Altering Distance Perception from Hitting with a Stick by Superimposing Vibration to Holding Hand

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Abstract. Distance perception by hitting objects with a handheld stick is an important cue for people with visual impairments who use a white cane in daily life. In a previous paper, we found that adding vibration to the thumb side of the cane shortened the perceived collision distance more than adding vibration to the little-finger side, which partly agrees with our hypothetical model. In this paper, we conducted a similar experiment, changing the real distance between the palm and the object to explore the robustness of our hypothetical model. The experimental results showed that perceived collision distance shortened regardless of the real distance, but may be easily induced when the object is placed far from the palm.

Keywords: Distance perception, Hitting, Stick, Vibrotactile.

1 Introduction

Most people have experience of perceiving distance by hitting objects with a stick. This perception is quite important, especially for the visually impaired who use white canes to guide them in daily life. Therefore, understanding the perception mechanism underlying this phenomenon might help in the development of supporting devices, such as an electric white cane that consists of a range sensor and a haptic display [1].

The mechanical characteristics of held objects can be perceived by haptic cues even if the objects are visually occluded [2]. This exploratory behavior is known as dynamic touch, and has mainly been studied as part of ecological psychology [3]. The length of a handheld rod can be estimated from cues such as its density, diameter, center of gravity, the user's swing, and grasping posture [4][5][6]. The "sweet spot" of a handheld tennis racket can be estimated before the actual hit [7]. In recent years, researchers have succeeded in producing the illusion of length, weight, or center of gravity of a virtual object by using haptic devices [8].

However, most studies have dealt with estimating the mechanical characteristics of the handheld object itself and have not directly considered distance perception from percussing objects with a handheld stick. Yao and Hayward [9] found that "rolling" a small object inside the rod can be expressed by simple vibration, but they did not directly deal with distance perception from hitting an object. The contribution of the

adfa, p. 1, 2011.
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rotational moment was considered but not fully explored [10]. Sreng et al. proposed that transient frequency components after hitting with a stick may play a role in perception [11]. However, the vibration frequency is easily affected by the material and length of the stick, which leads to frequency cues not being robust. We presume therefore that simpler yet more robust cutaneous cues play a role in this perception.

In our previous study [12], we advanced the hypothesis that the distance information obtained from hitting with a stick can be retrieved by the "center of gravity" of vibration in the palm, and tried to verify this hypothesis by superimposing external vibrations onto the real vibrations caused while percussing. In this paper, we conducted an experiment with various real distance conditions between the palm and the object, to explore the relationship between the effect of artificial vibrations from actuators and the real distance between the palm and the object.

2 Hypothetical Model of Distance Perception by Cutaneous Cues

Fig. 1 shows a simplified mechanical model for percussing an object with a handheld rod. P_1, P_2, and P_3 indicate the positions of the object, thumb, and little finger, respectively. We assumed that the hand only contacts the rod with the thumb and little finger to simply the model, although in real-world cases the rod is held with the whole palm. F_1, F_2, and F_3 represent the generated forces by percussion, and L_1 and L_2 indicate the distances between P_1 and P_2 and P_2 and P_3, respectively.

As the handheld rod stops after the contact, the total rotational moment and translational force must be zero, which leads to the following equations.

$$F_1 + F_2 + \mathrm{F}_3 = 0 \tag{1}$$

$$\mathrm{F}_1 \cdot \mathrm{L}_1 = F_3 \cdot \mathrm{L}_2 \tag{2}$$

From these equations of balance, distance L_1 is obtained as follows:

$$\mathrm{L}_1 = \frac{F_3 \cdot L_2}{F_1} = \frac{-F_3 \cdot L_2}{\mathrm{F}_2 + \mathrm{F}_3}. \tag{3}$$

As L_2 (distance between the thumb and little finger) is constant, this equation means that the distance of the percussed object L_1 is directly related to the ratio of F_2 and F_3, which are perceived as cutaneous sensations at the thumb side and little-finger side.

For instance, when the object is quite close, L_1 is nearly equal to zero, which gives $F_3 = 0$ in the equation. This means that the transmitted vibration at the thumb (P_2) is greater than that at the little finger (P_3) (**Fig. 2**, left). In contrast, when the position of the percussed object P_1 is far away, L_1 is infinite, which gives the solution $F_2 = -F_3$. Therefore, the intensities of the transmitted vibrations to the thumb and little finger become equal (**Fig. 2**, right).

This simple model shows that the position of the percussed object P_1 can be estimated from the ratio of transmitted vibrations to the thumb (F_2) and little finger (F_3). This model is not completely accurate because we usually grasp the rod with the whole palm, but it shows that we may estimate the position of the percussed object by perceiving the position of the "center of gravity" of vibration in the palm. Presenting vibration at multiple sites is known to elicit the perception of a center of gravity, which is called a funneling or phantom sensation [13].

Based on this hypothesis, we fabricated an experimental device embedded with two actuators located at the bases of the thumb and little finger. We conducted an experiment to determine whether changing the center of gravity of the vibration that is transmitted to the palm modifies the perception of the percussed object's position.

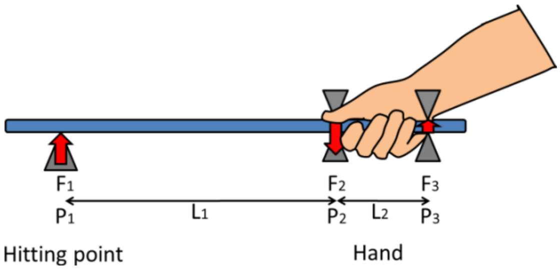

Fig. 1. Hypothetical model for distance perception of percussion with handheld rod.

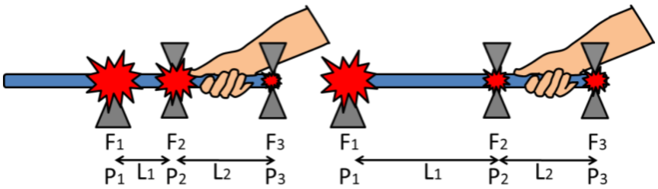

Fig. 2. Hypothesis of distance perception with cutaneous cue. Hitting a closer point induces a stronger vibration at the thumb side (left). Hitting farther induces equally distributed vibrations (right).

3 Experimental Device

We developed a stick-type experimental device that can superimpose vibrations generated by actuators to the real vibration induced by percussion.

The device (**Fig. 3** left) comprises an aluminum pipe (diameter: 15 mm, length: 1000 mm, weight: 110 g), an acrylic grip, a single-axis accelerometer (±250 g, ADXL193, Analog Devices), two vibrotactile actuators (Haptuator Mark II, TactileLabs) on the grip, a pre-amplifier circuit, and an audio amplifier (RSDA202, Rasteme Systems Inc.) (**Fig. 3** right). The accelerometer was placed at the tip of the aluminum pipe to record the real contact (**Fig. 4**), and its analog output was connected to the two actuators through the pre-amplifier circuit and audio amplifier. The two actuators were mounted on the grip beneath the bases of the thumb and little finger. They directly touched the skin surface when the device was grasped. A sponge was installed between the acrylic grip and actuators to avoid possible howling caused by the actuators and accelerometer. The total weight of the device was about 250 g.

Thanks to the simplicity of the implementation, the time delay between the actual contact to the replayed vibration became imperceptible. Each actuator was connected to the right and left channels of the audio amplifier; the amplitude ratio of the two actuators could be controlled by the balance control knob of the audio amplifier.

We prepared an object made of acrylic plate (height: 100 mm, width: 200 mm, thickness: 5 mm). It was attached vertically to the linear servomotor (F14-20-200-5L, Yamaha Motor Co., Ltd.) with a vice. To avoid possible damage to the stick and object, a rubber sheet (thickness: 5 mm) was attached on top of the object. This rubber sheet also helped mute the percussive sound, which can act as a cue for distance estimation.

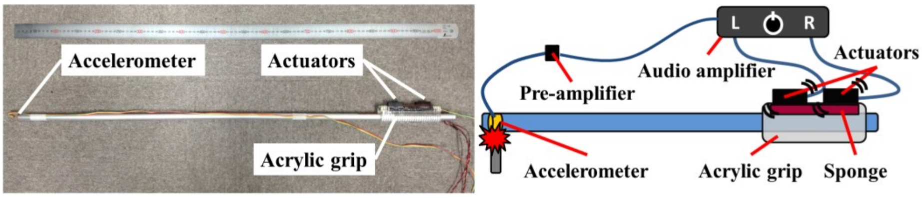

Fig. 3. (left) Stick-type experimental device. (right) The system configuration.

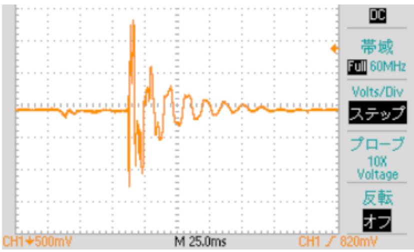

Fig. 4. The waveform of the hitting measured by the accelerometer.

4 Experiment

We conducted an experiment to verify the hypothesis of percussion distance perception. We assumed that participants would misjudge the position of the percussed object when vibration was superimposed, since this would alter the vibration center of gravity in the palm.

Experimental Conditions

Four pairs of vibration conditions were prepared: (a) superimposing vibration from the thumb-side actuator to the real collision, (b) superimposing vibration from both actuators, (c) superimposing vibration from the little-finger side actuator, (d) without superimposing vibration. In condition (b), the vibration amplitude of each actuator was set to half that of the other conditions (**Fig. 5**).

To investigate the relationship between the effect of artificial vibrations from the actuators and the real distance between the palm and the object, we also prepared three different distance conditions: (1) the distance between the end tail of the device and the object was set to 500 mm, (2) 600 mm, and (3) 700 mm. The distance was controlled by the linear servomotor via computer.

Experiment Procedure

We recruited seven participants (all males, 21–29 years old, no reported tactile impairments). The participants sat on a chair and grasped the stick-type device with their right hands. To avoid visual and aural estimation of the collision distance [14], a black wall was installed on the right side of the participants, and they wore active noise-canceling headphones (QuietComfort, BOSE) and listened to white noise at a maximum pleasant volume. A 1000 mm scale ruler was placed in front of the participants to determine the visually and aurally occluded collision position (**Fig. 6**).

On each trial, participants percussed the object using the stick-device. Each trial had no time limit or limit on the number of percussions. The participants were instructed to keep their right hand at the same height so that they could not estimate the distance from the stick angle at the moment of percussion. Similarly, they were instructed to keep the end tail of the stick-device at the same position so that the collision position was only decided by the position of the linear servomotor (500, 600, or 700 mm). Also, an armrest was installed on the participants' right sides to allow them to maintain the position of their arms and to prevent fatigue. After percussion, participants estimated the perceived distance using the scale of the ruler. No feedback about correct distance was provided during the experiment. Each vibration condition was presented ten times, at three different distances randomized across trials; each participant performed 120 trials. To prevent fatigue, participants rested at least once every ten trials.

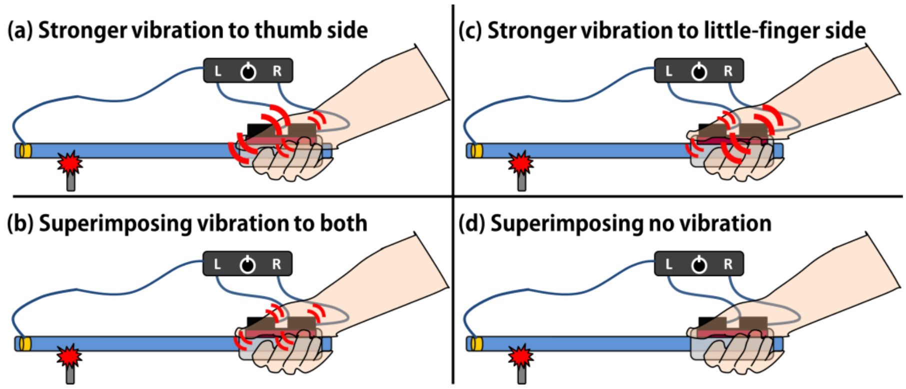

Fig. 5. Four pairs of vibrations were prepared for the experimental conditions.

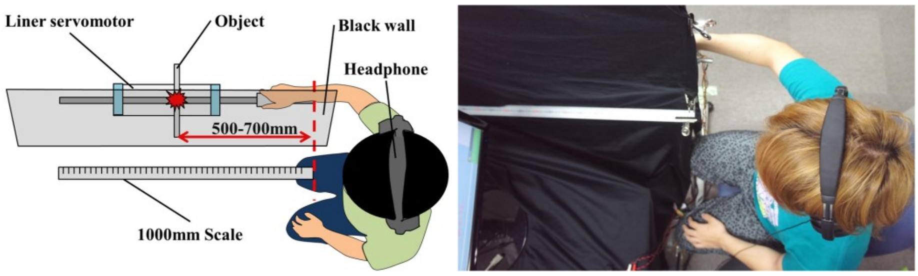

Fig. 6. Top view of experimental setup.

5 Results and Discussion

To verify the difference among conditions, a one-way repeated measures ANOVA and multiple comparisons (Ryan's method) were performed. Through all vibration and distance conditions, all participants tended to perceive the collision distance as shorter than the actual distance (500, 600, or 700 mm), including condition (d) (the natural condition).

Results at the distance of 700 mm are shown in **Fig. 7** (A). The vertical axis represents the average results of the perceived collision distance among all participants. The horizontal axis represents the conditions. The error bars indicate the standard deviation. There were significant differences between conditions (a) and (b), (a) and (c), and (a) and (d) ($p < 0.05$). Results at the distance of 600 mm are shown in **Fig. 7** (B). Similar to the 700 mm case, there were significant differences between conditions (a) and (b), (a) and (c), and (a) and (d) ($p < 0.05$). Results at the distance of 500 mm are shown in **Fig. 7** (C). Different from the other two results, there were significant differences only between conditions (a) and (c), and (b) and (c) ($p < 0.05$).

Discussion

As an overall tendency, the perceived collision distance was shorter than the actual distance, including for condition (d) (the natural condition). This can be explained from the viewpoint of dynamic touch. Chan reported that the increase in the diameter of the hand-held stick shortens the perception of the stick's length [4]. In the case of our device, the diameter of the acrylic grip (about 33 mm) was twice as big as that of the aluminum pipe (15 mm). Therefore, there is a possibility that the distance perception became shorter because of this length perception effect.

Then, we compared each statistical result with our proposed hypothetical model. As there was a significant difference between conditions (a) (vibration added to thumb side) and (d) (the natural condition), superimposing vibration onto the thumb side shortened the perceived collision distance compared with the natural condition at the 600 mm and 700 mm distances. Furthermore, there was also a significant difference between conditions (a) and (c) (vibration added to little-finger side), indicating that presenting the vibration to the thumb side shortened the perceived collision distance more than vibration to the little-finger side in all distance conditions. These results agreed with our proposed hypothesis.

On the other hand, there was no significant difference between condition (c) and (d) in all conditions. If we only perceive the distance by the vibration center of gravity in the palm, condition (c) should be perceived as longer than condition (d). Therefore, the results of condition (c) do not fully support our hypothesis. Thus, our hypothesis and device setup may need to be reconsidered, and we may need to include other factors such as the contribution of kinetic sensation or the resonance characteristics of the rod.

In sum, the perceived collision distance was altered by providing additional vibration, and increasing the vibration ratio on the thumb side significantly shortened the perceived collision distance compared to doing so on the little-finger side (which we consider counterintuitive). Also, this tendency was observed regardless of the real distance between palm and object, but may be easily induced when the object is placed far from the palm.

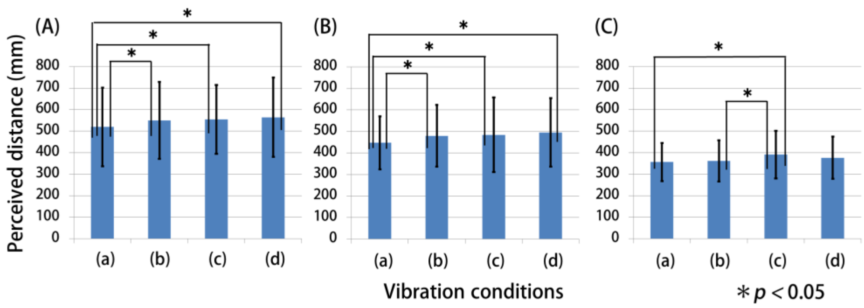

Fig. 7. Results for different vibration conditions at a distance of (A) 700 mm, (B) 600 mm, (C) 500 mm.

6 Conclusion

In our previous study, we proposed the hypothesis that distance information produced when hitting with a stick can be retrieved by the “center of gravity” of vibration in the palm, and tried to verify this hypothesis by superimposing external vibration onto the real vibration while percussing.

In this paper, we further used various real distance conditions between the palm and the object to investigate the relationship between the effect of artificial vibrations from actuators and the real distance. The experimental results were partly positive and partly negative: vibration to the thumb side shortened the perceived collision distance more than vibration to the little-finger side, which agreed with our hypothesis, but vibration to the little-finger side did not change the perceived distance relative to the natural condition, which did not agree with our hypothesis. These tendencies were observed regardless of the real distance between palm and object, but may be easily induced when the object is placed far from the palm.

In the present study, we superimposed external vibration onto the real vibration from percussion. In future work, we will investigate the reason why the vibration to the little-finger side did not affect the perceived distance by further developing our hypothesis, including other factors such as the contribution of kinetic sensation or the resonance characteristics of the rod, and determine how to intuitively present positional information from the collision.

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