the finger pressure values and the number of seconds each participant traced the test piece. The results are shown in Fig. 7.

First, the participants' accuracy rate is shown. In this context, accuracy rate 1 is calculated as the correct answer for cases where the real and virtual textures either have the same macro-roughness and the participants answer "same" or different macro-roughness and the participants answer "different". The accuracy rate 2 is calculated as the correct answer only when the macro-roughness of the real and virtual textures is the same and the participant answers "same" or "almost same" or when the macro-roughness is different and the participant answers "different" or "almost different".

Around 40% and 61% of the participants had average accuracy rates of 1 and 2, respectively. For acrylic, the mean accuracy rates of 1 and 2 were 39% and 61%, respectively. For MDF, the average accuracy rates of 1 and 2 were 41% and 61%, respectively. Therefore, there was almost no difference in the accuracy rate between materials.

The accuracy rate for cases where the virtual texture was 0.4 mm narrower than the real object (12, 23, 45, 56) were lower than those for cases where the virtual texture was 0.4 mm wider than the real object (21, 32, 54, 65). In other words, more participants answered that both had the same macro-roughness. This applies to all combinations of virtual and real objects with interchanged unevenness, as well as to both acrylic and MDF materials. In other words, participants answered relatively more often, that they did not perceive dissonance in the macro-roughness when the unevenness width of the virtual texture was 0.4 mm narrower than that of the real object (12, 23, 45, 56). The correlations between the materials in Fig. 7 were 0.97 and 0.88 for accuracy rates 1 and 2, respectively.

3) TRENDS OF FINGER PRESSURE WHEN TRACING THE TEST PIECES

In this experiment, finger pressure was measured when participants traced the test piece for up to 3 s at a time [31], [32]. Fig. 8 shows the finger pressure values measured every 0.2 s after the participant touched the test piece, and that there was no obvious change in finger pressure. The average finger pressure under the acrylic and MDF test pieces were 28.6 g, and 37.3 g, respectively. Thus, the finger pressure for the MDF test piece was on an average 8.66 g higher than for the acrylic test piece.

V. DISCUSSION

The acceptable range of the macro-roughness shown in Fig. 5 indicates that for both acrylic and MDF materials, the real object of 1.0 mm and 1.8 mm significantly caused dissonance, regardless of whether the acceptable range of the

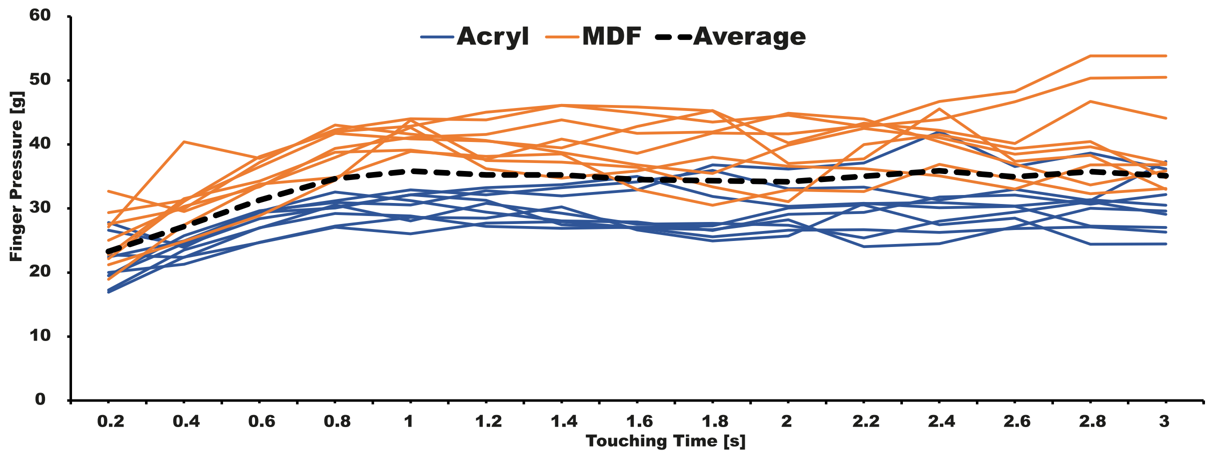

FIGURE 8. Average of participants' finger pressure in each experimental pattern (every 0.2 s).

virtual texture was 1.0 mm, 1.4 mm, or 1.8 mm. When the difference in macro-roughness between the real objects and virtual textures was less than 0.4 mm, there were both areas with significant differences and areas without significant differences.

Tactile sensation accounts for approximately only 4% of information judgments made by the five human senses. In contrast, vision accounts for approximately 70% [33]. This suggests that humans are visually dependent, and that the function of the sense of touch in relation to the macro-roughness of virtual textures is affected by this dependence. In addition, in their research, Yamaguchi et al. presented the acceptable range of macro-roughness to be 0.6 mm or less, and the results are consistent with this [13]. Participants in our study ranged in age from 15 to 22 years, and participants in Yamaguchi's study ranged in age from 22 to 25 years, so there is almost no difference in terms of age.

Fig. 6 shows the detailed trends of the acceptable range. As a result, there were all significant differences between the results of the participants' answers when the macro-roughness of the real objects and virtual textures were the same (fourth bar from the left) and those to the right of it (fifth to seventh bars from the left). While, in some cases, there was no significant difference between the results of the participants' answers when the macro-roughness of the real objects and virtual textures were the same and those to the left of it (first to third from the left). This suggests that, under the condition where a virtual texture is displayed on a real object and a finger is located in front of the virtual texture, the user perceives the inconsistency of the macro-roughness between both textures more sensitively in the case where the real object's texture is rougher than the virtual texture than in the opposite case. This result indicates that, for example, when preparing a mockup in the field of industrial AR and overlaying virtual textures of different macro-roughness on it to check the feel, a real object should be prepared with a lower spatial period than the average of the macro-roughness of the virtual textures in use.

Fig. 7 shows that there is not much difference in the percentage of correct responses between the experimental patterns with different materials and the same macro-roughness. Correlation analysis was performed on the accuracy rate data for acrylic and MDF, and a strong positive correlation was confirmed. As the accuracy rate was almost the same among the materials, it is considered that the difference in the acceptable range was not influenced by the change in material. As shown in Fig. 8, there were differences in finger pressure between the materials, suggesting that as friction increases when tracing the real object, finger pressure might also become stronger. A similar trend was observed in research using polyurethane test pieces by Roberts et al. [30]. Conversely, Tanaka et al.'s [34] research using sandpaper concluded that the magnitude of roughness is inversely proportional to finger pressure. The reason for this is thought to be, that aversiveness occurs when participants touch the test piece, especially with coarser sandpaper, resulting in lower contact force. The study's results are similar in trend to those of Roberta et al. However, while previous research [30], [32] reached their conclusions from a single test piece of material, this study unfolded the possibility about the magnitude of friction being proportional to finger pressure from two different materials: acrylic and MDF.

The limitations of this study include the use of only actual photographs as virtual textures, considering only three patterns for each physical object to determine an acceptable range. The reason for this is that the current experiment requires about 30 minutes per person, and increasing the number of experimental conditions increases the strain on the participants. In the future, we aim to expand the variety of test pieces used in experiments to investigate more detailed acceptable ranges. In addition, this study focused on examining the impact of texture variations on acceptable ranges using only two materials, acrylic and MDF. For future investigations, we intend to incorporate three or more types of materials to explore the correlation of acceptance ranges.

VI. CONCLUSION

In this study, we investigated the range, in which, macro-roughness does not cause a sense of dissonance by overlaying a virtual texture on top of a real object, which solves the positional consistency problem. We implemented an experimental system to investigate the acceptable range of macro-roughness using the people occlusion technique, in which, the area where the participants' fingers overlay on the virtual texture is processed, so that it is not drawn.

We conducted evaluation experiments using the proposed system, and statistically found that, under the condition where a virtual texture is displayed on a real object and a finger is located in front of the virtual texture, the user perceives the inconsistency of the macro-roughness between both textures more sensitively in the case where the real object's texture is rougher than the virtual texture than in the opposite case.

The study involved 30 participants, with 26 males and 4 females, and an average age of 19.4 years. Determining whether the findings can be generalized to older adults or younger children, who might have different sensory perceptions and motor skills, requires further research. Future work will include analyzing the effects of factors such as the gender and age of the participants, as well as the resolution of the camera and display.

LIST OF ACRONYMS

AR:	Augmented reality.
CGI:	Computer-generated imagery.
HMD:	Head-mounted display.
MDF:	Medium density fiberboard.
MR:	Mixed reality.
RM ANOVA:	Repeated measures analysis of variance

DATA AVAILABILITY

Data are fully available through the corresponding authors.

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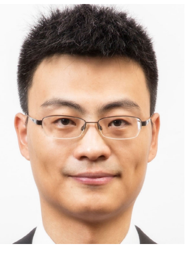

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