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# Effects of Auditory Feedback on Tactile Roughness Perception

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Usually, when we touch and explore textured surfaces, sounds are simultaneously produced. Recent studies have shown that roughness perception in touch is affected by auditory feedback. We investigated whether the amplitude manipulations of specific frequency sounds, which had different components between coarse and fine textures, would affect perceived tactile roughness. In Experiment 1, we used the magnitude estimation method of perceived tactile roughness in three conditions: frequency-modified sound feedback, veridical sound feedback, and no-sound feedback conditions. In Experiment 2, we examined whether frequency modification would affect the auditory roughness estimations of touch-produced sounds. The results of these experiments showed that the effects of the frequency modification in the touch-produced sounds were significant in the auditory roughness estimations but not in the tactile roughness estimations. The slopes of the roughness estimation functions were largest in the touch alone condition (no-auditory feedback) and smallest in the auditory roughness with modified sounds. The slopes of the tactile roughness with the sound feedback laid between the slopes of the touch alone roughness and the auditory roughness and had the value near to that of touch alone condition. The intercept of the auditory roughness estimation function with veridical sounds was significantly larger than that of the auditory roughness with modified sounds. These results suggest that auditory information affects tactile roughness estimations, but to a small extent; therefore, sound modification has no substantial effect on perceived tactile roughness, whereas the modified sounds affect perceived auditory roughness in a different manner.

**Key words**: roughness, texture, cross-modal, touch, audition

## Introduction

In our daily lives, we often perceive objects in our surroundings through the simultaneous stimulation of several senses (Driver and Spence, 2000). For instance, when we touch something, it is accompanied by a certain sound; for example, when we comb our hair, rub our hands together, and wipe windows, certain sounds are produced.

Recent brain imaging studies of humans or macaque monkeys have provided evidence for the involvement of the cortices for the integration of touch and audition; a subregion of human auditory cortex along the superior temporal gyrus (Foxe, Wylie, Martinez, Schroeder, Javitt, Guilfoyle, Ritter, & Murray, 2002), the caudal auditory belt, which is the second stage of the auditory cortex in macaque (Kayser, Petkov, Augath, & Logothetis, 2005), and the posterior

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parietal cortex and parietal opercula between the secondary somatosensory cortex (SII) and the auditory cortex (Gobbelé, Schürmann, Forss, Juottonen, Bunchner, & Hari, 2003) have been found to be involved in the integration of sound and touch.

It has been previously reported that when we perceive surface texture, tactile cues completely dominate auditory cues (Heller, 1982; Lederman, 1979). Some studies showed that neither the auditory cues improved texture judgment by touch and vision (Heller, 1982) nor they affected tactile roughness estimations (Lederman, 1979). However, recent studies have demonstrated that auditory cues can, in fact, alter tactile texture perception with respect to both roughness and wetness (Jousmäki and Hari, 1998; Guest, Catmur, Lloyd, & Spence, 2002). In the "parchment-skin illusion," so named by Jousmäki and Hari (1998), participants rubbed their hands together, and the sounds produced were recorded online and played back to them through headphones. Either the high-frequency component or the overall frequency of this auditory information was amplified or attenuated. Jousmäki and Hari (1998) reported that the amplification of both the high-frequency component and the overall frequency of the auditory feedback increased the perception of smoothness/dryness of the palmar skin. In contrast, the results of Guest et al. (2002) showed that the amplification of the high-frequency component of the auditory feedback increased the perception of roughness and dryness of the hands' surface. In addition, the perception of the dryness of the surface increased with overall amplification.

Lederman, Klatzky, Morgan, and Hamilton (2002) examined haptic and auditory roughness perception by using a rigid probe against plastic plates. They used rigid materials in order to produce louder sounds than the touch-produced sounds generated by bare fingers touching aluminum plates used by Lederman (1979). In Lederman et al. (2002), participants made magnitude estimations in three conditions: touch, audition, and bimodality. As a result, in the bimodal estimations, both tactual and auditory information were used and revealed to be weighted at 62% and 38%, respectively.

On the other hand, Guest et al. (2002) demonstrated that tactile roughness perception was altered by frequency manipulations of touch-produced sound feedback, even when the participants were instructed to ignore the sounds. With online sound feedback provided through headphones, the participants were asked to judge which stimulus was smoother. The touch-produced sound frequencies in the 2-20 kHz range were either attenuated or amplified. Their results showed that the high-frequency attenuation led to the stimulus being perceived as smoother, whereas amplification resulted in the stimulus being perceived as rougher.

The experimental results of Lederman et al. (2002) and Guest et al. (2002) suggest that auditory information can affect tactile roughness perception if the auditory information is sufficiently loud and set at a well-perceptible level. Effective methods of presenting auditory information to the participants include either sound amplification through headphones or the use of rigid materials for touch. In this respect, Kitagawa, Zampini, and Spence (2005) conducted experiments on cross-modal spatial interactions and reported that white noise distracters presented from a position close to the back of the head produced greater interference with tactile discriminations than noises presented from a position far from the head.

The interference effects of white noise were greater than that of pure tone stimuli in the both of the far condition and the near condition. The differences of the results between white noise and pure tone were considered to reflect ecological validity (Kitagawa et al., 2005) since sounds in the surrounding environment typically have a broad spectral distribution (Moore, 1989).

The touch-produced sounds of abrasive surfaces also have a broad spectral distribution like white noise; therefore, they may affect tactile perception more than pure tone. In addition, touch-produced sound feedback through headphones directly stimulates the ears; thus, it may have a stronger effect than the sounds produced directly by the fingertips.

In Experiment 1, we investigated how tactile roughness perception would be affected by the feedback of veridical or manipulated sounds, which were produced by touching surfaces with a relatively broad range of roughness. Our participants were required to ignore the sounds, and they made tactile roughness estimations of abrasive papers with their bare fingers and palms, unlike the unimodal or bimodal roughness estimations with the rigid probe used by Lederman et al. (2002).

We manipulated the low- and middle-frequency components (25 Hz-6.3 kHz) as the modified sound feedback condition, while Jousmäki and Hari (1998) and Guest et al. (2002) manipulated the relatively high-frequency components (2 kHz-20 kHz). It has been considered that one of the possible physical parameters that determine auditory roughness is the degree of the amplitude modulation of sounds (Guirao and Garavilla, 1976). However, the different spectral distributions of touch-produced sounds may also be cues of roughness. Therefore, we compared the spectral distributions of touch-produced sounds of fine abrasive surfaces (grade 1200) and coarse abrasive (grade 60) by using a real-time frequency analyzer. The sounds produced on touching the coarse surface had the low- and middle-frequency components more dominantly than the sounds produced on touching the fine surface. Therefore, we manipulated the low- and middle-frequency components because these components were considered to be important cues of auditory roughness. We expected that if the touch-produced sounds could affect tactile roughness perception, when the frequency bands were attenuated, the auditory cues would be reduced, resulting in the differences in tactile roughness being perceived as smaller than those in the veridical sound feedback condition. Therefore, the slope of the magnitude estimation functions of tactile roughness was expected to be smaller in the frequency-modified sound condition than that in the veridical sound feedback condition.

In Experiment 2, we examined whether low- and middle-frequency manipulations would alter magnitude estimations of auditory roughness by using touch-produced sounds of the abrasive papers. If the frequency attenuations could reduce the cues of auditory roughness, the slope of the magnitude estimation functions of auditory roughness would be smaller for the frequency modified sounds than for the veridical sounds. Further, we expected that the intercept of the estimation functions would be smaller for the frequency modified sounds than for the veridical sounds, since it is possible that the frequency attenuations would reduce the overall magnitude of perceived roughness.

## Experiment 1: Cross-modal estimate of surface roughness

### Method

*Participants*

Fourteen undergraduate students participated in Experiment 1. All participants were right-handed and had tactile sensitivity of the fingers and palms as well as normal hearing.

*Apparatus*

To present the tactile stimuli, a balance apparatus was used for controlling the force while touching (Figure 1). The balance apparatus was modeled in Lederman and Taylor (1972) to control finger force. The participants touched the stimuli with a force of approximately 0.6 N so that the balance arm would remain steadily on the level. A condenser microphone (Rode; NT1-A) powered by a mixer (Yamaha; MG10/2) was located 15 cm above the tactile stimulus (abrasive paper). The output from the mixer was sent to a one-third-octave graphic equalizer (Phonic; i7600). Irrespective of whether or not the sounds were modified, they were fed back to the participants through the closed headphones (Audio-technica; ATH-PRO700).

*Stimuli*

The tactile stimuli consisted of rectangular pieces (18.5 × 26 cm) of various grades of abrasive paper affixed to rigid plastic plates. Seven grades of abrasive paper (grades 60, 100, 150, 240, 360, 600, and 1200) were used with particle diameters ranging from 0.015 to 0.275 mm. As the auditory stimuli, the touch-produced sounds were fed back to the participants. The auditory feedback was either identical to the original sounds or the low- and middle-frequency

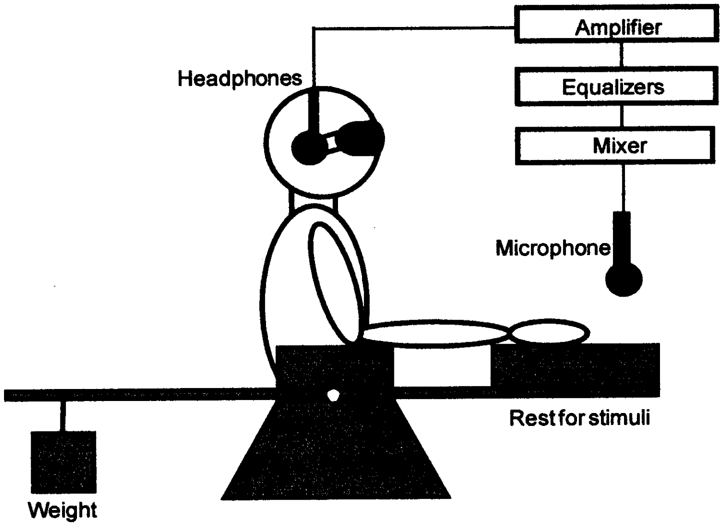

*Figure 1.* The apparatus used for controlling the force while touching and the equipment for the feedback of touch-produced sounds.

(25 Hz-6.3 kHz) sounds attenuated by 12 dB in terms of the equalizer. We manipulated the frequency bands based on the analysis of touch-produced sounds by using the function of the analyzer attached to the equalizer. The amplification level was set at approximately 52 dB (a comfortable listening level) for the unmodified touch-produced sounds of the modulus. The loudness level was measured by the subjective matching technique, using loudspeakers. In the touch-alone condition, no auditory feedback was provided through the headphones.

*Procedure*

The participants were blindfolded and seated on a stool beside the balance apparatus, with their right elbow resting on a padded armrest mounted on the fulcrum of the balance apparatus. Magnitude estimation was performed with the modulus. The participants were specifically instructed to estimate the tactile roughness and ignore the touch-produced sounds they heard from the headphones. The modulus (grade 240 with no sounds) was presented first, and the participants were instructed to consider its roughness as being "10." The participants were told to assign numbers in proportion to the tactile roughness of each stimulus in comparison with that of the modulus. For example, if the perceived roughness was twice as rough as the modulus, they would have to assign "20." The participants were permitted to use any positive number. The participants were told to move the tips of their right fingers and palm back and forth on the stimulus surface at the rate of one cycle per second and to keep the balance apparatus steadily on the level. Before the experiment, the participants practiced touching the stimulus by adjusting the rate of their hand movement to the metronome.

In all the three conditions (veridical sound feedback, modified sound feedback, and no-feedback), the participants wore headphones. They experienced one initial practice trial for each of the seven stimuli only in the no-feedback condition. These data were not included in the analysis. After the practice, three experimental blocks including five trials for each stimulus in each condition were conducted in random order. The presentation order of the three blocks was counterbalanced across the participants. The modulus was repeatedly presented before every seven stimuli. In total, the participants judged the roughness 105 times, excluding the practice trials.

## Results and Discussion

For the three feedback conditions, the mean magnitude estimates of the perceived tactile roughness for each participant were logarithmically transformed and plotted as a function of the logarithmic grid size of each stimulus. From the equations obtained by a least squares method, the slopes (i.e., exponents) and intercepts of the functions were calculated for each participant. In the present study, we defined the intercept as the value of the function corresponding to the log value of the modulus. Two participants were excluded from the analysis because they had slopes that exceeded the mean by greater than two standard deviations. The mean coefficient of determination across the twelve participants was 0.904 (SD = 0.053). Figure 2 shows the comparison of the estimations across three conditions (the frequency-modified sound feedback, the veridical sound feedback, and the no-sound feedback) in the estimation of tactile roughness.

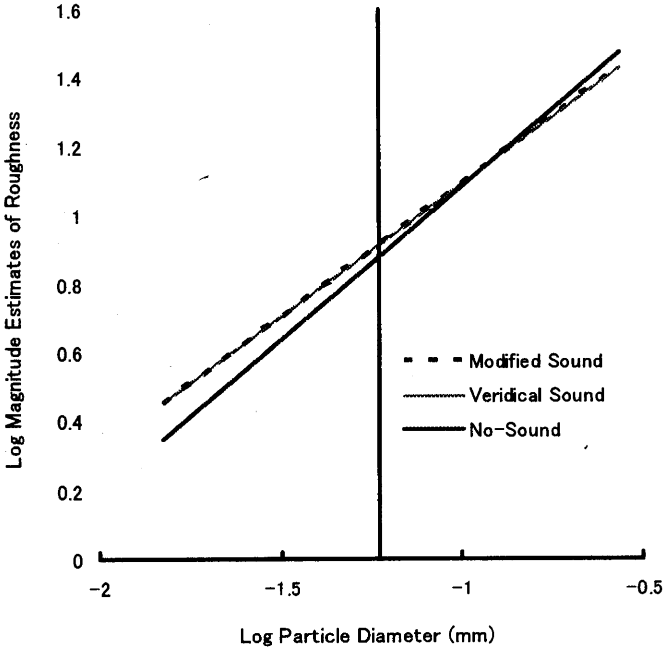

*Figure 2.* The functions of tactile roughness estimates in the three conditions. These functions are depicted based on the mean slope and intercept of the estimates of the participants. The abscissa indicates the log average diameter (mm) of the particles on the abrasive paper. The ordinate indicates the log estimated roughness corresponding to the modulus. The function of the modified sound condition and that of the veridical sound feedback condition overlap each other.

These functions were depicted based on the mean slope and intercept for the twelve participants in the three conditions.

Then, the slopes and intercepts obtained from the data of each participant were analyzed by a one-way repeated-measure analysis of variance with the three feedback conditions as a factor. The main effect of the auditory feedback was found to be significant in the slope ($F$ (2, 22) = 5.117, $p < .05$) and insignificant in the intercept ($F$ (2, 22) = 1.934, $p = .17$). The post hoc comparisons, that is, Ryan's method (where $p < .05$ prior to correction), revealed that the main effect of the auditory feedback in the slopes was significant only between the feedback conditions (the veridical sound feedback or the modified sound feedback) and the no-feedback condition. The slope was larger in the no-feedback condition than in the two auditory feedback conditions.

In Experiment 1, we examined the effects of auditory feedback on tactile roughness estimations. The results showed that the tactile roughness estimations were altered by the touch-produced sounds. The slope of the roughness estimation functions was larger in the no-sound feedback condition than that in the auditory feedback condition regardless of whether or not the sound frequency was modified. In particular, the estimated roughness of relatively fine surface stimuli was greater in the sound feedback conditions than in the no-sound feedback condition.

In Experiment 1, there was no difference in the slopes of the estimation functions between the low- and middle-frequency manipulated sound condition and the veridical sound condition. However, Guest et al. (2002) reported the effects of the sound frequency modification of the high-frequency component (2 kHz-20 kHz) on tactile roughness perception. It is possible that high-frequency manipulation of the sounds affects tactile roughness perception more dominantly.

Although in Experiment 1, the sound modification of the low- and middle-frequency components did not affect the tactile roughness estimations with the auditory feedback, it was not clear whether or not (the result indicated) the low- and middle-frequency modification affected intramodal (auditory) roughness perception. Therefore, we verified that the manipulation of the low- and middle-frequency components affects intramodal auditory roughness estimations in Experiment 2, as described below.

## Experiment 2: Auditory roughness estimation of touch-produced sounds

### Method

*Participants*

From among the fourteen participants in Experiment 1, six participated in Experiment 2.

*Apparatus*

Auditory stimuli were the sounds generated by touching the abrasive surfaces that were produced and recorded in Experiment 1. A personal computer (SONY; VAIO, PCG-FX55V/BP) was used for the recording and presentation of the stimulus to the participants; the stimulus was presented through an amplifier connected to the headphones.

*Stimuli*

The auditory stimuli were the same sounds that the participant produced by touching the stimuli in Experiment 1. There were two conditions: the frequency-modified sound condition and the veridical sound condition. In the frequency-modified sound condition, the low- and middle-frequency components (25 Hz-6.3 kHz) of the recorded sounds were attenuated by 12 dB with the equalizer used in Experiment 1. In the veridical sound condition, the frequency of the recorded sounds produced by touching the stimuli was not manipulated. The modulus was the veridical sound that each participant produced by touching the modulus stimulus (grade 240) of Experiment 1. The amplification level for each participant corresponded to the loudness of their own touch-produced sounds, which was obtained by using the subjective matching technique. The experiment comprised two blocks of conditions (the frequency-modified sound condition and the veridical sound condition). The presentation order for all participants was the same as that in Experiment 1. In all, the participants judged the auditory roughness 70 times (7 stimuli × 5 trials in the two conditions), and the modulus was repeatedly presented before every seven stimuli.

*Procedure*

The participants were blindfolded and were seated with headphones on. They made magnitude estimations of the auditory roughness of the stimuli. The participants were presented the touch-produced sounds that individual participants produced in Experiment 1, although they were informed that the sounds were produced by one of experimenters in advance. The procedure of the magnitude estimation was the same as that in Experiment 1. The task was the estimation of auditory roughness of each stimulus by comparing the auditory roughness of the modulus, whose value was assigned as "10."

## Results and Discussion

The data analysis was the same as that in Experiment 1. The mean magnitude estimates of the perceived auditory roughness were logarithmically transformed and plotted as a function of the logarithmic grid size of each abrasive stimulus in the frequency-modified sound condition and the veridical sound condition. From the functions obtained by the least square approximation method, the slopes (exponents) and the intercepts of the functions for the two conditions were calculated for each participant. The mean coefficient of determination across the six participants was 0.715 (SD = 0.236). Figure 3 shows the functions based on the mean slope and intercept across the participants in the two conditions.

Paired $t$-tests of the slopes and intercepts showed that the slope in the frequency-modified condition was marginally smaller than that in the veridical condition ($t$ (5) = 2.031, $p < .10$) and that the intercept in the frequency manipulated condition was significantly smaller than that in the veridical condition ($t$ (5) = 10.388, $p < .001$). The low- and middle-frequency attenuated sounds were estimated as being less rough than the veridical sounds.

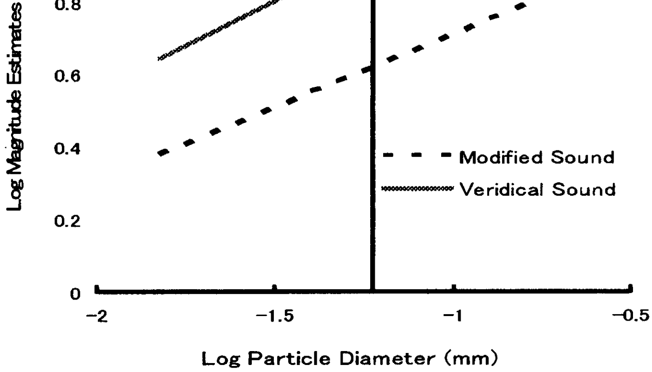

*Figure 3.* The functions of auditory roughness estimates in the two conditions. These functions are depicted based on the mean slopes and intercepts for the participants. The abscissa indicates the log average diameter (mm) of the particles on the abrasive paper. The ordinate indicates the log estimated roughness corresponding to the modulus.

**Table 1** The mean slopes of the roughness estimation functions in Experiments 1 and 2. In the tactile roughness estimations, veridical, modified, and no sounds were fed back to the participants. In the auditory roughness estimations, the participants estimated the roughness of the sounds.

| | Veridical Sound | Modified Sound | No-Sound |
|---|---|---|---|
| Tactile Roughness | 0.774 (0.17) | 0.775 (0.17) | 0.891 (0.17) |
| Auditory Roughness | 0.492 (0.24) | 0.403 (0.31) | |

The figures in parentheses indicate the standard deviations for each condition for 12 participants in the tactile roughness estimations and for 6 participants in the auditory roughness estimations.

The results of Experiment 2 show that the slopes of the estimation functions of the frequency manipulated sounds were marginally smaller than those of the veridical sounds; this suggests that the low- and middle-frequency attenuations reduce the available cues of auditory roughness. On the other hand, the differences in the intercepts of the roughness estimation functions may reflect the difference in the absolute loudness of the sounds because the low- and middle-frequency attenuations led to an overall attenuation. Lederman et al. (2002) conducted a separate experiment and suggested that the intercept of the psychophysical function for the roughness estimation in bimodality (audition and touch) was greater when the amplitude of the available sounds was increased. Table 1 shows the slopes of the roughness estimation functions of each condition in Experiments 1 and 2. The results of these two experiments suggest that the sound frequency manipulations significantly altered the magnitude estimations of auditory roughness, although they did not substantially affect the tactile roughness estimations when they were fed back to the participants.

## General Discussion

In the present study, we examined the effects of touch-produced sound feedback on tactile roughness estimations for abrasive surfaces. The results of Experiment 1 showed that auditory feedback altered tactile roughness perception. The slopes of the roughness estimation functions were significantly smaller in the sound feedback conditions than in the no-auditory feedback condition. These results are consistent with those of Jousmäki and Hari (1998) and Guest et al. (2002). They reported that the online feedback of the sounds produced by rubbing the hands or touching abrasive surfaces affected tactile texture perception.

With regard to the effects of auditory information on roughness perception, our results partially corresponded with those of Lederman et al. (2002), in the sense that they showed the differences in roughness perception between unimodality (audition or touch) and bimodality (audition and touch). The present study indicated the interactions between the particle size of the stimuli and cross-modal roughness perception as seen in the difference in the slopes of the estimation functions. Unlike in the present experiment, Lederman et al. (2002) used rigid materials and showed that the magnitudes of roughness in the touch-only condition were larger than those in the bimodal condition of touch and audition. Their results showed that the magnitudes of perceived roughness were consistently the largest in the touch-only condition and the smallest in the audition-only condition; therefore, there was no significant interaction between the modality and interelement spacing of the stimuli. The difference between our results and those of Lederman et al. (2002) may reflect the difference in the range of tactile stimuli that was used. We used abrasive papers of particle diameters ranging from 0.015 to 0.275 mm, while Lederman et al. (2002) used stimuli with a range above that used in this study. They employed plastic polymer plates containing raised elements in the form of truncated cones, with the interelement spacing ranging from 0.500 to 3.125 mm. It is known that the magnitude of the perceived tactile roughness tends to demonstrate an inverted U-shaped function for the dot spacing that peaks near the 3.0 mm spacing (Connor, Hsiao, Phillips, & Johnson, 1990). In fact, the results of Lederman et al. (2002) revealed that a quadratic equation best describes the psychological function for both the audition-only and the bimodal conditions. The coarsest stimulus used in their experiment had an interelement spacing of around 3 mm; therefore, it was observed that the peak of its function was included in the range of the stimuli. The particle size of the stimuli used in our experiments was below 0.3 mm, so that the roughness estimation functions could be described by a linear equation that is different from the functions obtained in Lederman et al. (2002).

Unexpectedly, in Experiment 1, the effect of the frequency manipulations of auditory feedback on tactile roughness was not significant. We predicted that when low- and middle-frequency bands of the sounds were attenuated and fed back, the perceived differences in tactile roughness would be reduced because of a decrease in the auditory roughness cues. In this respect, Guest et al. (2002) compared the discrimination errors between the conditions of high-frequency amplification and attenuation and reported significant differences between them. It is possible that the high-frequency manipulation of the sounds affects tactile roughness perception more dominantly. However, Guest et al. (2002) used only two abrasive stimuli; therefore, it is necessary to conduct a detailed investigation and verify the effects of high-frequency manipulations of touch-produced sounds using a broader range of roughness.

In Experiment 2, we verified the differences in the auditory roughness estimations of touch-produced sounds between the low- and middle-frequency modified sounds and the veridical sounds. The results showed that frequency manipulations significantly altered the auditory roughness perception. The intercepts of the estimation functions were much larger in the veridical sound condition than in the frequency modified sound condition. These results clearly showed that the magnitudes of auditory roughness were perceived to be much smaller when the low- and middle-frequencies of the sounds were attenuated as opposed to when the sounds were not modified. The slopes of the auditory roughness estimation functions were also marginally affected by the frequency manipulations. These results may be produced by the reduction of the auditory roughness cues due to low- and middle-frequency attenuation. However, we should also consider and separate the effect of absolute loudness change, which accompanies the frequency component attenuation, since Lederman et al. (2002) suggested that the amplification of absolute loudness leads to perception of greater bimodal roughness. Therefore, it is necessary to investigate the interactions of touch and audition in roughness perception by modifying overall amplitude and manipulating the frequency bands without changing the overall amplitude so as to clarify which parameters of the touch-produced sounds are substantial cues for auditory roughness, resulting in an alteration of the tactile roughness perception.

The results of Experiments 1 and 2 showed that the low- and middle-frequency modification of the sounds altered intramodal auditory roughness perception, but did not affect cross-modal (tactile) roughness perception. The slope of the function was the largest in the tactile roughness estimations in the no-auditory feedback condition and the smallest in the auditory roughness estimations of the modified sound condition. In the auditory roughness estimations, the slope of the veridical sound condition was slightly larger than that of the modified sound condition. The slopes of both the functions of tactile roughness for the two sound (veridical and the frequency modified) conditions lie between the slope of the no-feedback condition in the perception of tactile roughness and that of the veridical sound condition for auditory roughness; on the other hand, they were close to the slope of the no-feedback condition in the perception of tactile roughness. These results suggested that roughness perception was altered by touch-produced sound feedback, even when the participants were required to ignore the sounds; however, the weight of the auditory information might be small in the tactile roughness estimation, so that the tactile roughness was unaffected by the substantial auditory cues of roughness, even though the auditory roughness estimations were affected.

It is necessary to investigate further whether the enhancement of auditory information availability decreases the slope of the tactile roughness function or whether it increases the overall perceived roughness, as shown by Lederman et al. (2002). In addition, we should consider some other factors that affect the interaction in roughness perception. One is whether participants conduct a bimodal roughness estimation or a unimodal estimation. Depending on the instructions to ignore one modality, the relative weights given to the cues in each modality are likely to vary. Another factor is the possibility that auditory information may also have different effects, depending on the interelement spacing of the stimuli. Therefore, an examination of the stimuli using a broader range of interelement spacing is necessary in future studies.

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