Psychophysical Influence of Mixed-Reality Visual Stimulation on Sense of Hardness

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ABSTRACT

In a mixed-reality (MR) environment, the appearance of touchable objects can be changed by superimposing a computer-generated image (CGI) onto them (MR visual stimulation). At the same time, when humans sense the hardness of real objects, it is known that their perception is influenced not only by tactile information but also by visual information. In this paper, we studied the psychophysical influence on the sense of hardness by using a real object that has a CGI superimposed on it. In this experiment, we deform in an extreme way the CGI animation on the real object, while the subject pushes the real object using his/her finger. The results of the experiments found that human subjects sensed different hardnesses by emphasizing the dent deformation of the CGI animation.

KEYWORDS: Mixed Reality, Sense of Hardness, Psychophysical Influence, Visual Stimulation

1 INTRODUCTION

This paper describes the influence of visual stimulation on tactual sense in a mixed-reality (MR) environment, i.e., how the sense of hardness of a real object is affected by seeing a superimposed image of hardness different from that of the real object.

MR technology [1][2] has two features: first, objects that exist in the real world can be directly used, and second, only the desired information can be superimposed on the objects with no change in tactual sense. In other words, users have tactile feelings of real objects, and at the same time, can view superimposed digital data only visually [3].

In such situations, the following question may arise: how does the user perceive if the hardness of the object is different between the visual and tactile senses? He/she might feel discomfort, but the tactile sense could be affected by the visual sense. If it is veridical, it could be a kind of illusion. It is extremely interesting from a scientific viewpoint to investigate situations in which this influence (illusion) occurs and how it behaves.

Therefore, we have systematically performed various experiments that deal with the influence on the tactile sense by "MR visual stimulation". We have already indicated that when objects with different roughness are presented to both the visual and tactile senses, and its tactile stimulus is given over a certain threshold of roughness, human subjects perceive the objects tactually different, even though the objects have no physical difference [4]. This means that the tactile impression can be changed intentionally by receiving the appropriate visual stimulation. Next, we added an auditory stimulus representing the roughness/smoothness to the visual and tactile stimulus of the earlier experiment. In this experiment, it was confirmed that the foregoing influence was amplified by the auditory stimulation [5].

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As a next step, we focus on the sense of hardness. It is known that when a human perceives an object's hardness, his/her sense is affected not only by touch information but also by visual information [6][7]. So what happens when a human pushes a real object and it deforms differently from the real object only in a visual way? Could it happen that a hard object is perceived softer than a soft object, when a CGI representing the soft object is superimposed on the hard object and a CGI representing the hard object is superimposed on the soft object?

In this study, we conduct an experiment to verify whether a change in appearance by MR visual stimulation can influence human hardness perception. Additionally, in the next experiment, an alternation in perception is investigated. In this paper, we describe these intended experiments and analyze the results.

2 RELATED WORK

Some studies have reported that visual stimulation affects the tactile sense. Biocca *et al.* indicate that subjects could feel physical resistance (e.g., gravity, inertia) while moving some virtual objects with their first two fingers in a VR environment without any haptic devices [8].

Other studies have reported that the sense of hardness could also be affected by information regarding the appearance of an object. Pressman *et al*. [9], Mochizuki *et al*. [10], and Knorlein *et al*. [11] revealed that objects are perceived softer when force feedback is delayed. For instance, Knorlein *et al*. conducted an experiment in which visual information was presented slightly later than tactual information by using PHANToM (SensAble Technologies Inc.) as a haptic display and a head-mounted display (HMD) as a visual display. It was found that because of the delay between these two senses, the subjects felt that the object was softer than in the case without the delay.

In contrast, we aim to confirm that an illusion of hardness can occur when CGI that represents hardness different from the real one is superimposed on a real object by means of various systematic experiments.

3 PURPOSE AND PREPARATION

3.1 Purpose of Our Study

To confirm the illusion of the hardness, we conducted two experiments. In the first experiment, to verify whether a real object with the same hardness was perceived as harder or softer than another real object, three CGI animations with different deformations were superimposed in turns on the real object, while the subjects pushed down the real object.

In the second experiment, we examined whether the reverse phenomenon in hardness perception would be observed, by presenting MR visual stimulations on real objects with different hardness whose CGI animations were inverted in deformation. For example, a soft real object was superimposed on a CGI animation that is hard and changes little in shape, and a hard real object was superimposed on a CGI animation that is soft and changes in shape significantly. In these experiments, the animations were deformed depending on the finger action of the subjects.

3.2 Preparation of Experiments

[Experimental Environment]

As shown in **Fig. 1**, in the following experiments, we adopted an MR system with a video see-through mechanism which merges the real and virtual worlds visually [12]. Wearing an HMD VH-2002 (Canon Inc. Display resolution is 640x480 and running frame rate is 30fps.) in which a pair of video cameras is built, the subject can view the stereoscopic images that are composed by CGI in the scene in front of his/her eyes. In other words, the subject can see the CGIs that have been texture-mapped onto the objects with high geometric precision. The head position is constantly tracked in 6-DOF by a magnetic sensor 3SPACE FASTRAK (Polhemus Inc.), thus the subject can move his/her head freely. The position and rotation of the real objects were previously measured.

In the experiment, the CGI animation is deformed according to the depth of the indention by a subject's finger into the real objects. To measure this depth value, a bend sensor is attached to the top center of the real-object surface (**Fig.2**). A marker is placed on the middle of the bend sensor, so that the same place on the sensor is pushed by all of the subjects.

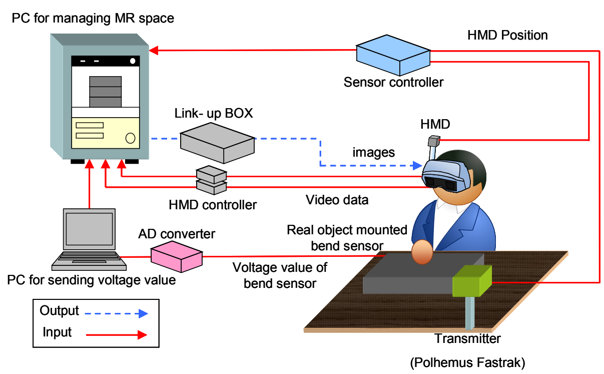


Fig. 1 System configuration.

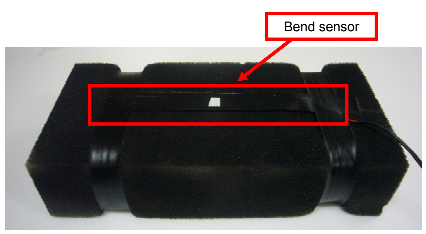


Fig. 2 A bend sensor is attached on the top center of the real object surface.

(a) Without masking. (b) With masking.

Fig. 3 Extracting hand's area.

Table 1 Type of urethanes.

Name of Urethane	Density	Hardness
Urethane 1 (hard)	40 ± 4.0 kg / m3	E 26
Urethane 2 (soft)	35 ± 3.0 kg / m3	E 15
Urethane 3 (softer)	16 ± 1.5 kg / m3	E 8

Hardness: Value measured with a hardness meter JIS K 6253 type E

When the CGI is superimposed onto an object in the real scene, the CGI is inevitably rendered in the foreground. Then, as a general problem, the user's hand is hidden by the CGI. We solve this occlusion problem, since the results of our primary experiment showed that the user's feeling of touching the object increased with image of his/her hand moving. We utilized the video see-through mechanism, and extracted the area of the hands from the captured images in real time in order to mask the area. Thus, the CGI was not rendered in the area of the hand. **Fig. 3** shows the result of this process.

[Experimental Object and CGI]

Fig. 4 shows a scene of the experiments. As the real objects used in the experiments, urethanes are employed because of their simplicity of shape and a wide variety of hardness. We used three different urethanes (INOAC Inc.) with tactually-perceived different hardnesses (**Table 1**). Their shape was a flat surface (W 210 × D 105 × H 50 mm).

As the CGI animations on the urethane, we prepared three animations, CGI-CG3, as shown in **Fig. 5**, which represent and emphasize the dent deformations of the urethanes with different hardnesses. When the real object is pushed, the top surface of the CGI sinks at the position corresponding to the pushed position of the real object and rises in the area around there (**Fig. 5**). Each CGI animations' depth of sinking is as following;

(a) CGI 1: Maximum depth of sink is 10 mm (Fig. 5 (b))
(b) CGI 2: Maximum depth of sink is 20 mm (Fig. 5 (c))
(c) CGI 3: Maximum depth of sink is 40 mm (Fig. 5 (d))

They were then texture-mapped onto the geometric models of the real objects.

Hereinafter, we call the stimuli *Urethane 1* to *Urethane 3* and the texture images *CGI 1* to *CGI 3; Urethane 1* and *CGI 1* correspond to the maximum hardness and *Urethane 3* and *CGI 3* to the minimum. The hardness was previously evaluated for visual and tactual stimulation, respectively and independently, and it was confirmed that the order of roughness was the same as we expected.

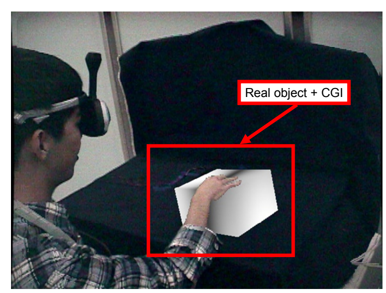
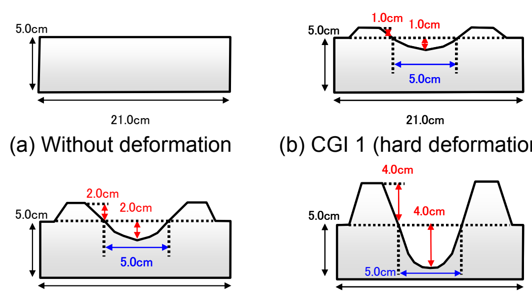


Fig. 4 Experimental scene.



(a) Without deformation (b) CGI 1 (hard deformation)

(c) CGI 2 (soft deformation) (d) CGI 3 (softer deformation)

Fig. 5 CGI animations.

4 EXPERIMENT 1

4.1 Procedure

The experimental procedure to confirm the illusion of hardness is as described below:

(1) A real urethane object is apposed in front of the subject wearing the HMD.

(2) Two of the three CGI animations (Fig. 5) representing different hardnesses are selected and superimposed onto it alternately.

(3) The subject pushes the real object with his/her middle finger while watching the CGI animation through the HMD, and answers how he/she tactually perceives the first MR stimulus as compared with the second. The answer is selected from a seven-point scale (−3 (very soft) to +3 (very hard)).

(4) Two CGI animations are selected randomly, and steps (1) to (3) are repeated until all combinations of the three CGI animations are selected.

Since elastic objects like urethane have a characteristic that the stronger it is pressed, the more repulsion force it produces, if the pressing depths of each trial are not constant, this repulsion force could influence the hardness perception. Therefore, the system beeps when the urethane is pushed until a certain depth. The subjects are taught to press the urethane until the beep and not to press it further.

This sequence of experiments is applied to all the three urethanes with different hardnesses. Each experiment using a different urethane is performed after an interval of more than a day to avoid the influence of the hardness impression from the previous experiment. After all the urethanes experiments, the subjects are asked for comments.

The collected answers from the fifteen subjects were calculated by the pair comparison method to obtain a psychological scale. Some biases would appear in the results if the hardness impression was influenced by MR visual stimulation. The results were analyzed and compared to investigate whether the illusion of hardness occurs, and whether the results are different between urethanes with different hardnesses.

4.2 Result

Fig. 6 shows the result of experiment 1. Each axis shows the psychological scale of hardness impression for each tactual stimulus (*Urethane 1* to *Urethane 3*). The arrows and the values on the axes describe the degree of the tactually perceived hardness for each visual stimulus. The smaller value means that the subject has tactually perceived the object as softer, and the larger value means that the subject has tactually perceived the object as harder. The results can be summarized as follows:

(a) There are always significant differences ($P<0.01$) between the psychological scales of the CGI animations with different dent deformations, regardless of the difference in tactual stimulation (difference of urethane).

(b) The larger the CGI animation is dented, the softer the subjects have tactually perceived, regardless of the difference in tactual stimulation.

(c) The psychological scale distances between *CGI 1* and *CGI 2* are always closer than those between *CGI 2* and *CGI 3*, regardless of the difference in tactual stimulation. The maximum sinking depths of CGI animations are not equally distanced (10, 20, and 40mm) and their ratios are similar to those of the psychological scale distances.

(d) The results of the experiments using the three different urethanes show the same tendency of hardness perception.

From result (a), we find that the MR visual stimulation influences the hardness perception of most subjects. In addition, from results

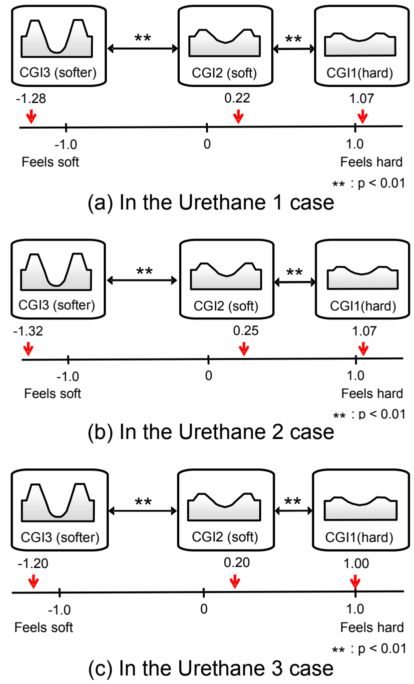


Fig. 6 Result of experiment 1. There are always significant differences between the psychological scales of the CGI animations with different dent deformations, regardless of the difference in tactual stimulation.

(b) and (d), it is indicated that the visual sense has a significant impact on the human hardness perception, and the hardness perception with MR visual stimulation is less affected by the difference of real object hardness within the hardness range of the urethanes used in this experiment. The subjects' comments such as "I could feel the difference of hardness easier when the dent deformation of CGI animation was large" "I knew that I pushed the same real object but I felt the hardness of the object changed when different CGI animation was displayed on it" also supported these. Result (c) shows that the sinking depth of the CGI animation greatly affects the hardness perception.

In this experiment, there were differences in the influence among individuals; however, no subject perceived the object superimposed soft CGI animation hard or the object superimposed hard CGI animation soft.

5 EXPERIMENT 2

5.1 Procedure

In experiment 2, we examine whether the reverse phenomenon in hardness perception is observed. The procedure of this experiment is as described below;

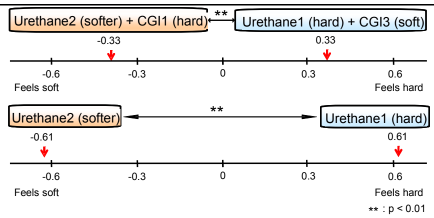
(1) Two of the three urethane objects with different hardnesses are selected randomly and apposed in front of the subject wearing the HMD.

(2) Two CGI animations (*CGI 1* and *CGI 3*) are superimposed onto them in the combination shown in **Table 2**.

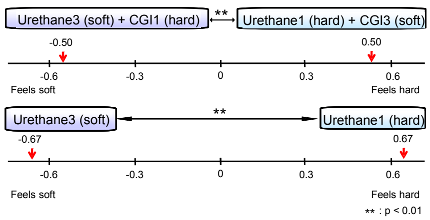
(3) The subject pushes the real object with his/her middle finger while watching the CGI animation through the HMD, and answers how he/she tactually perceives the first MR stimuli compared with the second. Since, in this experiment, differences in hardness are not very clear between the stimuli compared with experiment 1, the answer is selected not from a 7-point scale but from a 5-point scale (-2 (soft) to +2 (hard)). The subjects push the urethane in the same manner as experiment 1.

Table 2 Combination of real objects and virtual objects presented in experiment 2

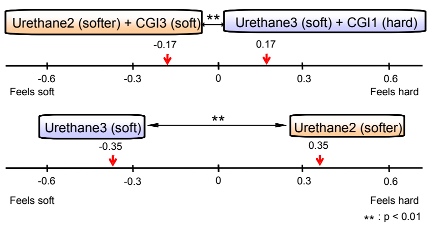
(a)	*Urethane 1* + *CGI 3*, *Urethane 2* + *CGI 1*
(b)	*Urethane 1* + *CGI 3*, *Urethane 3* + *CGI 1*
(c)	*Urethane 2* + *CGI 3*, *Urethane 3* + *CGI 1*



(a) In the *Urethane 1* and *Urethane 2* case



(b) In the *Urethane 1* and *Urethane 3* case



(c) In the *Urethane 2* and *Urethane 3* case

Fig. 7 Result of experiment 2. In the case (c), the subjects perceived the harder real object with the soft CGI animation as softer than the softer real object with the hard CGI animation.

(4) Two urethane objects are selected randomly, and steps (1) to (3) are repeated until all combinations of the three urethanes are selected.
(5) Then the subject removes the HMD, and steps (1) to (4) are repeated again without the HMD. In other words, this is a fundamental experiment conducted by using only urethane and without MR visual stimulation.
Eleven subjects participated, and after the experiment of all urethanes, they were asked for comments. The pair comparison method is used to obtain the psychological scale.
The combination shown in Table 2 is designed to superimpose a soft CGI (*CGI 3*) on a harder urethane and a hard CGI (*CGI 1*) on a softer urethane, in order to investigate the reverse phenomenon in hardness perception.

5.2 Result and Discussion

Fig. 7 shows the result of experiment 2. The notation is the same as in the previous experiment. In Fig. 7 (a) to (c), the charts above are the results presenting MR visual stimulation, and the charts below are the results pushing only the real objects without the use of the HMD.
Fig. 7 (c) shows that in the result of a comparatively soft urethane combination (*Urethane 2* and*Urethane 3*), the reverse phenomenon in hardness perception was observed, in which the subjects sense the harder real object as softer than the softer real object. However, in the result of the combination including *Urethane 1*, the reverse phenomenon did not occur. The subjects commented "*Urethane 1* was too hard for me to perceive soft even if the soft CGI animation is superimposed on it visually" and "Through the HMD, I certainly felt that *Urethane 3* was harder than *Urethane 2*. However, when releasing the HMD and touching them again, I felt that *Urethane 3* was softer than *Urethane 2*. It was a curious experience." For all of these reasons, the reverse phenomenon in hardness perception could occur when real objects were not different in their hardness.

6 Conclusion

In this study, we focused on the sense of hardness and described the investigation results concerning the psychophysical influence of MR visual stimulation on the sense of hardness. We conducted experiments using various urethanes with different hardnesses, and CGI animations with different dent deformations superimposed on them. As a result, when the maximum sinking depth of the CGI animation superimposed on the real object changed, the subjects confused its hardness as harder or softer than the real object. In some cases, visual information has a significantly larger effect than the hardness of the real object.
As for future works, we plan to study hard, real objects that are nearly undeformable.

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