Edge angle perception precision of active and passive touches for haptic VR using dot-matrix display

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Received: 10 January 2019; Revised: 22 May 2019; Accepted: 23 June 2019

Abstract
In haptic virtual reality (VR), there are two important challenges: one is the difficulty of reproducing a surface feeling with haptic devices, and the other is the presentation method used for the display. We developed a tactile mouse using palm presentation for the former challenge to tackle the issue, “which tactile perception is superior for texture recognition, active or passive touch?” In a psychophysical experiment, two oblique edges of dot-patterns are presented consecutively as simple textures, and human subjects compare them to determine which is larger. We evaluated the precision of perception using the difference threshold of the edge angles calculated by the constant stimuli method. Experimental results show that the perception precision at low edge movement speeds (45 and 90 mm/s) was higher than that at high speeds (130 and 170 mm/s), and moreover, that there was no significant difference in precision of the edge angle perception between active and passive touches. The former finding seems to be caused by how well the mechanoreceptive unit handles uneven surfaces. The latter finding is due to the mechanism of the efference copy of a motor signal provided from the motor cortex not having a significant influence on texture recognition. The tactile image deterioration induced by the object movement might be compensated for with information processing in the central nervous system, which keeps stable tactile image without help from the efference copy. This work contributes to developing the haptic device which provides visually impaired persons with the tactile map.

Keywords: Haptic device, Virtual reality, Tactile display, Active and passive touch, Edge angle, Efference copy

1. Introduction

Recently, researchers in virtual reality (VR) have developed several types of haptic devices, such as delta haptic devices (Grange et al., 2001), vibro-tactile displays (Ikei et al., 1999), and tactile-force displays (Ikei and Shiratori, 2002). These haptic devices are expected to be used for applications such as VR-based entertainment, rehabilitation, and remote-control robotics. Such haptic devices are capable of presenting force as well as tactile sensations, and they have great potential for further implementations (Massie and Salisbury, 1994; Broeren et al, 2004; Halvorsen et al., 2006). However, they must overcome two challenges: one is the difficulty of reproducing a surface feeling, and the other is the presentation method used for the display.

The first challenge is the difficulty of mechanically reproducing the feeling of touching a surface. To produce this feeling, we developed haptic devices equipped with a refreshable dot-matrix display, which offers superior presentation in a convex shape (Tsuboi et al., 2013). Although the dot-pattern-type displays meet the performance requirements of this challenge, they still face problems related to hardware. The hardware problem involves the resolution of the dot-matrix display, which reproduces any figure through dot-patterns created by the stimulus pins’ protrusions. Specifically, we cannot reduce the distance between dots to less than roughly 2 mm due to the limitations of the current micro actuator technology. As an overview of the current technology level, we present a survey of the dot-matrix display’s actuators in Section 2.

Since our fingertips have an approximately 2-mm two-point threshold, we should reduce the distance between the
dots as much as possible. This is why we focus on the palm, which has an approximately 13-mm two-point threshold (Johansson and Vallbo, 1983; Fox, 2002). As one approach to this problem, in our previous study (Rajaei et al., 2016), we introduced a dot-matrix display called SC10 with a pin distance of 2.4 mm, which is sufficiently smaller than 13 mm. We applied this to our tactile mouse exhibiting convex dot patterns on the palm to evaluate the dot-matrix display in VR, since the only difference between the fingertip and the palm is the receptor distribution. If in future tactile devices the current actuator technology advances to produce a fine pin distribution of less than 1 mm, the findings obtained from our tactile mouse will thus provide design parameters for new haptic devices applied to the fingertips.

Next, the second challenge is how to direct the surface-touch feeling. We believe that the lack of hardware capabilities mentioned above can be compensated through the direction of tactile presentation. Here, we assume that the hardware problem is covered with a surface feeling modulated by the kinesthetic feeling of the arm in an active touch because we believe that multimodal interaction enhances our perceptual sensitivity and precision. The possibility of compensation is approached by examining the issue, “which touch is superior, active or passive?” While an active touch positively perceives a stationary object with hand movement, a passive touch perceives a moving object without hand movements. In the active touch, surface texture is decided not only by tactile sensation but also by an efference copy of the motor signal. Furthermore, the active touch is performed in the optimal touching manner. Although the active touch seems be superior to the passive touch, it remains undetermined which touch is superior for VR.

This paper’s objective is to examine the above issues for our tactile mouse equipped with a refreshable dot-matrix display. For active tactile sensations, which require a more difficult presentation method than passive touching, the dot-pattern created on the display pad must be refreshed dynamically and synchronized with the user’s hand movements when using the mouse. We conducted a series of experiments with the tactile mouse to explore the oblique edges created by the pins’ protrusions and evaluated the edge slopes. Two different directional edges are presented consecutively, and the subjects compared them to determine which edge angle is larger. We evaluated the perception precision through the difference threshold of edge angles determined by a psychometric function obtained through the constant stimuli method (Gescheider, 1997). Based on the experimental results, we discuss the optimum movement velocity of the tactile mouse and the difference between passive and active touches in manipulating the tactile mouse. Our results will clarify not only the hardware design but also the software development in VR.

After we survey the current refreshable dot-matrix displays in the next section, the tactile mouse produced in this study is described in Section 3. Then, explaining the psychophysical procedure used to evaluate our tactile mouse in Section 4, we discuss our experimental results in Section 5. Finally, we give our conclusions of this study in Section 6.

2. Survey of refreshable dot-matrix displays

In this chapter, we survey the existing refreshable dot-matrix display technologies to compare our design with them. Several studies on refreshable dot-matrix displays have been conducted beginning in the 1990s, as shown in Table 1. In a dot-matrix display, it is very important to make the dot spacing as small as possible so that human subjects can perceive a continuous line, even though the line is actually composed of dots. Response time, compactness, energy consumption, and cost are also important factors in addition to the dot spacing. Consequently, many researchers have developed dot-matrix displays using several kinds of actuators to optimize these factors.

Although there are many refreshable braille displays using various actuators as shown in Table 1, none has simultaneously satisfied the requirements of distance between pins and response time for haptic devices. Although the piezoelectric actuator does not satisfy all of the specifications discussed above, we adopt it in this paper by taking into account its controllability and compactness.

3. Display system
3.1 Design of tactile mouse

In this section, we explain the tactile mouse developed for the human palm (Rajaei et al., 2016). We adopted the mouse-type display because it is very easy for subjects to move it and touch a virtual object with natural motions. We adopted a refreshable braille display, SC10, which is equipped with 12×32 (= 384), 2.4-mm pitch stimulus pins. Each stimulus pin protrudes with an approximately 0.7-mm stroke when 200 V is applied to a bimorph piezoelectric ceramic actuator, which pushes the pin’s bottom.
Table 1  Survey of refreshable dot-matrix display technologies

| Actuator                        | Year | Authors         | Matrix | Resolution | Stroke | Presentation area | Force   | Frequency   |
|---------------------------------|------|-----------------|--------|------------|--------|-------------------|---------|-------------|
| 1. Piezoelectric actuator       | 1999 | Watanabe        | 4 × 8  | 2.4 mm     | 0.7 mm | 21 mm × 25.6 mm   | 0.177 N | 100 Hz      |
|                                 | 2007 | Ohka et al.     | 8 × 8  | 1.0 mm     | 0.7 mm | 7 mm × 7 mm       | 0.177 N | 100 Hz      |
|                                 | 2008 | Kyung et al.    | 5 × 6  | 1.8 mm     | 0.7 mm | 9.7 mm × 7.9 mm   | 0.06 N  | 350 Hz      |
|                                 | 2014 | Ros et al.      | 8 × 8  | 1.5 mm     | 0.7 mm | 10.5 mm × 10.5 mm | 0.0833 N| 20 Hz       |
| 2. Shape Memory Alloy (SMA)     | 1998 | Taylor et al.   | 4 × 16 | 3.6 mm     | 1.7 mm | 20 mm × 40 mm     | -       | 2 - 3 Hz    |
|                                 | 2012 | Zhao et al.     | 3 × 8  | 2 mm       | 3 mm   | 4.5 mm × 17.6 mm  | -       | -           |
|                                 | 2013 | Matsunaga et al.| 10 × 10| 1.27 mm    | 2 mm   | -                 | 0.1 - 0.15 N | 3 Hz      |
| 3. Micro stepping motor         | 1998 | Shinohara et al.| 64 × 64| 3 mm       | 10 mm  | 200 mm × 170 mm   | 2.94 N  | 0.067 Hz    |
| 4. Servomotors                  | 2002 | Wagner et al.   | 6 × 6  | 2 mm       | 2 mm   | 10 mm × 10 mm     | -       | 7.5 Hz (max. 25 Hz) |
| 5. Pneumatic pressure and low-temp. melting metal | 2004 | Nakashige et al.| 10 × 10| 2 mm       | -      | 20 mm × 20 mm     | Depends on pneumatic pressure | 0.06 Hz |
| 6. Phase-change material actuator | 2005 | Lee et al.      | -      | 2.5 mm     | 1 mm   | -                 | 0.3 W   | 0.01 - 0.04 Hz |
| 7. Electroactive polymer (EAP)  | 2007 | Kato et al.     | -      | -          | -      | -                 | 0.0147 N | 1-2 Hz |
|                                 | 2008 | Koo et al.      | 4 × 5  | 3 mm       | 0.5 mm | 11 mm × 14 mm     | 10 W/cm² | 50 Hz |
| 8. Flapper-type actuator        | 2007 | Yeh & Liang     | -      | 2.5 mm     | 0.7 mm | -                 | 0.156 N | -           |
| 9. Pneumatic actuator           | 2012 | Wu et al.       | 2 × 3  | 2.5 mm     | 0.6 mm | 2.5 mm × 5 mm     | 0.05 N  | 0.2-150 Hz |
| 10. Polyoxymethylene (POM)      | 2014 | Torrasa et al.  | 10 × 10| 3 mm       | 3 mm   | 25 mm × 25 mm     | 0.04 N  | 0.28 Hz (max.) |

Fig. 1  (a): Tactile display for a palm consists of an optical mouse and SC10, which is a braille display; (b), (c): Usage of this tactile display by touching the display pad with the palm

Fig. 2 Relationship between tactile sensation on hands and presentation capability of our tactile display
Since this dot-matrix display was designed for a blind person to read the text information through braille at their fingertip, the distance between dots is 2.4 mm which is larger than two-point threshold of the fingertip (Fig. 2). This distance between pins is very suitable to read the braille on the fingertip, but this is not suitable to feel a dots’ line pattern as a continuous line. This is because the operator perceives the dots’ line pattern as a series of dots due to the high resolution of the fingertip. On the other hand, in the palm case, the operator perceives the dots’ pattern as a consecutive line when touching it through their palm. This is because the resolution of the palm is much lower than the fingertip. That’s why SC10 is suitable presenting shape of the virtual object for the palm because the pin pitch of SC10 is 2.4 mm, which is much shorter than the two-point threshold of the palm 13 mm (Johansson and Vallbo, 1983; Fox, 2002).

Our tactile mouse system consists of a PC (OS: Windows 7), a DIO (PCI-2772C, Interface), an SC10, and an optical mouse. When the mouse cursor is moved and touches a virtual object that is projected on a liquid crystal display, the corresponding pins are pushed out to stimulate the subject’s palm (Figs. 1 and 2).

In the experiments explained in Section 4, since the virtual edge movement is restricted to the horizontal movement, the mouse movement is guided by wood rails and rollers. In Fig. 1(a), four wood rails appear as thin straight bars; their upper surfaces are mated to grooves of a miniature roller installed the bottom of tactile display. Hence, the tactile mouse is mobile only along the rails to keep a straight horizontal motion.

The software was corded with C++ and Open GL in order to perform several different experiments. To evaluate the contact between the mouse cursor and the virtual object, we used the RGB value of Open GL (Fig. 3). The mouse cursor consists of a 12 × 32 matrix corresponding to the dot-matrix display and the each cell color of this matrix is adopted as green (RGB value: 0, 255, 0); a virtual object’s color is adopted as red (RGB value: 255, 0, 0). The cursor matrix is moved according to the mouse movement. When the cursor matrix touches and overlaps the virtual object, the color of the overlapped matrix cells is changed from green to yellow (RGB value: 255, 255, 0) to protrude the corresponding pins of the display. Since this contact determination system does not require calculation of distance between the mouse cursor and the virtual object, the calculation cost of contact determination is reduced to present pin stimulation to participants without a time delay. Consequently, this approach has the advantage of making it easy to create experimental tasks.

3.2 Active touch and passive touch

In this study, we experimentally revealed the perception precision when objects were touched with the palm. There are two kinds of touching methods: passive and active touches. In a passive touch, the subjects kept their right hand motionlessly on the tactile display, and the virtual edges were moved front-and-back under their hand (Fig. 4). In the active touch, the subjects moved their hand with the tactile display by keeping their hand on it.

In the following, we will discuss whether the active touch is superior or not based on the viewpoint of neuroscience using Fig. 5, of which a diagram was first presented by Taylor et al. (Taylor et al., 1973), to explain the active touch.
Fig. 4 Virtual edge presentation in passive touch and active touch

Fig. 5 Active touch and passive touch (Redraw the previously published figures of Taylor et al., 1973; Iwamura, 2001)

The process of active touch is based on planning the behavior in the brain and the signal being sent to the kinesthesis to move the hand, as shown in Fig. 5. Then, after touching the object to obtain texture interactions, the sensory signals of tactile sensation captured by the receptor systems return to the brain. On the other hand, in the passive touch, there are no motor signals sent to the kinesthesis. Especially, there is a significant difference between the active touch and passive touch whether the efference copy produced by the behavior control is generated or not. We assumed that the efference copy significantly affected the precision of the tactile texture obtained by the texture analyzer.

3.3 Modified constant stimuli method

We adopted the modified constant stimuli method to examine different thresholds of angle. In the constant stimuli method (Gescheider, 1997), a subject compares two stimuli and judges which stimulus is larger. In this case, a subject touches the edges of the oblique sides of two figures, which are the standard stimulus and the comparison stimulus, and judge which edge’s angle is larger. This trial is performed with various combinations and with many subjects. The probability of the comparison stimulus being judged as larger than the standard stimulus can be converted to a z-score, and the difference threshold of the angle can be calculated using psychometric functions of the z-score. If we conduct a task under a bad condition of perception precision, the inclination of the psychometric function decreases and the difference threshold of the angle increases. Therefore, a statistical procedure is required to estimate the angle-detection ability.

In this study, we modified the constant stimuli method to decrease the number of trials in the experiment and to increase the concentration of the subjects. This experiment was conducted with the standard and comparison stimuli...
presented in random order. A single test is comprised of \( n \) trials, calculated as \( n = m (l + 1) \), where \( m \) and \( l \) are standard and comparison stimuli numbers, respectively. The participants should compare all combinations of standard and comparison stimuli. However, when standard stimulus and the comparison stimulus are same, the participants should compare this combination twice because of excluding influence of stimulation order. Thus, the \( "+1" \) appearance in the parentheses means a double count of the same stimulus cases. Although the standard stimuli are equivalent to those used in the constant stimuli method, where \( m = l \) is normally adopted, in this study \( m < l \) is adopted. After statistical analysis, we obtained the difference threshold (Differentz Liemen; DL) for several conditions based on a psychophysical procedure (Gescheider, 1997).

We conducted two experiments: Experiment 1 is a passive touch task to clarify the relationship between the object movement velocity and perception precision; Experiment 2 is a task to clarify whether passive or active touch is superior.

4. Psychophysical experiment
4.1 Participants

Seventeen students (2 females and 15 males, from 22 to 25 years old) of Nagoya University took part in the psychophysical experiments of our study and were paid for their participation. All tests were approved by the Ethics Committee of Nagoya University. In the following Experiments 1 and 2, we made the students wear a sleep mask to eliminate all visual information.

4.2 Experiment 1

In Experiment 1, we performed a passive touch experiment. The purpose of this experiment was to reveal the relationship between perception precision and object velocity in passive touch. Accordingly, we prepared virtual edges that were moved front-and-back under the subject’s hand at four velocities: 45, 90, 130, and 170 mm/s. In each velocity condition, the difference threshold of the angle was calculated by the modified constant stimuli method, whose conditions are shown in Table 2. In each test, each subject performed 96 trials, a number which was calculated as follows: (four kinds of velocities) × (three kinds of standard stimuli) × (seven kinds of comparison stimuli + 1). The test includes pairs of identical stimuli, i.e. 65° vs. 65°, 70° vs. 70°, and 75° vs. 75°, excluding error of stimulus order. These trials and the orders of the standard and comparison stimuli were performed randomly; three identical tests were performed by each subject.

4.3 Experiment 2

Experiment 2 consisted of both passive and active touches. The purpose of this experiment was to reveal which type of touch is superior. The active touch needs a command to move the hand, from the brain to relevant muscles and actual hand movement, while the passive touch does not need such a command. In Experiment 2, we investigated how this difference between active and passive touches affected the perception precision by the modified constant stimuli method, whose conditions are shown in Table 3. In the active touch, the subjects horizontally move the tactile mouse, of which motion is restricted with the rails and rollers, as mentioned in Section 3.1. To equalize the experimental conditions (e.g. touching speed) between active and passive touches, except for sensory processing, the passive task was performed by playing back the recorded previous movement of the active touch. Consequently, in Experiment 2 we conducted a fixed-order trial: active touch followed by passive touch. In Experiment 2, one test consisted of 30 trials: (3 standard stimuli) × (9 comparison stimuli + 1). Pairs of stimuli were randomly presented to the subjects. The test was repeated three times for each subject.

Table 2 Experiment 1 conditions

| Parameter          | Value          |
|--------------------|----------------|
| Velocity           | 45, 90, 130, and 170 mm/s |
| Standard stimuli   | 65°, 70°, 75°  |
| Comparison stimuli | 55°, 60°, 65°, 70°, 75°, 80°, 85° |

Table 3 Experiment 2 conditions

| Parameter          | Value          |
|--------------------|----------------|
| Velocity           | According to subject’s manner |
| Standard stimuli   | 65°, 70°, 75° |
| Comparison stimuli | 50°, 55°, 60°, 65°, 70°, 75°, 80°, 85°, 90° |
5. Experimental results and discussion

5.1 Experiment 1
5.1.1 Experimental result

In Experiment 1, we investigated the difference thresholds of angles under four velocity conditions: 45, 90, 130, and 170 mm/s. The z-scores and psychometric functions with four velocity conditions for each standard stimulus are summarized in Fig. 6. The difference thresholds of angle were calculated through psychometric functions (Fig. 7). We statistically analyzed the z-scores and psychometric functions using SPSS version 16.0 and conducted an analysis of covariance (ANCOVA) to compare their inclinations. In Fig. 7, the significance level between two velocity conditions and the pairs of significant difference are symbolized by * and ** for $p < 0.05$ and $p < 0.01$, respectively. Here, the lower-speed conditions (45 to 90 mm/s) had better results than the higher-speed condition (130 mm/s), and the highest-speed condition (170 mm/s) had the worst result when the difference threshold of the angle is measured in the passive touch.

5.1.2 Discussion

The perception precision at low speed (45 to 90 mm/s) is better than that at high speed (130 to 170 mm/s) in passive touch. As is well known, frequency $f$ is calculated by $f = v/\lambda$; where $v$ and $\lambda$ are velocity and wavelength, respectively. Here we assume a convex line movement on the dot-matrix display with velocity $v$. Then, distance between two dots (pin pitch) is adopted as the wavelength $\lambda$ because the actuator should protrude a pin during the line traveling the distance to...
demonstrate continuous movement of the line. Therefore, the frequency is calculated by the following equation:

\[
f \text{(Frequency)} = \frac{v \text{ (velocity)}}{d \text{(pin pitch)}}
\]  

(1)

Since pin diameter \(d\) is 2.4 mm, the low speeds of 45 and 90 mm/s correspond to 19 and 38 Hz, respectively. On the other hand, the high speeds of 130 and 170 mm/s are 54 and 71 Hz, respectively. Since the fast adaptive type I unit (FA I) can accept a low frequency under approximately 50 Hz (Rajaei et al., 2012) while the slowly adaptive type I unit (SA I) can accept a convex shape on the surface, we obtained a higher perception precision in the low speed condition due to SA I and FA I activation. Therefore, the improved object speed was less than 90 mm/s for a refreshable dot-pattern type display.

![Image](image_url)

**Fig. 8** z-score in active and passive touch (left side: standard stimulus is 65°, center: standard stimulus is 70°, right side: standard stimulus is 75°)

![Image](image_url)

**Fig. 9** Difference thresholds of the angle (left side: standard stimulus is 65°, center: standard stimulus is 70°, right side: standard stimulus is 75°)

### 5.2 Experiment 2

#### 5.2.1 Experimental result

In Experiment 2, the perception precisions of active touch and passive touch were investigated. The z-scored psychometric functions are shown in Fig. 8, and the difference thresholds of edge angles are shown in Fig. 9. ANCOVA was performed to investigate the significant difference between these two z-scored psychometric functions. From the analysis, we obtained \(p = 0.49, 0.11\) and 0.16 for 60, 70 and 75°-cases, respectively.

#### 5.2.2 Discussion

The results of Experiment 2 indicate that there was no difference between the passive touch and the active touch, despite the difference of the sensory processing process from the viewpoint of neuroscience explained by Fig. 5. In the
case of active touch, the speed was perceived by the afferent muscle signal and efferent motor command while moving the hand as the shape was perceived by one’s tactile sense. On the other hand, in the passive touch, all object information was perceived simultaneously by tactile sense, while there was no significant difference between the passive and active touches. This result suggests that humans have the ability to recognize an object’s shape precisely from tactile information only. We assume that information instead of the efference copy is produced in the texture analyzer shown in Fig. 5 based on time variation in the tactile information. The tactile image deterioration induced by the object movement might be compensated for with information processing in the brain, which keeps stable tactile images without help from the efference copy. Furthermore, from the viewpoint of a VR engineer, the abovementioned ability of passive touch can be utilized in the development of smaller VR devices that do not require motor-driven parts for texture presentation.

Next, we consider the adaptation of tactile velocity observed in the active touch. In Experiment 1, we clarified that the lower-speed conditions (45 mm/s and 90 mm/s) are better for recognizing an object precisely. Therefore, we hypothesized that humans might control the speed of touching an object between 45 and 90 mm/s in order to maximize their perception precision. Figure 10 shows the relationship between average speed and the number of tests in the active touch. This figure shows that the speed increases to 56, 62, and 67 mm/s, which are within 45–90 mm/s, as the tests progress from the 1st to the 2nd and 3rd tests, respectively. This result suggests that humans seem to adjust their speed of touching an object in the range of 45 to 90 mm/s, which provides FA I activation. If these tests were repeated, they would be able to clarify the optimal speed of touching the object.

Finally, we consider the difference threshold of the fingertip and the palm. The biggest difference between the palm and the fingertip is the density of sensory receptors. The sensory receptors of the fingertips are distributed at a density roughly five times that of the palm. However, the difference threshold of the edge angle is nearly equal between the palm (7.1°) (Zhou et al., 2011) and the fingertip (7–9°). This fact suggests that the perception precision of edge direction depends on both of the receptor density and the touching area.

6. Conclusion

For the development of compact and inexpensive VR device technology, we investigated whether active or passive touch is superior as a movement style for touching an object. We developed a tactile mouse with a refreshable braille display and conducted a series of psychophysical experiments to determine the difference thresholds of edge angles in passive and active touches. In Experiment 1, we clarified that the perception precision becomes maximum when FA I is the most activated. In Experiment 2, we identified no difference between active and passive touches, even though they apply different recognition mechanisms. We conclude that humans have the ability to accurately recognize an object’s speed and shape in the palm simply from tactile information. From this result, if a presentation item is restricted to an object shape, we can develop a haptic device that does not require a motor-driven mechanism.

The abovementioned finding generally contributes miniaturization of any haptic device because the movement mechanism generating active touch sensation is not always required to keep presentation quality. For example, this result will contribute a design of tactile map device for visually impaired persons. There is a tactile map to provide navigation information for the visually impaired person through convex patterns showing roads and buildings. If the pattern of map...
is refreshed according to the visual impaired person’s walking, it can used as a navigation device. Since the result of this study shows that the person can obtain the object’s accurate speed and shape simultaneously displayed on the haptic device through passive sensation, the person can recognize displayed map data without any mechanism to move the whole dot-matrix display.

In future work, we will investigate two strategies to enhance haptic presentation: one is the cooperation of another modality of tactile presentation, and the other is to apply tactile recognition phenomena based on the human neural system. For the former strategy, we intend to use tangential stimulation to excite SA II, since the authors demonstrated the effect of tangential stimulation in a previous paper (Zhou et al., 2011). For the latter strategy, we have two plans. The first involves the velvet hand illusion, which was examined in a previous paper (Rajaei et al., 2013). The second strategy is to use stochastic resonance, which enhances human sensitivity using a proper level of vibro-tactile stimulation (Beceren et al., 2013).

Acknowledgments

The authors would like to thank the support of JSPS Kakenhi Grant Number 17K20100 and the Toyoaki Scholarship Foundation.

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