Impact Vibration Source Localization in Two-Dimensional Space Around Hand

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Abstract—This study investigated the localization ability of an impulse vibration source outside the body in two-dimensional space. We tested whether humans can recognize the direction or distance of an impulse vibration source when using their hand to detect spatiotemporal vibrotactile information provided by the propagated vibrational wave from the source. Specifically, we had users put their hands on a silicone rubber sheet in several postures. We asked users to indicate the position of the vibration source when a location on the sheet was indented. Experimental results suggested that the direction of the impact vibration source can be recognized to some extent, although recognition accuracy depends on hand posture and the position of the vibration source. The best results were achieved when the fingers and palm were grounded and a vibration source was presented around the middle fingertip, and the directional recognition error in this case was 6°. In contrast, results suggest it is difficult to accurately recognize the distance of the vibration. The results of this study suggest a new possibility for directional display where vibrotactile actuators are embedded at a distance from the user's hand.

Index Terms—Haptics, Vibration, Vibrotactile, Vibration Localization

1 Introduction

The human auditory system can identify both the direction and distance of sound sources [1], [2]. The auditory system uses several cues for sound source localization, such as interaural differences in time and intensity between both ears, spectral information, and pattern matching [3], [4]. This knowledge of auditory mechanisms is used for simulating sound fields [5], [6] to present spatial information in the user's peripheral space. Considering that sound is the perceptual result of mechanical vibrations traveling through a medium such as air, we hypothesized that humans could identify vibration sources outside the body not only with the ear but also with the hand's vibrotactile sense.

Vibrotactile stimuli as a feedback modality have been widely explored in various application scenarios, particularly to present spatial information when the visual and auditory channels are overloaded [7] or impaired [8]. For example, when we ride in cars, the visual and auditory channels are not vacant, and recent research is increasingly focusing on the presentation of spatial information using the vibrotactile channel [9], [10]. If the position of a vibration source in relation to users were recognized, then this information could support the user's activity such as monitoring of autonomous robotic systems moving in two-dimensional space. For example, humans can monitor an autonomous robotic system if the recognition of the positions of the obstacles by the autonomous robotic system in two-dimensional space can be conveyed to the humans.

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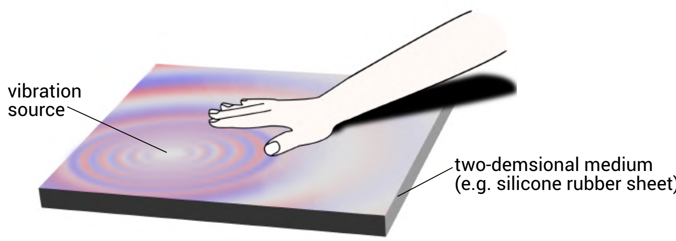

Fig. 1: We investigate human two-dimensional localization ability of vibration sources outside the body using spatiotemporal cues provided by propagated waves.

Previous studies investigated the localization ability of vibration sources on the body's surface and the use of that ability for direction information presentation. Researchers attached a vibrator array directly to the surface areas of users' bodies such as the hand [11], torso [12] or wrist [13]. This method was effective for indicating direction to the user, but attaching a vibrator directly to a user's body is not always a viable option. The vibrotactile actuators must be laid out for the limited space in contact with the body. For example, when it is desired to present directions with high resolution, it is necessary to arrange vibrotactile actuators at a high density, but it is costly to miniaturize and integrate the actuators in a limited mechnical spaces. In addition, the heat generated by the presentation system including the vibrotactile actuator might make it worse the tactile impression of the display. These problems are unavoidable when the vibrotactile actuators are in contact with the body.

This study explores another possibility of presenting spatial information from vibration sources that are remotely placed from the user's body. In this setup, it is not necessary to contact the vibrotactile actuators to the body, and thus the problem of the layout of the vibrating actuator in a limited space and the problem of heat are alleviated. In this case, the localized vibrator source position information emanating from outside the hand might indicate the direction and distance from the hand. However, it is still unclear how well humans can localize the vibration source. Thus, we investigated the localization ability of an impact vibration source outside the body. We made participants judge the vibrator source position when they put their hands on a silicone rubber sheet, and a location on the sheet was indented (shown in Fig.1). In this case, the localized vibrator source position information emanating from outside the hand might indicate the direction and distance from the hand.

The contribution of present study is the clarification that the direction of the impact vibration source can be recognized to some extent, although recognition accuracy depends on the hand posture and the position of the vibration source. The best results were achieved when the fingers and palm were grounded, and a vibration source was presented around the middle fingertip, and in this case, the directional recognition error was 6°. In contrast, results suggest it is difficult to recognize the distance of the vibration accurately. Our results open possibilities for interfaces that present direction information to a user without requiring the attachment of a vibrator to the user's body.

2 Related Work

We introduce previous studies on vibration localization on the body's surface and localization outside the body, and we clarify differences from our study.

2.1 Localization of Vibration Source on Body Surface

A number of studies have examined the localization vibrotactile stimuli applied to different areas of the body's surface such as hands [14], wrists [13], [15], arms [16], [17], the abdomen [12], [18], [19], waist [20], back [21], and head [22]. For example, Chen et al. [13] used a 3×3 array of linear resonance actuators to investigate vibrator localization performance at the wrist. Similarly, Sofia et al. [23] used a 3×3 array on the palm.

The localization accuracy depended not only on the area of the body but also the number of vibrators or inter-vibrator distance. The work [18] found that as the number of vibrators increased from 6 (inter-vibrator distance: 140 mm) to 12 (inter-vibrator distance: 72 mm), the localization accuracy decreased from 97 % to 74 %. Compared to these variables, the frequency of vibration had little effect on the ability to localize [24]. In addition, it was reported that head [25] or gaze direction [26] affected the accuracy of localization.

Localized vibration sources on body surfaces do indicate direction, and the applicability of direction presentation has been widely explored in various application scenarios. These include the presentation of tactile directional navigation [27] and warning signals for drivers [28] and possibly also for blind people.

However, attaching vibrators to the user's body surface may take time and effort and sometimes be uncomfortable. We explored the possibilities for interfaces that present direction information to the user without requiring the attachment of a vibrator to the user's body.

2.2 Localization of Vibration Source Outside Body

There are some studies that investigated localization ability when users held the edge of a one-dimensional medium (e.g., a stick) which was stimulated at some distance from the holding point. In this situation, the localized vibration position information indicates the distance from users. Miller et al. [29], [30] showed that when humans actually held a wooden stick with one hand, they could recognize the distance of an object when the stick contacted said object. The localization succeeded with both self-generated action and passive reception of impact. Gongora et al. [31] investigated recognition of the point to which the impact was applied when users held a rod with both hands. First, they recorded the vibration when users gripped both ends of either wooden, aluminum, or oxymethylene sticks with both hands and a location on the stick was hit. Then, they presented users with recorded vibrations and made users judge the location of impact. The estimated position of impact was imprecise and depended on the kind of material. In addition, their results suggested that the amplitude and duration of vibration were cues to recognition. Sreng et al. [32] investigated whether users could recognize the distance when they held a vibrator as well as when they held a rod by its ends. They used a vibration model of the Euler–Bernoulli beam or simplified decaying sinusoids. Their experiment showed that users could associate the impact location with vibration patterns.

In contrast to studies that investigated the localization ability via propagating waves through a one-dimensional medium, we focused on the localization ability via waves propagating through a two-dimensional medium. In such a situation, the localized point indicates not only distance but also direction information to users. The work by [33] proposed a similar concept to ours, with a system to present users with a vibration source in two-dimensional space, but the work did not clarify how well users can localize the source because they did not conduct an experiment. Our contribution is to provide experimental results and discussions of such a situation.

There are other studies extending phantom sensation [34], [35], which is a phenomenon of tactile illusion that can act as a reference for the presentation of the sense of movement. In this phenomenon, the amplitude of the vibrating stimuli presented to the two points can be controlled such that the user can perceive an illusionary motion in the area on the body surface between the two points. The work by [36], [37], [38] extended the phantom sensation and attempted to present the illusory phantom sensation in the air where there are no body surfaces.

In these cases, as we describe in the introduction section, the vibrotactile actuator contact with the body surface, and thus there is the problem of the layout of the vibrating actuator or the problem of heat. Thus, we examined the possibility of localization of vibration sources that are remotely placed from the user's body.

3 Research Question

This study assumes specific situations where users place a specific body site on a two-dimensional medium and the vibration originating from a single point travels to the human body site. The system for realizing such situations has three components: vibration source, medium, and human (shown in Fig. 2). We focused on specific parameters related to each component that could affect the localization ability. The parameters related to the vibration source include the vibration waveform and the position of the vibrator source. The parameters related to the medium include the material and size. The parameters related to the human include the body sites and posture, which indicate how to locate the body site with regard to the medium.

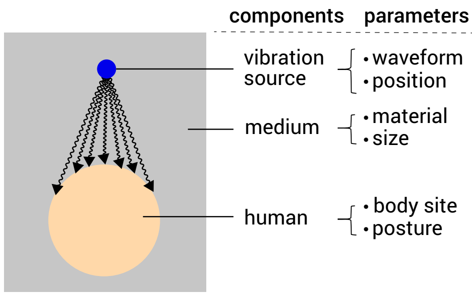

Fig. 2: Components and parameters that could affect localization ability.

From here, we discuss each component's parameters. First, we focus on the parameters related to the human.

- Regarding the body site, this study used the hand because the human hand has a relatively high sensitivity to vibration among all body sites and is the ordinary input/output area when touching interface devices. The hand grounded to the medium receives spatiotactile cues given by the propagating vibration wave (shown in Fig. 3). When the stimulus position changes, the spatiotemporal cues change, and it is expected that users will be able to localize the source position using the characterization of the cues.
- The posture, or the method of locating the human distributed tactile sensors of the hand on a medium, could affect what spatiotemporal cue is obtained. We regard posture as a variable to test how it affects the localization ability in an experiment.

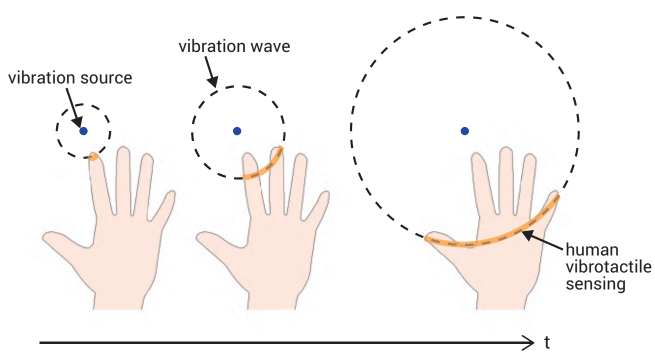

Fig. 3: Vibration propagates through medium and gives human hands spatiotemporal tactile cues.

Next, we focus on the parameters related to the vibration source.

- Regarding the waveform of a vibration source, we used an impulse signal – as in previous studies that investigated vibration localization outside the body [29], [30], [31] – instead of a cyclic signal.
- The position of the vibration source could affect what spatiotemporal cue is obtained. This is because the body sites that sense a propagated vibration change depending on the position of the vibration source, and thus the localization ability is influenced. We regard the position of the vibration source as a variable to test how it affects the localization ability in an experiment.

Last, we focus on the parameters related to the medium.

- Regarding the material of the medium, we used materials such as urethane foam, plastic, aluminum, and silicone rubber sheets. When we used urethane foam, users could not feel slight vibrotactile cues from faraway points owing to vibration attenuation. When we used plastic or aluminum plates, the propagated vibration could reach the user's body, but we felt that the entire medium vibrated at the same time, and it was difficult to localize the source. This was owing to the high speed of vibrations traveling through hard materials such as plastic or aluminum plates. On the other hand, when we used a soft silicone rubber sheet, we felt that we could localize the vibration source owing to the slow travel speed of the vibration. We used a silicone rubber sheet as the medium in the experiment.
- Regarding the medium size, we compared several silicone rubber sheets that were different in thickness. The thicker the silicone rubber sheet, the better we could locate the vibration source. When the silicone rubber sheet was thin, the vibration easily attenuated at the place first indicated by the user, and there were fewer vibrational cues at other body sites. By contrast, when the silicone rubber sheet was thick, the vibration did not easily attenuate.

Based on these considerations, the research questions of this study are as follows:

- How well can humans recognize a vibration source's direction and distance from the body?
- How does the hand posture on the medium affect the localization ability?
- How does the vibration source position affect the localization ability?

4 Experiment

Twelve participants (12 male, all right-handed, with a mean age of 23.1 (SD: 1.6) years) participated. All participants were naive to the purpose of the study. Written informed consent was obtained from each individual before the experiments were performed. This study was approved by the ethics committee of the University of Electro-Communications (approved number: 20053).

4.1 Apparatus and Stimulus

Participants were seated comfortably on a chair (shown in Fig. 4). Visual information, such as the change in the reflection of the sheet's illumination when the sheet was indented, was recognizable to the participants, so the participants were blindfolded during the task with a sleep mask. They wore noise-canceling headphones playing white noise to muffle external sounds. Their right arm was placed in an armrest. Their hand was set on the designated area on the silicone rubber sheet under several posture conditions. The size of the silicone rubber sheet was 500 mm×500 mm, and the thickness was 10 mm. The hardness of the silicone rubber sheet was 30 (tested by a durometer of type Shore A). We drew a red grid on the sheet to make it easier for the experimenter to read the subject's answer position. The unit of the red grid was 10 mm. The silicone rubber sheet was placed on soft urethane foam (INOAC CORP, ECZ, 25 % ILD was 80) to diminish the influence of vibration propagation via the ground. The size of the soft urethane foam was 500 mm×500 mm, and the thickness was 100 mm. The solenoids (CBS10290100, TAKAHA KIKOU Co.) were placed inside the urethane foam. The diameter of the contactor at the top of the solenoid was 3 mm. The soft urethane foam was put on a desk.

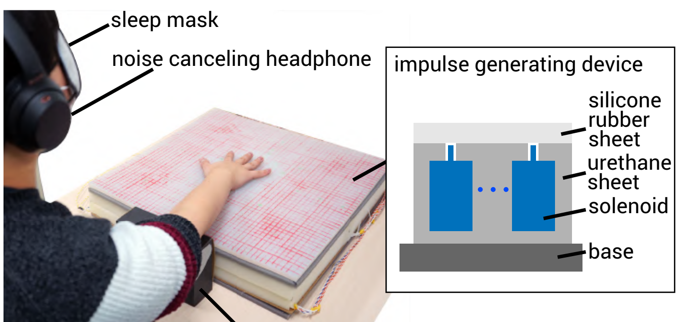

Fig. 4: Apparatus.

There were 24 points that were indented by the solenoid's contactors in eight directions on three circumferences (shown in Fig. 5). The radii of the three circumferences were 130 mm, 170 mm, 230 mm. Participants did not know that only those discrete 24 points would be stimulated. They only knew that some location on the whole area of the silicon rubber sheet would be stimulated.

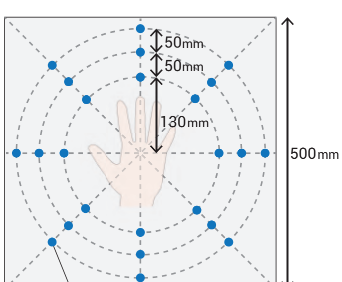

Fig. 5: Layout of 24 points of solenoid's contactors.

The solenoids were actuated by a driver circuit (SB-6565-01, TAKAHA KIKOU Co.). When configuring amplitude of impulse, we found that it was difficult to localize the source when the amplitude was too small, but it was too intense to use as a user interface when the amplitude was too large. We adjusted the amplitude to be as large as possible without being too intense. We measured the displacement of the silicone rubber sheet indented by the solenoid contactor using a laser displacement sensor (ZX2-LD50, OMRON Co.). The measured displacement is shown in Fig. 6, which shows that the maximum displacement was approximately 1 mm and the duration was approximately 0.2 s at the point of contact of the solenoid contactor. In addition, Fig. 7 provides information about attenuation of acceleration. We set the acceleration sensor (MPU-6050) at the center of the silicone rubber sheet and set another sensor (MPU-6050) on one of the discrete 24 points. We recorded acceleration at 2kHz individually when the 24 points were individually indented. The maximum amplitude of the accelerations is summarized in Fig. 7. The "0 mm" means the measurement at the point of indentation. The measurements at "130", "180", and "230" mm are the data measured at the center of the sheet. This suggests the stability of stimuli from any direction at the same distance. We also show the power spectral density of the propagated wave shown in Fig. 8 as supporting information.

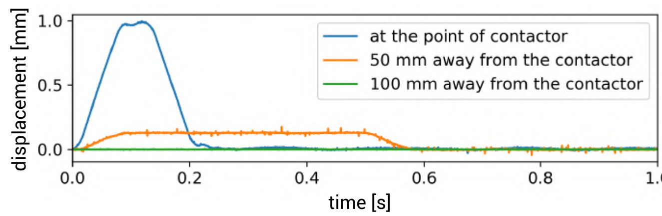

Fig. 6: Displacement of silicone rubber sheet at the point of contact of the solenoid contactor, 50 mm away from the point of contact, and 100 mm away from the point of contact when indented by solenoid's contactor.

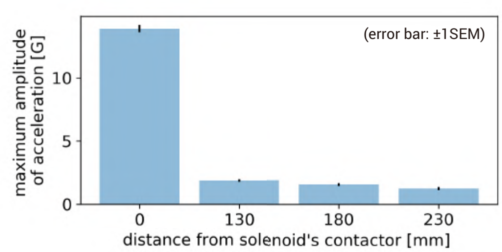

Fig. 7: Maximum acceleration of silicone rubber sheet at the point of contact of the solenoid contactor, 130 mm, 180 mm, and 230 mm away from the point when indented by solenoid's contactor.

In this experiment, there were three different conditions of hand posture. We call these "posture conditions." The conditions were related to touch with "two-fingertip", "five-fingertip", and "hand" (shown in Fig. 9).

- **two-fingertip condition**

  Under the two-fingertip condition, users grounded

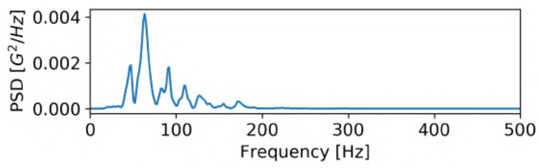

Fig. 8: Power spectral density of the propagated wave from 130 mm distant place.

the tips of their index and middle fingers on the sheet. This simulated the human ear situation in terms of the time difference and intensity difference between two sensing points. Of course, this only worked on the premise that the fingertip could be regarded as a point (although the fingertip was actually a surface with a small area).

- **five-fingertip condition**
  Under the five-fingertip condition, users grounded the tips of all their fingers (of the hand in question) on the sheet. This simulated a situation with five sensing points, and recognized the time and intensity difference between the five points.
- **hand condition**
  Under the hand condition, users put their hand flat on the sheet. This simulated the situation as if there are multiple distributed sensing points.

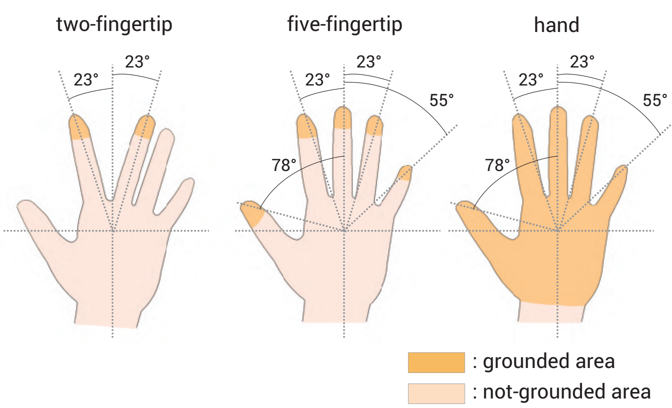

Fig. 9: Posture conditions.

We measured the width and height of the hand for each participant when the participant placed the hand under the "hand" posture condition. The measured width and height of the hands are summarized in Table 1. We defined the center of the hand as the middle point of its width and height. Participants set the center of their hand to the center of the silicone rubber sheet. Then, the angle of the fingers was adjusted as shown in Fig. 9. For all of the hand postures, participants placed their hands naturally without exerting any force on the silicone rubber sheet.

TABLE 1: Measured width and height of participant's hand.

	min	max	mean±SD
width [cm]	13	18	15.6±1.4
height [cm]	17	19	17.9±0.6

4.2 Task

This experiment used a within-participants design. At the beginning of the experiment, the participants were presented with written instructions that described the situation and tasks of the experiment. After reading this, participants moved on to the experiment. The experiment was composed of three blocks corresponding to three posture conditions. Each block comprised a familiarization phase and a test phase.

In the familiarization phase, all 24 points were stimulated sequentially at 5-s intervals. The order of stimulation was randomly assigned. No information about the positions which were stimulated was given to the participant. After this was completed, the test phase started.

In the test phase, one of the 24 points was stimulated in each trial. Participants answered where the stimulus point was by touching the point with their non-dominant hand's index finger. We adopted this method following previous work by [39], which investigated localization on the hand surface. To prevent the participant from noticing that the solenoids were not present under their fingers or hands, we told participants that the vibration might occur anywhere on the sheet, and participants were allowed to point to any area including the area where their hands or fingers were. The answered points were recorded. The experimenter stimulated each point once, and thus there were 24 trials that participants answered. The order of stimulation positions was randomly assigned. After all trials, there was a 3-min break before the next block started. Participants were not allowed to move their grounded hand for the duration of each block. The order of posture conditions assigned to the three blocks was randomized across participants. There were 24 trials for each block, and there were 3 blocks. Thus, the total number of trials was 72 per participant.

4.3 Results Comparing Three Posture Conditions

Fig. 10 (a) shows the mean answer position for each stimulus point. The start point of the arrow represents the stimulus position, and the arrowhead represents the answer position.

For each condition, the absolute value of positional error, which is the absolute value of the difference in the positions of answer and stimulus, was averaged across participants. Fig. 10 (b) shows the absolute value of the positional recognition error for each stimulus point. In the figure, the value of the points which were not stimulated was linearly interpolated from the near stimulus points. Fig. 11 (a) shows the absolute positional error averaged across all stimulus points. After checking normality (by a Shapiro-Wilk test) and sphericity (Bartlett's test) of distribution, a one-way repeated measure ANOVA was conducted with the posture condition as a within-subject factor. The main effect of the posture condition was significant ($F(2, 22) = 77.22, p < 0.0001$). All post-hoc Tukey HSD tests on the pairs of posture conditions were significant ($p < 0.01$).

For each condition, the absolute value of the directional error, which is the absolute difference in the direction of the answer point from the center and the direction of the stimulus point from the center, was averaged across participants. Fig. 10 (c) shows the absolute directional error for each

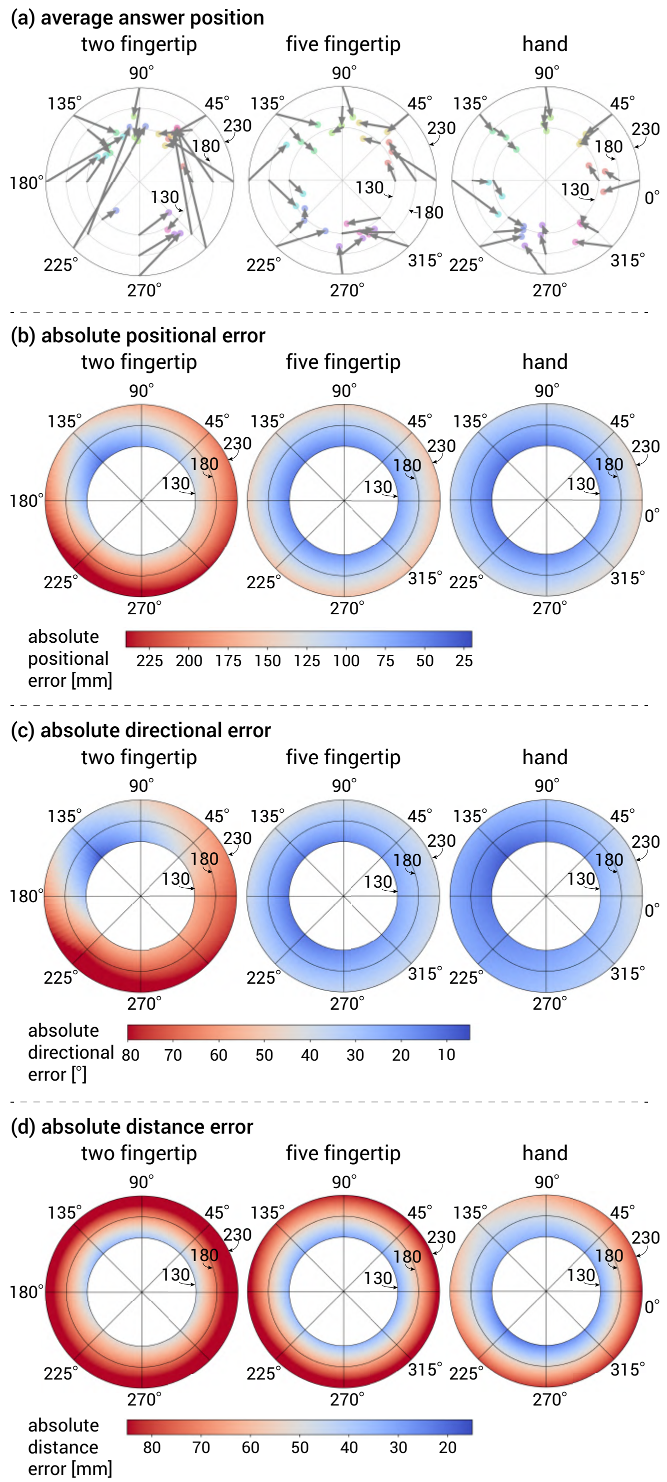

Fig. 10: (a) Average answer position, (b) absolute positional error, (c) absolute directional error, and (d) absolute distance error between stimulus and answer for each stimulating point.

stimulus point. Fig. 11 (b) shows the absolute directional error averaged across all stimulus points. After checking the normality and sphericity of distribution, a one-way repeated measure ANOVA was conducted with the posture condition as a within-subject factor. The main effect of the posture condition was significant ($F(2,22) = 75.93, p < 0.0001$). All

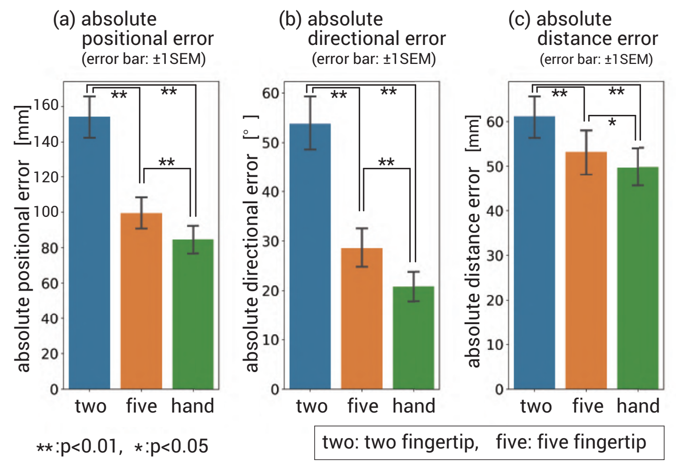

Fig. 11: (a) Absolute positional error, (b) absolute directional error, and (c) absolute distance error for each posture condition.

post-hoc Tukey HSD tests on the pairs of posture conditions were significant ($p < 0.01$).

For each condition, the absolute value of the distance error, which is the absolute difference in the distance of the answer point from the center and the distance of the stimulus point from the center, was averaged across participants. Fig. 10 (d) shows the absolute distance error for each stimulus point. Fig. 11 (c) shows the absolute distance error averaged across all stimulus points. After checking the normality and sphericity of distribution, a one-way repeated measure ANOVA was conducted with the posture condition as a within-subject factor. The main effect of the posture condition was significant ($F(2,22) = 6.99, p = 0.0045$). Post-hoc Tukey's HSD test revealed that there was a significant difference between the two-fingertip and five-fingertip conditions ($p = 0.03$), between two-fingertip and hand conditions ($p < 0.001$), and between the five fingertip and hand conditions ($p = 0.007$).

4.4 Results Focusing on "Hand" Posture Condition

From the results shown in Fig. 11, participants could localize the impact vibration source more accurately under the hand posture condition than under other conditions, and thus we focused on the hand posture condition for further analysis.

4.4.1 Absolute Positional Error

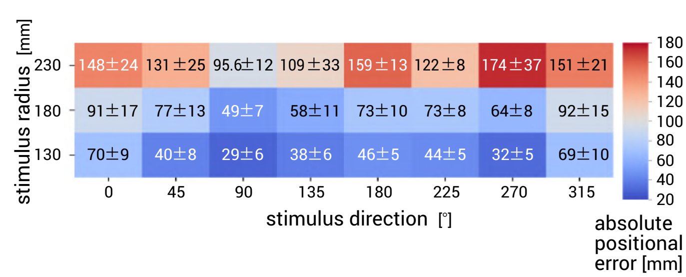

Fig. 12: Absolute positional error for each stimulus radius and direction under hand posture condition.

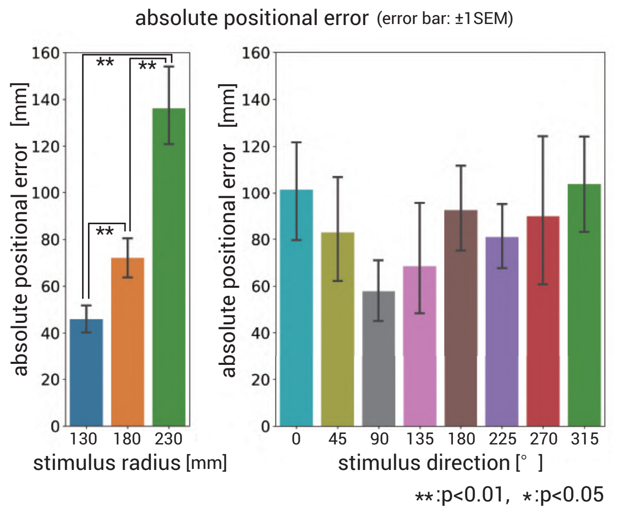

Fig. 13: Left: absolute positional error for each stimulus radius. Right: absolute positional error for each stimulus direction.

Fig. 12 shows the absolute positional error for each stimulus radius and direction. The smallest positional error was 29 mm, recorded when the stimulus radius was 130 mm and the stimulus direction was 90°.

We conducted a two-way repeated measure ANOVA of the stimulus radius and direction on the absolute positional error (shown in Fig. 10 right). We checked the normality and sphericity of each distribution in advance. There was a significant effect for the radius ($F(2, 22) = 187.7, p < 0.0001$). There was also a significant effect for the direction ($F(7, 77) = 2.7, p = 0.0158$). There was no significant interaction effect ($F(14, 154) = 0.9, p = 0.61$).

Fig. 13 (a) shows the absolute positional error for each stimulus radius. Post-hoc Tukey HSD tests on all of the radius pairs were significant ($p < 0.01$). Fig. 13 (b) shows the absolute positional error for each stimulus direction. According to a post-hoc Tukey HSD test on the pairs of different stimulus directions, there was no significant difference between all pairs of stimulus direction ($p > 0.05$).

4.4.2 Absolute Directional Error

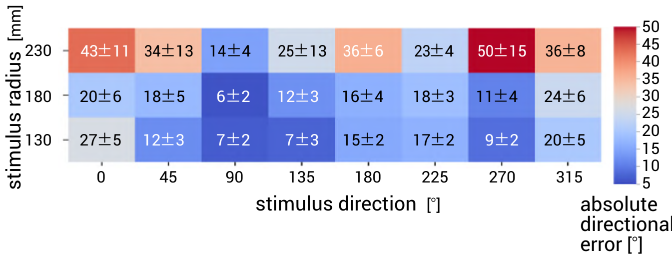

Fig. 14: Absolute directional error for each stimulus radius and direction under hand posture condition.

Fig. 14 shows the absolute directional error for each stimulus radius and direction. We found that the smallest directional error was 6°, recorded when the stimulus radius was 130 or 180 mm and the stimulus direction was 90°.

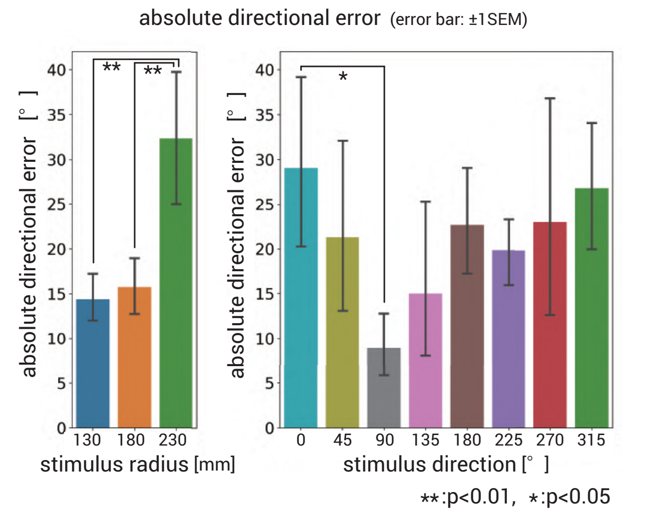

Fig. 15: Left: absolute directional error for each stimulus radius. Right: absolute directional error for each stimulus direction.

We conducted a two-way repeated measure ANOVA of the stimulus radius and direction on the absolute directional error after checking the normality and sphericity of each distribution. There was a significant effect for the radius ($F(2, 22) = 68.1, p < 0.0001$). There was also a significant effect for the direction ($F(7, 77) = 2.37, p = 0.03$). There was no significant interaction effect ($F(14, 154) = 1.0, p = 0.49$).

Fig. 15 (a) shows the absolute directional error for each stimulus radius. Post-hoc Tukey HSD tests revealed significant differences between the two radii pairs of 130°-230° ($p < 0.01$) and 180°-230° ($p < 0.01$). There was no significant difference between the pair of 130°-180° ($p = 0.9$) Fig. 15 (b) shows the absolute directional error for each stimulus direction. According to post-hoc Tukey HSD tests on the pairs of different stimulus directions, there was a significance between the pair of 0°-90° ($p = 0.018$).

4.4.3 Absolute Distance Error

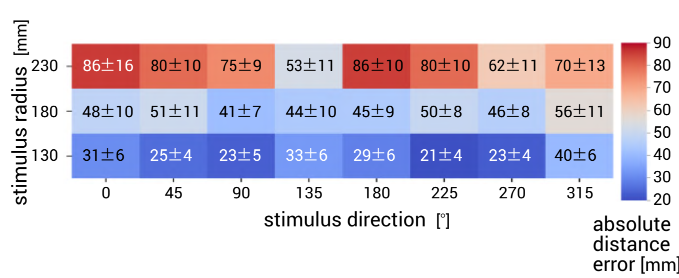

Fig. 16: Absolute distance error for each stimulus radius and direction under hand posture condition.

Fig. 16 shows the absolute distance error for each stimulus radius and direction. We found that the smallest distance error was 21 mm, recorded when the stimulus radius was 130 and stimulus direction was 225°.

We conducted a two-way repeated measure ANOVA of the stimulus radius and direction on the absolute distance error after checking the normality and sphericity of each

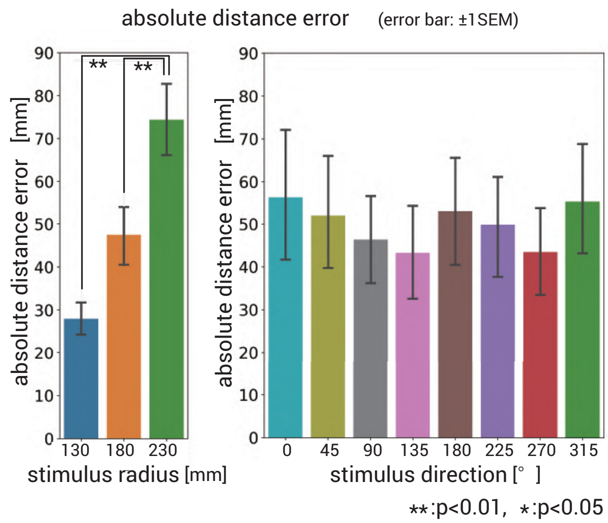

Fig. 17: Left: absolute distance error for each stimulus radius. Right: absolute distance error for each stimulus direction.

distribution. There was a significant effect of the radius ($F(2, 22) = 32.8, p < 0.0001$). There was no significant effect of the direction ($F(7, 77) = 1.5, p = 0.18$). There was no significant interaction effect ($F(14, 154) = 1.66, p = 0.069$).

Fig. 17 (a) shows the absolute distance error for each stimulus radius. Post-hoc Tukey HSD tests revealed significant differences between all radii pairs ($p < 0.01$). Fig. 17 (b) shows the absolute distance error for each stimulus direction. Because there was no main effect of stimulus direction from the ANOVA results, we did not conduct a post-hoc multiple comparison test.

4.4.4 Directional Bias

In this subsection, we focus on the directional bias and test whether the answered direction was biased from the stimulus direction. We conducted a two-way repeated measure ANOVA of the stimulus radius and direction on the directional bias after checking the normality and sphericity of each distribution. There was no significant effect of the radius ($F(2, 22) = 2.59, p = 0.09$), direction ($F(7, 77) = 1.86, p = 0.09$), or interaction effect ($F(14, 154) = 1.24, p = 0.25$).

Fig. 18 shows the directional bias for each stimulus radius or for each stimulus direction. To test whether the directional bias deviated from 0, we conducted a t-test (with Bonferroni correction) for each stimulus radius and stimulus direction. There was significance only under the condition of stimulus direction 270° (corrected $p < 0.05$).

4.4.5 Distance Bias

In this subsection, we focus on the distance bias and test whether the answered distance is biased from the stimulus distance. Before we conducted a two-way repeated measure ANOVA of the stimulus radius and direction on the distance bias, we tested the normality and sphericity of each distribution. We found that the normality was violated ($p > 0.05$) when the stimulus distance was 130 or 180, or when the stimulus direction was either 90°, 135°, 180°,

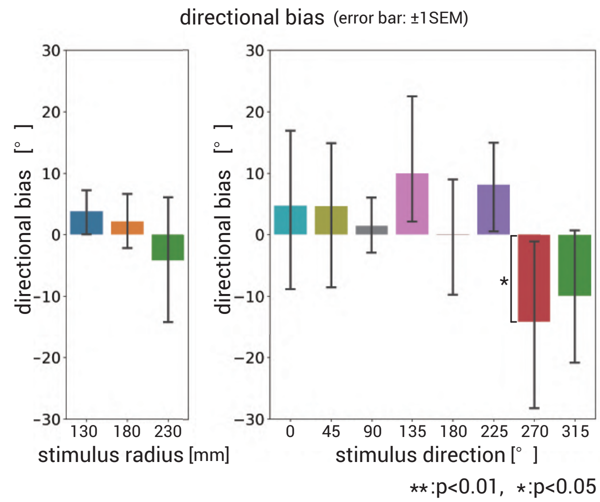

Fig. 18: Left: directional bias for each stimulus radius. Right: directional bias for each stimulus direction.

225°, or 270°. Then, we conducted the Kruskal-Wallis test and revealed that the stimulus distance affected the distance bias ($H(288) = 89.8, p < 0.0001$), but the stimulus direction did not affect the distance bias ($H(288) = 7.34, p = 0.39$).

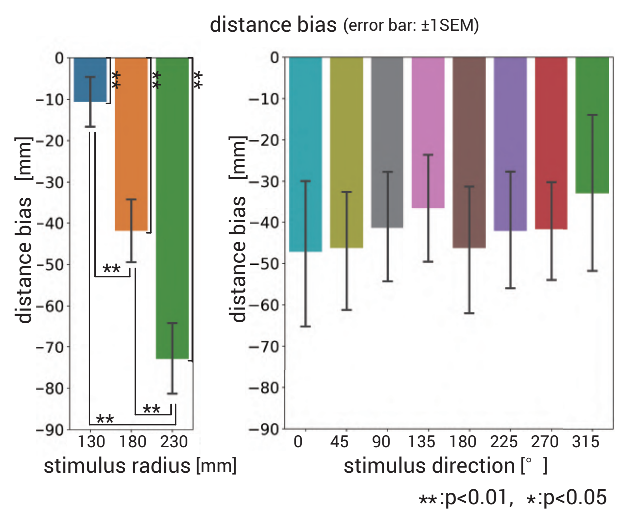

Fig. 19: Left: distance bias for each stimulus radius. Right: distance bias for each stimulus direction.

Fig. 19 shows the distance bias for each stimulus radius or for each stimulus direction. A Steel-Dwass post hoc test showed a significant difference between all pairs of stimulus distances (130–180 ($p < 0.0001$), 180–230 ($p < 0.0001$), and 130–230 ($p < 0.0001$)).

To test whether this bias deviated from zero significantly, we used 10000 bootstrap samples [40] to calculate the confidence interval (CI) of biases for each stimulus radius. If the Bonferroni-corrected 95% CI did not overlap to zero, we could conclude that the bias was statistically significant. As a result, under all of the three stimulus radii, the CI did not overlap to zero and we conclude that the biases were significant. This means that it is difficult to recognize an accurate distance in two-dimensional space with the setup we used.

Actually, the participant's recognized distances were 120 ± 32.0 mm, 138.1 ± 40.1 mm and 157 ± 43.7 mm and these were far from each stimulus radius (shown in Fig. 20). To test whether the answered distances were different between each stimulus radius or not, we conducted a Steel-Dwass test on the answered distances between three pairs of stimulus radii. We obtained significant results between all pairs between 130-180 ($p = 0.0012$), 130-230 ($p = 0.001$), and 180-230 ($p = 0.013$).

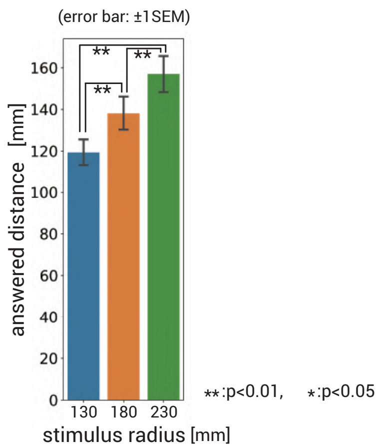

Fig. 20: Answered distance for each stimulus radius.

4.5 Results Focusing on Hand Size Parameter

As shown in Table 1, the participants' hand sizes were different. There is a possibility that the hand size parameter affected the localization ability under hand conditions. As hand size parameters, we used hand width, height, and area which is calculated by multiplication of width and height.

First, we tested whether the absolute directional error was affected by hand size parameters. The hand size parameters such as hand width could affect directional recognition with three stimuli radii and eight stimuli directions in different ways. For example, there is a possibility that hand height affects directional recognition when the vertical direction is stimulated but it does not affect directional recognition when the horizontal direction is stimulated. Thus, we independently tested how the three hand size parameters were correlated with directional recognition results with three stimuli radii and eight stimuli directions. In total, we conducted correlation analyses 33 times (=3 [hand size parameters such as height, width, area] x 11 [3 stimuli radii and 8 stimuli directions]). We set the significance level at 0.05 with Bonferroni correction. However, as a result, we could not find any correlation under these 33 conditions.

Second, we also tested whether the absolute distance error was affected by hand size parameters. We conducted correlation analyses 33 times (=3 [hand size parameters] x 11 [3 stimuli radii and 8 stimuli directions]) but we could not find any correlation.

4.6 Discussions

4.6.1 Differences between Posture Conditions

By comparing the results with the three posture conditions, the main effect of the posture condition was confirmed on all three viewpoints of error (absolute positional error, absolute directional error, and absolute distance error). Post-hoc multiple comparisons clarified that the hand condition was the best. In addition, the five-fingertip condition was better than the two-fingertip condition.

Under the two-fingertip condition, the localization error was better near the area of the two fingertips and worse in the area furthest from the fingertips (see Fig. 10). According to Fig. 10 (a), participants recognized the far indentation points as if they were close to their two fingertips. This suggests that the area of the human body in contact with the medium surface was an important factor for the localization. It was in accordance with the better results under the five-fingertip or hand conditions in which the hand was in contact with a greater surface area than under the two-fingertip condition.

When comparing the results between the five-fingertip condition and the hand condition, the difference in both the absolute directional and distance error was significant. The difference in posture was the presence of a grounded area of the fingers (for the five-fingertip condition) instead of both fingertips and palm (for the hand condition, which had those extra grounded areas). Thus, in the case of the hand condition, the grounded areas were larger, and participants could use this for vibrotactile sensing to recognize the spatiotemporal cues illustrated in Fig. 3, which led to smaller errors.

On the other hand, under the hand posture condition, the hand size parameters between participants were not correlated with directional or distance errors. We consider the hand size effect was small since the difference in hand size was relatively small compared with the differences between posture conditions. Since this study is preliminary at this point, more investigation would be required to clarify this.

4.6.2 Analysis Focusing on Hand Condition and Directional Recognition

From here, we will focus on the hand condition, and we discuss directional recognition in this section.

Regarding the absolute directional error, there was a main effect of the stimulus radius. The absolute directional error became larger when the stimulus radius was 230 mm rather than 130 or 180 mm. We assume that the participants recognized the direction mainly by judging where they felt the intensive vibration in their hand and we speculate that the reason for the deterioration was that the intensity cue would be reduced when a more distant point was stimulated (see Fig. 7). There was also a main effect of the stimulus direction. The performance was better in the 90° direction and worse in the 0° direction. In the 90° direction, where the performance was better, the fingertips of the middle finger, index finger, and ring finger were placed. It is known that the fingertips are better in terms of sensitivity [41] or acuity [42] than the palm area, and this knowledge can explain the better performance of the 90° direction. On the other hand, the 0° direction, where the performance was poor, is where the hypothenar eminence was located. We surveyed previous studies that investigated the vibrotactile sensitivity or acuity of the hypothenar eminence, but we could not find the information. However, in the palm area, the hypothenar eminence has a smaller mechanoreceptor density than the thenar eminence, which is thought to have led to this poor result in the 0° direction.

Regarding the directional bias, there was no main effect of either stimulus radius or direction. However, as a result of a t-test to examine whether the directional bias deviated from 0, we found that there was a significant bias when the stimulus direction was 270°. The reason for the bias was unclear, but there is a possibility that this is owing to the answer method we adopted. We asked participants to indicate the estimated position with the index finger of their non-dominant hand, which was a method similarly adopted by work [39]. In this experiment, all participants were right-handed, and they answered with the index fingers of their left hand. Around 270° is the space under the participant's right arm, and there is a possibility that the pointing finger position veered to the left-hand side when pointing to that space.

4.6.3 Analysis Focusing on Hand Condition and Distance Recognition

According to Fig. 19 and Fig. 20, distance recognition was worse as compared to direction recognition. Though the answered distances were different between stimuli radii (see Fig. 20), it was difficult to accurately recognize the distance in two-dimensional space with the setup we used (see Fig. 19).

In previous research investigating distance recognition in a one-dimensional medium [29], [30], [31], [32], participants were able to recognize the distance. There are several differences between our work and theirs. First, in their experimental setup, participants actively move the medium and voluntarily cause the impact. For example, the participant in the work by [31] moves the rod and causes the collision with the virtual floor. The active sensing could provide additional cues other than the vibrotactile feedback. Thus, if we make participants actively lift up and put down their hands and provide impact feedback in time with the putting down, there is a possibility that distance recognition would be better.

Second, the type of wave pattern was different. In previous studies such as [29], the touch information was encoded in the standing wave. On the other hand, according to our measurement of acceleration in Fig. 6, the wave attenuated 17.4 dB with 130 mm. Since the attenuation was large, it is considered that there was almost no standing wave in the entire sheet. It suggests that the touch information was encoded in the traveling wave in our setup. In addition, fig. 8 shows that the peak of the propagated waves was around 70 Hz. According to this, we consider that our setup activated both RA (rapidly adapting) channel and PC (Pacinian) channels with our setup. There is a possibility that distance recognition would be changed if we activate mainly either one of the channels using cyclic waves of 30 Hz or 230 Hz.

4.6.4 Limitations

Attention has to be paid to the possibility that the presence of the bias originated from the experimental design.

Since we needed to exclude the effect of visual information of the sheet deformation cue on the localization result, we asked participants to wear sleep masks. Note that previous studies suggested that blindfolded participants could have a bias when pointing their finger at specific locations [43] and thus there is a possibility that the obtained values of absolute errors and biases were affected by the pointing bias.

Participants could see the silicone rubber sheet with the red grid before they put on their sleep masks during the familiarization phase of the first block. The red grid covered all areas of the silicone sheet including areas where participants put their hands or fingers. Thus, we consider that the illustration of the hatch marks itself did not give additional cues. However, considering the difficulty of manual read by the experimenter of the point under participants' fingers or hands where the red grid is hidden, we can not completely exclude the possibility that participants might have assumed the vibration location would be outside the area of their hands.

4.6.5 Use of Vibration Localization Outside Body in Applications

Among haptic displays, the vibrotactile display is the most widespread class of haptic devices, found in a variety of consumer electronics devices [44], and thus it is expected that the human ability to localize vibration outside the body will be used in applications.

We found that the hand condition was better than the two- or five-fingertip conditions in terms of the absolute error of position, direction, and distance. From another point of view, considering that this vibration localization can be used as the user interface for some objectives, it is important that users be less tired while using it. The hand condition has the largest grounded area and is less likely to induce fatigue. By contrast, the five- or two-fingertip conditions have smaller grounded areas, and users can easily become tired. Therefore, the hand condition is considered to be suitable for the UI from the viewpoint of localization accuracy and resistance to fatigue.

Under the hand posture condition, we found that it is difficult for users to accurately recognize the distance of the stimuli. In contrast, participants were able to recognize the stimulus direction with an error of approximately 150° if we stimulated nearer than 180 mm. This is informative to the case where it is difficult to attach a vibrator to the user's body and it is required to embed the vibrator at a distance. For example, considering we assume the chair-type vibrotactile device, if we attach the vibrator on the surface contacting back or buttock, the tactile feeling of the vibrator makes the chair less comfortable. Thus, it is conceivable that it could be embedded in the back of the seat or deep in the seat surface and transmit the direction information by vibration presentation from that position. Of course, this study only investigates directional recognition when using the dominant hand, which is more sensitive to vibration, and we have to investigate whether directional recognition is possible using other body sites.

5 Conclusions and Future Study

This study evaluated the two-dimensional localization of an impulse vibration source outside the body. Participants reported the position of the impulse vibration by sensing the propagated vibrational wave from the source.

The results suggested the following characteristics:

- localization errors are smaller when the entire hand is grounded than when only the fingertips are grounded.
- localization positional and directional errors are smaller when the 90° (around index, middle, and ring fingertips) area of the hand is stimulated. They are larger when the 0° (around the hypothenar eminence) area of the hand is stimulated.
- Though the answered distances were significantly different between stimuli radii, it was difficult to accurately recognize the distance in two-dimensional space with the setup we used.

In this study, we used impulse stimuli to stimulate the medium. We are interested to know whether the same results would be reproduced if we used other waveforms such as cyclic ones (e.g., a sinusoid). In addition, this study used the hand as the body part to be grounded. As a user interface, there may be situations where it is more natural for other parts (e.g., the back or foot soles) to be grounded. Thus, we are also interested in the two-dimensional localization results when other parts are grounded.

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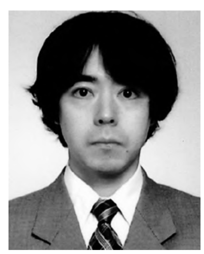

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