Analysis of Tactual Impression by Audio and Visual Stimulation for User Interface Design in Mixed Reality Environment

Mami Kagimoto[1], Asako Kimura[2], Fumihisa Shibata[1], and Hideyuki Tamura[1]

[1] Graduate School of Science and Engineering, Ritsumeikan University, 1-1-1 Noji-Higashi, Kusatsu, 525-8577, Shiga, Japan
[2] PRESTO, Japan Science and Technology Agency, 4-1-8 Honcho Kawaguchi, Saitama, Japan
kagimoto@rm.is.ritsumei.ac.jp

Abstract. In a mixed-reality (MR) environment, a touchable object can be made to change its appearance when a computer-generated image (MR visual stimulation) is superimposed onto it. In this research, we conduct experiments to study the effects of MR visual and audio stimuli on the tactual impression of the "roughness" of an object. We show that MR visual stimulation alters a subject's tactual impression of the roughness of an object and that the addition of MR audio stimulation intensifies that effect.

Keywords: Mixed Reality, Tactual Impression, Psychophysical Influence and Visual and Audio Stimulation.

1 Introduction

MR technology that merges real and virtual worlds has so far been investigated and implemented mainly in a visual sense [1][2]. MR is a powerful extension of conventional virtual reality (VR) technology, which deals with only a computer-generated electronic environment. The reason why MR is superior over VR is that everything in the experiencing environment need not be electronically modeled; that is, with MR, objects in the real world can be used without modification and only the necessary items are electronically modeled and merged to them.

There exist visual or auditory displays that are versatile and for general use. However, there are no displays in tactile or haptic functions, and only displays with the limited representative functions have been developed. In this regard, there is room for utilizing the MR technology. For example, a user would perceive the presence of a real object by grasping or pressing it, while electronic data is superimposed on it. The results of such studies could be highly useful for user-interface and other industrial design applications. For example, Ohshima et al. developed a system that enables automobile customers to test an automobile interior design in an MR environment (Fig. 1) [3]. Their system is capable of visual simulation of the interior design, where the customer touches real objects on which other images are superimposed in order to vary an object's color, shape, and material.

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However, this study raises a question: how is a user's tactile perception of an object affected by the object's visual appearance? He/she might be discomforted when touching, but the tactile sense could be affected by visual sense. To address this question, we conducted experiments to analyze the influence of "MR visual stimulation" in which texture images were superimposed onto real objects, on the tactile sense (specifically "roughness perception") [4]. We obtained the following results:

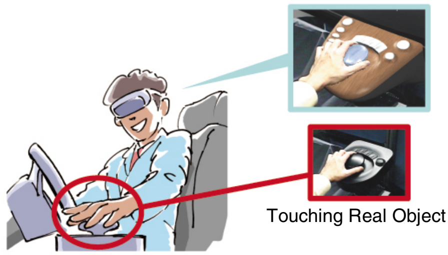

Fig. 1. Presentation of MR Visual Stimulation

- When objects of equal roughness appear to be of different roughness, people tend to perceive them to be tactually different.
- When objects of different roughness appear to be of equal roughness, people tend to perceive them to be tactually the same.
- In some cases, when a different material image is superimposed on a real object, people sometimes feel that they are touching an object of a different material.

Although these results did not occur in all cases, they did occur often enough to justify their use for industrial application, given the selection of suitable combinations of visual and tactual stimuli.

Moreover, these results suggest that one can intensify the limited "illusion of presenting materials" by changing the condition of presentation or adding other stimuli, which can be very useful for the simulation of user interface designs. For example, the sound generated when we touch an object (the "touch sound") also stimulates the audio sense. Thus, it is natural to suppose that the tactual impression (illusion) could be intensified by controlling the audio stimuli arbitrarily.

In this paper, expanding the systematic methodology of [4], we investigate how tactual impressions change with the addition of both visual and audio stimuli. Having found that the real touch sounds generated by touching experimental objects were insufficient for our experiment, we enhanced the touch sounds by mixing in friction and collision sounds. By making use of the sounds, we conducted the intended experiments and analyzed its results.

2 Related Work

Some studies exist on the influence of visual stimuli on the tactile sense. Lederman et al. [5] reported that when subjects looked at one sheet of sandpaper and touched another one of different roughness simultaneously, they perceived an intermediate roughness for both sandpapers. Biocca et al. [6] reported that subjects could feel physical resistance (e.g., gravity, inertia) while moving virtual objects with their first two fingers in a VR environment without any haptic devices. Based on these studies, Iesaki et al. [4] conducted experiments on the influence of MR visual stimuli. We also follow the same research approach.

Lederman et al. [7] studied the influence of audio stimuli on tactile sense. Subjects touched plastic plates with a patterned indented surface and evaluated the roughness of the plates under three conditions: only audio stimuli, only tactile stimuli, and both audio and tactile stimuli simultaneously. They reported that in the case presenting both audio and tactile stimuli, the subjects perceived the roughness to be intermediate between that with only audio and only tactile stimuli. Jousmäki et al. [8] reported that subjects felt their palmar skin to be drier when they heard the sound of hands rubbing together, amplified in the high-frequency range. Guest et al. [9] reported that subjects felt greater tactual roughness when they heard the sound of hands rubbing sandpaper, amplified in the high-frequency range. We focus on [8] and [9] using fabricated sounds different from the sound generated from the real object and adopt similar experimental methodologies.

3 Preparation and Evaluation of Audio Stimuli

3.1 Presentation Stimuli

Similar to the experiment in [4], we use tactual, visual, and audio stimuli, each with four levels of roughness (Fig. 2). We label the objects as follows: tactile stimuli Rough 1 to Rough 4, visual stimuli CGI 1 to CGI 4, and audio stimuli Sound 1 to Sound 4, in descending order of roughness. The real objects used in our experiments are rapid prototyping (RP) plates made from ABS plastic [11], whose roughnesses are fabricated to be discriminated tactually (Fig. 3). Similar to the experiment in [4], we use the pictured surface images of these plates as visual stimuli.

For audio stimuli, it is natural to use the touch sounds of the RP plates prepared for tactual stimulation without modification. However, as we recorded and compared the touch sounds of the four RP plates (Rough 1 to Rough 4), we found it difficult to discriminate among them.

Most people, when they touch an object without viewing it, cannot accurately guess the object's material or roughness from only the sound of touching the object. Conversely, when they view the object, they tend to presume what the touch sound will be produced. Our objective is to substantiate the existence of some type of "illusion", using touch sounds that emphasize their preconceptions. In other words, we create

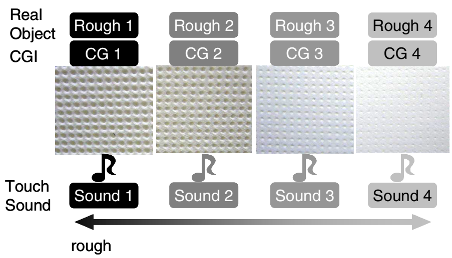

Fig. 2. Presentation Stimuli

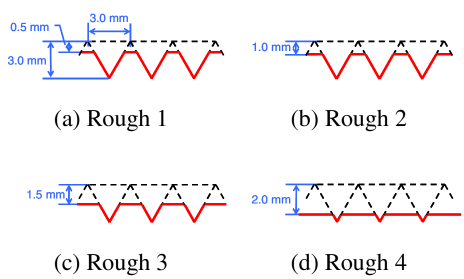

Fig. 3. Artificial Rough Surface (solid lines are the surface line)

"touch sounds" and use them as audio stimuli in the experiments. These sounds should hear like touching the experimental objects and should make the roughnesses of different objects distinguishable. We defined these sound "emphasized touch sounds" meet the following requirements:

- The sounds are created by modifying the real touch sounds of the RP plates.
- Each object's roughness is distinguishable according to four emphasized touch sounds.
- The sounds are as natural as the touch sounds of the RP plates.

3.2 Preparation and Evaluation of Audio Stimuli

Analysis of real touch sounds. As shown in Fig. 3, the surface of each experimental RP plate consists of indentations and flat areas. As scraping these surfaces by a palm or fingernails, touch sounds are generated. We break up the sounds, and define them as following;

- Collision sound: sound generated by hitting at a dent edge (Fig. 4 (a))
- Friction sound: sound generated by friction at a flat area (Fig. 4 (b))

Because a rougher object has deeper and larger dents and smaller flat areas, it is likely that sounds caused by touch of these objects are the result of more collision sounds and fewer friction sounds. For a smoother object, the opposite would be the case. Based on this idea, we thought that we could create touch sounds that enhance differences in roughness by controlling the mixing rate of collision and friction sounds.

Meanwhile collision and friction sounds differ in energy according to the hardness or material of the touching medium. For example, when an object is stroked with a rigid and smooth touch medium such as fingernails, the collision sound can be heard clearly but the friction sound cannot. In contrast, when an object is stroked with a soft touch medium such as a finger cushion, only the friction sound can be heard; the collision sound is absorbed by the finger.

We recorded the real touch sounds that are generated by stroking the four RP plates with fingernailss and palm, and performed a frequency analysis of each. The stroking speed is one round trip (about 30 cm) per second and the sampling frequency of the recorded sounds is 48 kHz. Figs. 5 and 6 show the frequency analyses results of these touch sounds (half round trip). We found that the touch sounds of fingernailss have cyclical high-frequency energy parts (streaky part in Fig. 5)—the rougher the object surface, the higher the energy. On the other hand, the touch sounds of palms did not vary with roughness (Fig. 6).

Creation of Enhanced Touch Sounds. From the results described above, we decided to create enhanced touch sounds using the touch sounds of a fingernails (containing much collision sound) and of a palm (containing much friction sound) as follows:

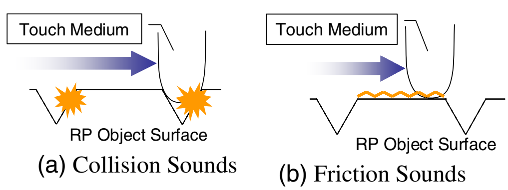

Fig. 4. Touch Sound Generated from RP Objects

(i) Normalize the fingernails and the palm touch sounds in all roughness to Rough 1. Each of the touch sounds of is clipped from the sounds recorded in 3.1. The length of each is one round trip (one second).
(ii) Attenuate fingernails touch sounds lower than 5 kHz by 20 dB. This is because the collision sounds of fingernails are too loud to mix without modification. At lower than 5 kHz, the energy of a fingernails touch sound is higher than that of a palm touch sound (Fig. 7), so the fingernails touch sounds are attenuated in this range to be natural after mixing.
(iii) Mix the fingernails and palm touch sounds at the rate shown in Table 1. In this step, the touch sounds of the RP plate corresponding to each roughness are mixed.
(iv) Normalize the mixed sound for all roughnesses to the sound of (i).
(v) Amplify the sound of (iv) at the rate shown in Table 1 to make the sound of rougher objects louder.

Evaluation Experiment. We conducted two preliminary experiments to determine whether subjects could distinguish the roughnesses of the four RP plate surfaces by hearing the four groups of audio stimuli (touch sounds of group A to D), and whether the sounds were as natural as the touch sounds of the RP plates shown in Fig. 2. We presented four round trips of the audio stimuli to 16 subjects with normal auditory sensation. The experimental description is as described below.

Preliminary Experiment 1

(1) The four audio stimuli of each group are presented one by one randomly. The interval time between each presentation is 1 second.
(2) After hearing all sounds, subjects report the order of roughness of the four audio stimuli.
(3) Step (1) and (2) are conducted in all groups (A to D) randomly.

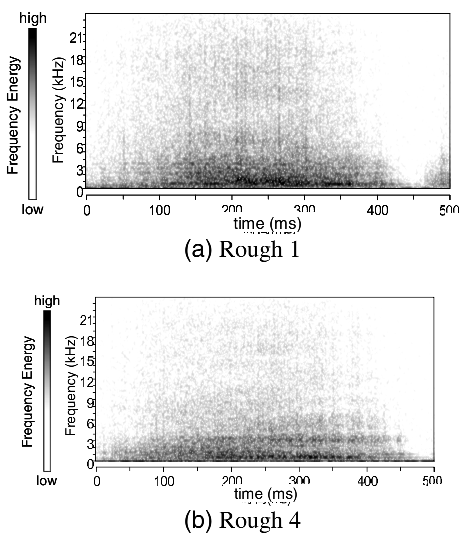

Fig. 5. Frequency Analysis Result of the Touch Sound (Fingernails)

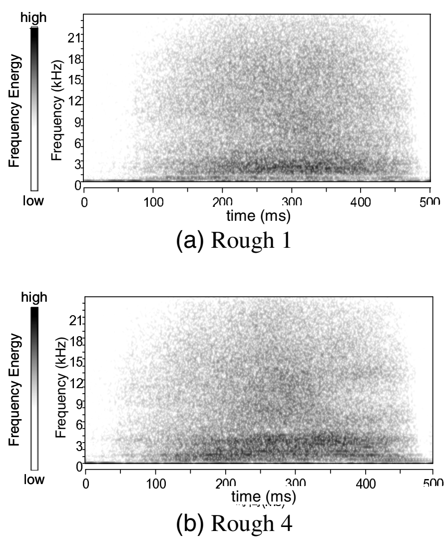

Fig. 6. Frequency Analysis Result of the Touch Sound (Palm)

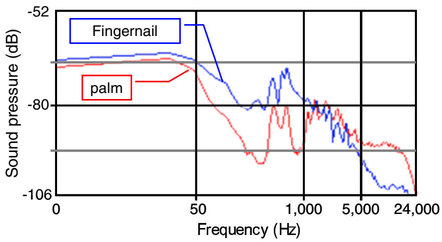

Fig. 7. Difference of Frequency Energy between Fingernails and Palm Touch Sound

Table 1. Fabricated Audio Stimulation

		Sound 1	Sound 2	Sound 3	Sound 4
The fingernail sound rate		1.0	1.0	1.0	1.0
Audio Stimuli A	The palm sound rate	0.9	1.0	1.1	1.2
	The amplification rate after the	1.1	1.0	0.9	0.8
Audio Stimuli B	The palm sound rate	0.9	1.0	1.1	1.2
	The amplification rate after the	1.2	1.0	0.8	0.6
Audio Stimuli C	The palm sound rate	0.8	1.0	1.2	1.4
	The amplification rate after the	1.1	1.0	0.9	0.8
Audio Stimuli D	The palm sound rate	0.8	1.0	1.2	1.4
	The amplification rate after the	1.2	1.0	0.8	0.6

Original sound volume: 1.0

Preliminary Experiment 2

(1) The four RP plates are placed in order of roughness in front of the subject, and the audio stimuli corresponding to each plate is presented in order. Only the groups of audio stimuli (group B and D) are used whose order was answered correctly in Preliminary Experiment 1. The presentation of audio stimuli is as for Preliminary Experiment 1.

(2) Subjects answer whether the four sounds are associated with each RP plate appearance.

(3) Step (1) and (2) are conducted in groups B and D randomly.

In Preliminary Experiment 1, the number of subjects who answered the order of roughness correctly are, in descending order, 13 in group D, 9 in group B, 7 in group C, and 6 in group A; all subjects answered correctly at least either group B or D. This result indicates that the difference of roughness in audio stimuli could be emphasized through the above procedure. In Preliminary Experiment 2, 13 out of 16 subjects answered that the audio stimuli of group B and/or D are associated with each RP plate appearance. Therefore, for this study, we adopted group B and D as the enhanced touch sounds that satisfied the three requirements in 3.1.

4 Experiment 1: Using Objects of Equal Surface Roughness

4.1 Purpose

Iesaki et al. [4] showed that the tactile sense was affected by MR visual stimuli under the following conditions:

- Two real RP plates of equal surface roughness are apposed.
- Two texture images of different surface roughness are superimposed onto each real object.
- The subjects answer which RP plate they tactually perceive to be rougher under the pair comparison method.

In this experiment, we investigate whether the touch impression is intensified by the addition of audio stimuli (enhanced touch sound), as compared to only MR visual stimuli. Specifically, we conduct experiments under the following two conditions and compare the results:

1a: Present combinations of a real object for touching, an audio stimulus with corresponding roughness, and a visual stimulus with noncorresponding roughness (similar to [4], except that natural touch sounds were presented in [4]).
1b: Present combinations of a real object for touching, and audio and visual stimuli with noncorresponding roughness.

4.2 Descriptions

Environment. Fig. 8 shows the experimental environment. The MR system configuration used in this study is similar to [4]. Subjects watch the MR space through a head-mounted display (HMD), and their head position and orientation is constantly tracked by a 3D laser tracker (Ascension laserBIRD). They hear the audio stimuli through inner-ear earphones (SANWA SUPPLY MM-HP106W) and wear earmuffs over them to insulate the real touch sounds generated when they actually stroke the objects.

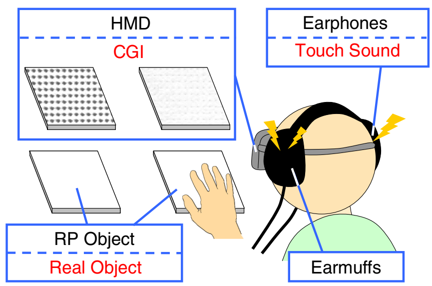

Fig. 8. Experimental Environment

Condition. Participants included 13 subjects who correctly associated enhanced touch sounds with object surface appearances in Preliminary Experiment 2. As the audio stimuli (enhanced touch sounds of group B or D) were presented, each subject answered associable with the roughness in Preliminary Experiment 2. The presentation time is six seconds, stroking one round trip per second. Preparation and procedure are as in Experiments 1a and b.

Preparation. (1) The subject practices stroking the RP plate, synchronizing hand motion with the touch sound. (2) He/she learns the roughness of touch sounds corresponding to the texture images. The four images of different surface roughness are placed in front of him/her wearing the HMD, and touch sounds corresponding to the roughness of the images are played.

Procedure. (3) Two RP plates of equal roughness, selected randomly, are placed in front of him/her. (4) Two texture images of different roughness are superimposed onto each object. (5) He/she strokes the RP plates one by one, just after each touch sound plays. Then he/she answers which plate is perceived to be tactually rougher (and is allowed the answer "indistinguishable"). (6) The RP plates are exchanged randomly, and steps (3) to (6) are repeated until all combinations of stimuli are presented.

4.3 Result and Discussion

Fig. 9 shows the result of Experiment 1. When only visual stimuli are changed (Experiment 1a), subjects tend to judge the visually rougher objects to be tactually rougher. In addition, they tend to judge the smoother objects to be indistinguishable (Rough 3 and Rough 4). In other words, the rougher surface object (Rough 1 and Rough 2) tends to be tactually perceived as being rougher by visual stimulation. These results are consistent with our previous study [4].

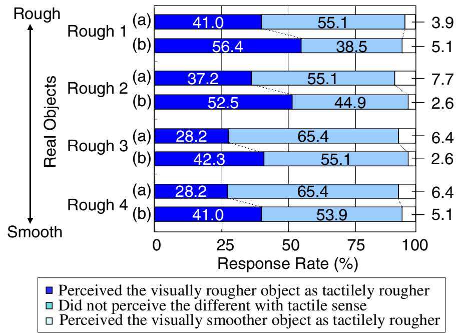

Fig. 9. Result of Experiment 1

When both visual and audio stimuli are changed (Experiment 1b), the percentage of subjects who felt the difference in roughness between two objects increases by 12–15% for all objects, as compared to Experiment 1a. Indeed, many subjects commented that when both visual and audio stimuli were changed, they perceived two identical objects to be tactually different. In addition, the tendency for rougher objects to be more affected by visual stimuli than smoother objects is as reported for Experiment 1a; however, in Experiment 1b, the number of subjects who felt the difference in roughness increases even for Rough 3 and Rough 4.

These results confirm that the influence of tactual impression (illusion) is intensified by adding both visual and audio fakes.

5 Experiment 2: Using Objects of Different Surface Roughness

5.1 Purpose

In Experiment 1, we confirm that the influence of tactual impression (illusion) is intensified by appending audio stimuli. In Experiment 2, we focus on the case of two real objects of different surface roughness. Specifically, we address two issues:

– Can a subject experience similar (Experiment 1) touch impressions when touching objects of different surface roughness?
– Can a subject perceive a rougher object (with appended visual and audio stimuli of smoothness) to be smoother than a smoother object (with appended stimuli of roughness)?

5.2 Descriptions

The experimental procedure (including environment, subjects, and stimuli) is as for Experiments 1a and b, except that objects are of different roughness. Objects are limited to only two RP plates (Rough 2 and Rough 3), so as to limit the trials to a number that avoids subject exhaustion and unwillingness or inability to continue.

5.3 Result and Discussion

When only visual stimuli are changed (Experiment 2a), the smoother object is perceived to be rougher than the rougher object 5.3% of the time and to be indistinguishable from the rougher object 10.1% of the time. When both visual and audio fakes are presented (Experiment 2b), these numbers change to 2.4% and 16.8%, respectively (the latter a 6.7% increase from the result of Experiment 2a) (Table 3). When both visual and audio stimuli of the same roughness are presented (Fig. 3 boxed cells), the percentage of subjects who perceive them to be indistinguishable grows to 46.2% (a 38.5% increase from Experiment 2a). These results show that by adding audio fake to its visual counterpart, differences in roughness become difficult to distinguish.

6 Conclusion

In this paper, we confirm that the tactual impression of the roughness of an object is intensified when audio stimuli are added to MR visual stimuli. As the real touch sounds generated by touching the experimental objects were not appropriate audio stimuli for the experiment, we created the audio stimuli (enhanced touch sounds), which were associated with the visual stimuli. Then we conducted the systematic and objective experiments.

We found that tactual impressions are intensified in the following cases:

– When subjects touch two objects of identical roughness, one of which is supplemented by visual and audio stimuli of different roughness from the object, they perceive the objects to be of different roughness.
– When subjects touch two objects of different roughness, one of which is supplemented by visual and audio stimuli of the same roughness as the other object, they find it difficult to perceive any difference in roughness.

As with the presentation of only MR visual stimuli, the results of these experiments are not applicable for every situation. However, they indicate that it is possible to intensify an intended illusion by selecting suitable stimuli. In other words, an impression can be changed (that is, one can be tricked more easily) by the addition of

Table 2. Result of Experiment 2b Number of Subjects Who Perceive Rough 3 as Rougher

		Real Object	Rough 3			
		CGI	CG 1	CG 2	CG 3	CG 4
Real Object	CGI	Touch Sound	Sound 1	Sound 2	Sound 3	Sound 4
Rough 2	CG 1	Sound 1	0 (+0)	0 (+0)	0 (+0)	0 (+0)
	CG 2	Sound 2	3 (+3)	0 (+0)	0 (+0)	0 (+0)
	CG 3	Sound 3	4 (+1)	1 (+0)	0 (+0)	0 (+0)
	CG 4	Sound 4	4 (+1)	1 (-1)	3 (+1)	0 (+0)

unit: Number of People

※ the number in parenthesis shows increase-decrease values compared with the results of (a)
: present same roughness CGI and touch sound
: present smoother stimulation on rougher object and rougher stimulation on

Table 3. Result of Experiment 2b Number of Subjects Who Perceive the Objects to Be Indistinguishable

		Real Object	Rough 3			
		CGI	CG 1	CG 2	CG 3	CG 4
Real Object	CGI	Touch Sound	Sound 1	Sound 2	Sound 3	Sound 4
Rough 2	CG 1	Sound 1	8 (+7)	2 (-1)	0 (+0)	0 (-1)
	CG 2	Sound 2	1 (-3)	6 (+4)	0 (-0)	0 (+0)
	CG 3	Sound 3	0 (-1)	2 (+0)	3 (+2)	0 (+0)
	CG 4	Sound 4	1 (+0)	2 (+1)	2 (+0)	7 (+7)

unit: Number of People

※ the number in parenthesis shows increase-decrease values compared with the results of (a)
: present same roughness CGI and touch sound
: present smoother stimulation on rougher object and rougher stimulation on

sounds. It is not easy to categorize and select suitable objects and stimuli; however, the existence of these objective facts is helpful for developing various MR application systems including product visualization for user interface design evaluation.

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