Short Note

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Discriminability of Virtual Roughness Presented by a Passive Haptic Interface

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Abstract – A passive haptic interface based on the damping brake of a DC motor was used to present surface roughness. Virtual roughness stimuli were expressed by using periodic resistance forces caused by switching the damping brake on and off at regular intervals. We investigated the ability of humans to discriminate such roughness stimuli through information transfer and signal detection theory. Our results revealed that the passive haptic interface can present three to four levels of roughness stimuli without confusion, which is slightly inferior to an active-type haptic interface.

Keywords : passive haptic interface, discrimination of roughness, damping brake

1. Introduction

Haptic interfaces where the hardware itself consists of passive elements have the merits of inherent safety and low-energy consumption. Thus far, passive force displays have been developed by several research groups. Such haptic interfaces are expected to be used in applications for many unspecified users. We previously assembled a passive haptic interface that uses the damping brake of a DC motor [1]. The device can present virtual roughness by repeatedly braking and releasing the hand.

In addition to audiovisual information, presenting surface textures can assist with human-computer interaction, such as virtual buttons with different textures. When using roughness stimuli as tools for such information transmission, the discriminability of the stimuli is important. In order to accurately deliver as much information (textures) as possible, there is a need to both increase the number of stimuli and design each stimulus to be discriminable from the others. Although studies have investigated the characteristics of human perception of roughness stimuli from passive haptic interfaces [2], [3], their objectives were mainly to specify dominant parameters that affect roughness perception. Thus far, the discriminability of roughness stimuli from passive haptic interfaces has rarely been investigated.

The objective of this research was to investigate the discriminating characteristics of roughness stimuli presented by a passive haptic interface through an identification experiment on six levels of roughness stimuli. This research was approved by the internal review board of the School of Engineering, Nagoya University (#15–12).

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2. Roughness stimuli from a passive haptic interface

2.1 Damping brake of a DC motor

We adopted the damping brake of a DC motor as a passive element. The damping brake functions by the back electromotive force of a short-circuited DC motor. Figure 1(a) shows a schematic of a computer-controlled short circuit in which R and L are the resistance and inductance, respectively, of the circuit. When a human rotates the short-circuited DC motor, he or she experiences the resistive torque of the damping brake. Based on Kirchhoff's law, the relationship between the angular velocity $\omega(t)$ and brake torque $\tau(t)$ is expressed as follows:

$$\frac{L}{R}\frac{d\tau(t)}{dt} + \tau(t) = -\frac{K^2}{R}\omega(t), \tag{1}$$

where K is the torque constant of the motor. Given that the inductance L is negligible, the brake torque $\tau(t)$ is proportional to the angular velocity $\omega(t)$, which indicates that the braking torque corresponds to a damping resistance. Figure 1(b) shows the passive haptic interface that uses the damping brake of a DC motor. This device consists of a DC motor fixed on a frame and a crank with a handle connected to the output shaft of the motor. The short circuit is switched by using a motor driver (TB6643KQ, TOSHIBA) at a control frequency of 2 kHz.

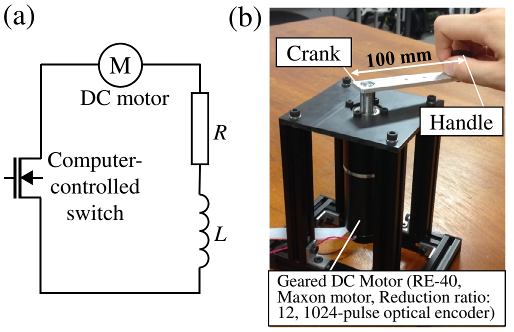

Fig. 1 Haptic interface based on the damping brake of a DC motor [1]: (a) computer-controlled short circuit of the DC motor, (b) overview of the device.

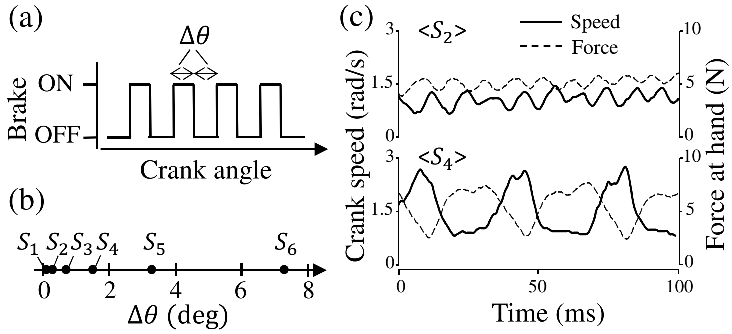

Fig. 2 Roughness stimuli by the damping brake: (a) brake operation, (b) interval of the brake operation ($\Delta\theta$) for six levels of stimuli, (c) examples of force at hand and crank speed for stimuli S_2 and S_4.

2.2 Roughness via the passive brake

Figure 2(a) shows the brake operations for presenting virtual roughness. When an operator rotates the crank, he or she experiences roughness from periodic resistance forces applied to the hand, which is caused by switching the brake on and off at regular intervals ($\Delta\theta$). Previous researchers have demonstrated that such a resistive force field on a plane can be effectively used to express virtual roughness without displacement in the normal direction [2]~[5].

3. Identification experiment

We performed an identification experiment for six levels of roughness stimuli to investigate the discriminating characteristics of roughness stimuli presented by a passive haptic interface [6].

3.1 Six levels of roughness stimuli

Six levels of roughness stimuli from the finest stimulus S_1 to the roughest stimulus S_6 were used in the experiment. The perception of roughness stimuli from a passive haptic interface is largely dependent on the spatial frequency of the stimuli [2]. The on/off intervals of the brake ($\Delta\theta$) correspond to the spatial frequency. Stimuli with extremely small or large $\Delta\theta$ do not feel like roughness. Hence, we set the lower and upper boundaries of $\Delta\theta$ to be 0.15 deg (S_1: finest) and 7.3 deg (S_6: roughest), respectively.

Stimuli located at equal psychological distances are easy to distinguish. Additionally, Weber's law generally holds for roughness stimuli by passive haptic interfaces [2]. Therefore, we designed stimuli S_2 to S_5 with each $\Delta\theta$ increasing by the same ratio from S_1 to S_6, as shown in Fig. 2(b). Because the length from the center of rotation to the handle was 100 mm, the spatial periods of S_1 to S_6 were 0.26, 0.56, 1.2, 2.7, 5.8, and 13 mm, respectively. Figure 2(c) shows examples of force at hand measured by a force sensor and crank speed for stimuli S_2 and S_4.

3.2 Participants

Participants were five naive males in their 20s and 30s, and informed consent was obtained from all before the experiment.

3.3 Task

Participants were asked to identify randomly presented stimuli S_1–S_6 according to the six levels of roughness. They rotated the crank at any speed to explore the roughness and responded with numbers from 1 to 6 in each trial. Each participant performed 20 trials for each of the six types of stimuli, which amounted to 120 trials. Each participant took part in four sessions, with one session comprising 30 trials. Participants memorized the stimuli during a 3-min training session prior to the first session in which they could experience the stimuli freely. Additionally, a similar 1-min training session was provided prior to the other sessions. This combination of free active exploration and training sessions enabled the participants to achieve the best performance.

4. Results

As presented in Table 1, the average correct answer ratio was in the range of 65.8%–81.7%. The average for all participants was 71.7%. No significant increases in the correct answer ratio between the first and final sessions was observed for all participants. In other words, the learning effect was not observed. The results for each participant were summarized in the form of a 6×6 stimulus-response confusion matrix. The information transfer (IT) for

Table 1 Correct answer ratio and information transfer (IT).

Participants	A	B	C	D	E	Ave.
Correct (%)	68.3	65.8	73.3	69.2	81.7	71.7
IT (bit)	1.58	1.32	1.68	1.55	1.88	1.60

Table 2 Average confusion matrix. S_i and R_j indicate the presented stimuli and answer, respectively.

	R_1	R_2	R_3	R_4	R_5	R_6
S_1	0.67	0.33	0	0	0	0
S_2	0.04	0.5	0.45	0.01	0	0
S_3	0.02	0.18	0.61	0.18	0.01	0
S_4	0	0	0.11	0.81	0.08	0
S_5	0	0	0.01	0.25	0.71	0.03
S_6	0	0	0	0.02	0.14	0.84

each participant was calculated from the confusion matrix. As given in Table 1, the IT values ranged from 1.32 to 1.88 bits with an average of 1.60 bits.

As discussed in the subsequent section, individual differences were relatively small. Therefore, we treated the average answer ratio. The average answer ratio of the participants is presented as a confusion matrix in Table 2. We calculated how far each stimulus was psychologically located from each other based on the signal detection theory [7]. We assumed that a response to each stimulus on the psychological continuum followed a Gaussian distribution and that the standard variations of all stimuli were equal (assumption of a case V score). Figure 3 shows the loci of roughness stimuli on the psychological continuum estimated from the confusion matrix in Table 2. We put the response to S_1 as zero. One unit on this continuum is equal to a standard deviation of the distribution for a stimulus. When two stimuli are distant from each other by 1 unit, they are distinguishable with a probability of 84%. In order to confirm the validity of the case V assumption, we calculated another confusion matrix for the answer ratio from the estimated loci and tested the goodness of fit with the matrix in Table 2. There was no significant discrepancy between the estimated and sample confusion matrices ($\chi^2 = 26.3$, d.o.f $= 30$, $p > 0.05$), which does not deny the use of the loci shown in Fig. 3.

5. Discussion

The results showed that the average IT values of roughness stimuli was 1.60 bits. Thus, our system

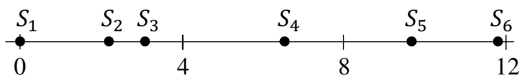

Fig. 3 Loci of roughness stimuli on the psychological continuum.

can present at least three levels of roughness without confusion ($2^{1.60} = 3.0$). Nonetheless, IT values can be underestimated when there are a number of stimuli involved in the experiment [8]. According to the displacements of the stimuli on the psychological continuum, as shown in Fig. 3, S_2 and S_3 were close and frequently confused. This led to a decrease in the average correct answer ratio and IT value. If S_2 to S_5 were placed at equal intervals between S_1 and S_6, then the IT and average correct answer ratio would be estimated to be 1.73 bits and 80.4%, respectively. Furthermore, if two stimuli were located at equal psychological distances between S_1 and S_6 and four stimuli were used in total, IT would reach its maximum value at 1.76 bits, and the average correct answer ratio would increase to 96.4%. Considering the high average correct answer ratio, our system may be able to deliver four levels of distinguishable roughness at most. When the loci of stimuli are calculated for individual participants and four equally distant stimuli are used, the IT values for each participant range from 1.59 to 1.82 bits with the average correct answer ratios of 92.9% and 97.6%.

Thus far, the discriminating characteristics for the roughness of textured surfaces or roughness stimuli by active haptic interfaces have been investigated. The Weber fractions for textured samples with a spatial period ranging from 0.77–1.0 mm and 2.5–10 mm were reported to be 5% and 6.4%–11.8%, respectively [9], [10]. Biet et al. [11] reported that the Weber fractions for spatial periods from 2.5 to 10 mm was 8.1%–9.6% when roughness stimuli were presented by a friction-based tactile texture display. The spatial period of the stimuli used in our experiment was 0.25–13 mm, which was in the range of those used in the previous studies. The discrimination threshold of the spatial period calculated based on the loci of the roughness stimuli was 28% at a threshold level of 84% and 20% at a threshold level of 75% for each spatial frequency. Although a comparison with previous studies is not accurate because of the differences in experimental designs or calculation methods of the

Weber fraction, the Weber fraction calculated from our experimental results is two to four times larger than that when using an active haptic display and actual textured surfaces. In other words, the passive haptic interface used in this research is slightly inferior to the active haptic interface in terms of presenting roughness, which is a tradeoff for the benefits of passive haptic interfaces. Nonetheless, the discriminability may be improved by employing a DC motor with a greater torque constant or smaller inductance and optimizing the moment arm.

6. Conclusion

We investigated the discriminating characteristics of roughness stimuli from a passive haptic interface. In the results of an identification task for six levels of roughness stimuli, the average correct answer ratio was 71.7%. The average IT value was approximately 1.60 bits, which indicates that the interface can present at least three levels of distinguishable roughness.

It is estimated that the system used in this research can present four levels of roughness stimuli at most without confusion by locating the stimuli at equal psychological distances from each other. This passive haptic interface is slightly inferior to active haptic interfaces in terms of the presentation of roughness.

The results will help us design stimuli when using roughness stimuli by a passive haptic interface as a tool of information transmission.

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Biography

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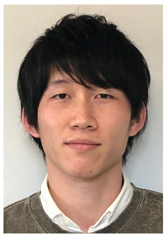

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