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FULL PAPER

Extended phantom sensation: Vibrotactile-based movement sensation in the area outside the inter-stimulus

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Vibrotactile phantom sensation is an intuitive methodology for perceiving the localization of a moving object. However, the presentation area is limited to the inter-stimulus. To extend the range of presentation beyond the inter-stimulus region, we attempted to establish a novel mathematical model for representing a wider range of phantom sensation than conventional models. The experiments 1-1 and 1-2 compared three methods (linear, exponential-like, and conventional inter-stimulus models). The results indicated that the proposed linear and exponential-like model effectively generated both the sense of outer and inner movement with and without training, and that the exponential-like model is best suited to represent accurate phantom sensations that cover the extended outer region. In the experiment 2, we examined the effect of γ, a parameter related to the magnitude of exponential-like model damping, on presentation accuracy. The results showed that the high-dumping model ($\gamma = 2$) showed high accuracy and suggested a trade-off between presentation accuracy and range. The findings of this study are expected to provide guideline for the effective presentation of a wide range of phantom sensations occurring outside the inter-stimulus.

Keywords: Vibrotactile display, human interface, phantom sensation

1. Introduction

1.1 *Background*

Humans have the ability to perceive the localization of objects moving around them. A sense of active movement is perceived when the perceiver is in control of the object, and a sense of passive movement is perceived when the object is moving around the perceiver on its own. In the former case, it can be perceived when the operator controls a drone, a mobile robot, or a virtual character as an avatar of the operator in a real or virtual environment. In the latter case, for example, while the subject is walking or driving, the perception of movement can occur for pedestrians or objects moving around the subject. Such perceptions of the localization of moving objects provide critical information; for example, in a tele-operation situation, perception of localization is known to be an important factor related to performance [1]. The contribution of visual information to the perception of the localization of moving objects is high. If the information from other modalities is used in addition to visual information to deliver a sense of motion of an object, it is expected that can be reduced the visual overload, which can potentially affect performance in human-machine interactions [2], and the realism and performance of the control experience can be consequently improved.

Auditory information is one of such modality that can contribute to the perception of the localization of moving objects [3]. However, because it is affected by other sound sources, in an environment where various sound sources are present, such as in the case of tele-operation, VR, and day to day situations, the

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effect may be reduced. In addition, auditory information is often used for communication between humans and human/robot/computer. Therefore, using audio information for both perception of localization and communication is expected to be challenging.

This study focuses on haptic information to improve the perception of the localization of moving objects. Mechanical vibrotactile stimulation, which is relatively small and light tactile displays and capable of an independent control of amplitude and frequency, is widely used [4–6]. One possible approach of presenting spatial information such as the perception of movement using mechanical vibrotactile stimuli involves placing of several vibrators on the body [7–9]. Bajpai et al. placed eight points of vibrating stimuli around the waist to transmit information in eight directions [9]. In such a method, the burden and cost to the user is significant as the number of vibrators is high.

In this study, we focus on a method based on tactile illusion that could potentially deliver localization perception with fewer stimulation points. In section 1.2, we describe the related studies on tactile illusions involving vibration stimuli, and identify the issues encountered by these studies when providing a perception of localization of moving objects. Section 1.3 states the purpose of this study.

1.2 *Related works*

Various tactile illusions have been reported to produce a sense of movement of stimuli when multiple vibrating stimuli are applied. For example, it has been reported that the stimuli appear to move between two points owing to the vibration of two vibrators with an appropriate time difference, and this movement is refereed to as the apparent motion [10, 11]. However, the start and end positions of this motion must be the where the vibration are placed. In addition, the perceptual movement range is limited to the space enclosed by the two vibrating points. Therefore, it is not suited to the representation of perception of the localization of objects moving around the subject.

In this study, we focus on phantom sensation as a phenomenon of tactile illusion that can act as a reference for the presentation of the sense of movement [12, 13]. In this phenomenon, the amplitude of the vibrating stimuli presented to the two points can be controlled such that the user can perceive a illusionary motion in the area between the two points. It this approach, the advantage lie in that the start and end points of the sense of movement are not limited to where the vibrators are placed. That is, the sense of movement has been reported to be felt in various parts of the body, including the back [14–16], head [17, 18], arm [19], wrist [20], between as well as on the hands [21–24]. Some studies have even reported the extension of the sensation to two dimensions [23–26]. However, in these studies, the objective was to generate phantom sensations within the space enclosed by the stimulating points, and the extent outside the enclosed space was not considered.

For instance, in one study, the perception of phantom sensation outside the space encompassed by the vibrating stimuli was investigated [27]. However, the mathematical relationship between the vibration

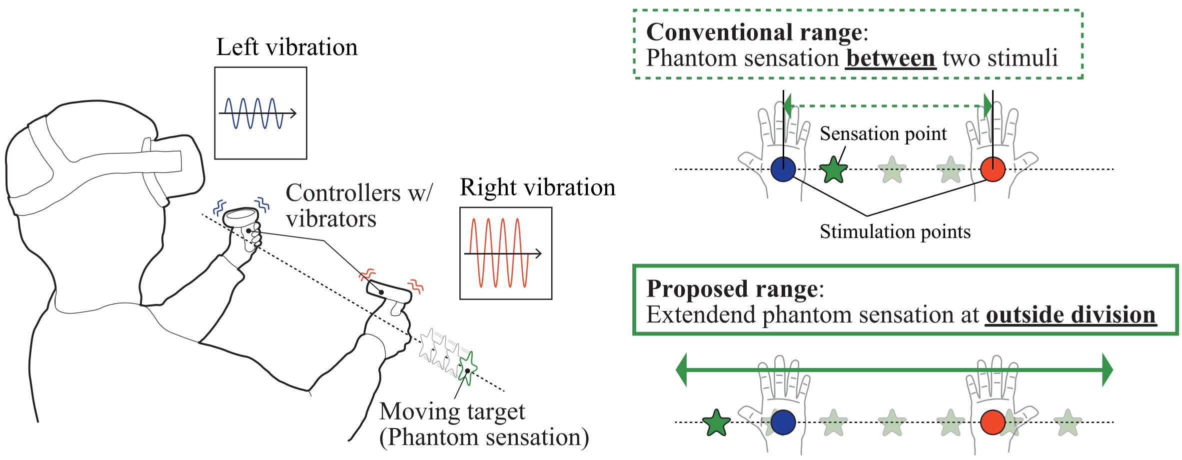


Figure 1. Concept of extended phantom sensation

amplitude and the distance between the stimulus position and the presentation position could not be established and as such, no equations could be provided for application such as in attentional or motion guidance [28]. To effectively render the perception of localization of an object moving around the subject, a mathematical model representing relationships between the vibrating intensity and the positional information must be established.

1.3 *Objective*

As illustrated in Fig. 1, our method attempts to control the amplitude of vibrating stimuli in the left and right hand to perceive a phantom sensation of movement in a region that includes the outside between the stimuli. To avoid increasing the number of experimental conditions to be considered, we perform the basic verification in one dimension. Furthermore, to extend the proposed method to 2D and 3D in the future, we formulate it based on the relative distance between the stimulus presentation position and the perceived target position.

Next, three experiments are conducted to establish and verify an effective mathematical model. The experiments 1-1 and 1-2 compare three mathematical methods in terms of subjective evaluation of the sense of movement and the localization accuracy of movement, respectively. The experiment 2 investigates the effect of the parameter of the method, which is evaluated in the experiments 1-1 and 1-2, on the accuracy of presentation. The main contribution of this paper is to establish a novel mathematical model for effectively rendering the perception of localization of an object moving in the area outside the inter-stimulus.

2. Method

2.1 *Conventional method of presenting phantom sensation*

In a conventional method of presenting phantom sensation, the relationship between the amplitude of the vibrating stimulus of a constant frequency is presented to two points and consequently, the phantom sensation is perceived. The point of phantom sensation is located between the two stimulus points, as depicted in Fig. 1.

Fig. 2 shows the concept of a conventional method, which has been widely adopted in several stud-

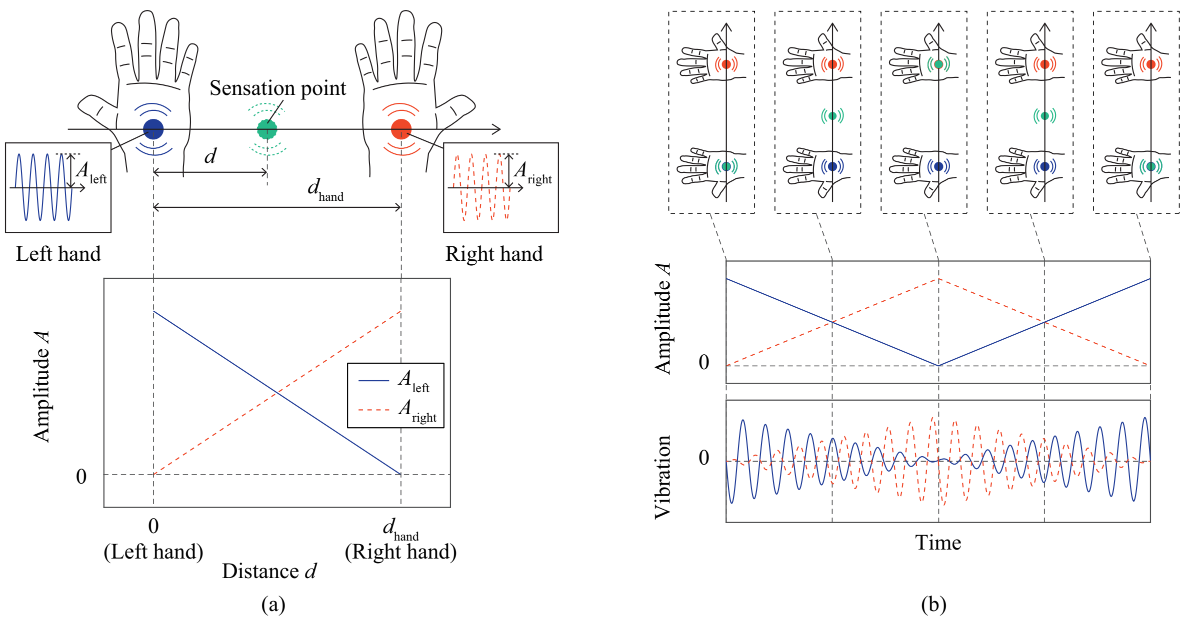


Figure 2. Conventional method of presenting phantom sensation

ies [13, 22, 29]. As shown in Fig. 2(a), the amplitude of the presented vibration decreases linearly with increasing distance between the stimulus presentation point and the phantom sensation point. Fig. 2(b) shows the profiles of amplitudes and waveforms of the two stimuli (in this case, vibration stimuli to the left and right hands) when the phantom sensation position was reciprocated between the two stimulus points at a constant velocity. The conventional method is formulated as follows:

$$A_{\text{left}}(d) = -\frac{A_{\max}}{d_{\text{hand}}}d + A_{\max}, \tag{1}$$

$$A_{\text{right}}(d) = -\frac{A_{\max}}{d_{\text{hand}}}(d_{\text{hand}} - d) + A_{\max}, \tag{2}$$

where $A_{\text{left}}, A_{\text{right}}, A_{\max}, d$, and d_{hand} represent the amplitude of the left and right hand vibration stimuli, the maximum amplitude of vibration, the distance from the left vibration point to the phantom sensation position, and the distance between the two hands, respectively. Furthermore, the presentation range formulated by the phantom sensation is limited to the inter-stimulus range ($d \in \{0, d_{\text{hand}}\}$.)

2.2 *Proposed method of presenting extended phantom sensation*

In studies that employ the conventional method, a phantom sensation occurs in the space encompassed by the multiple stimulus points. In this study, we propose and compare three methods of presenting the sensation of movement through phantom sensations that cover the outside of the space encompassed by the stimulus points. The method is formulated considering the amplitude of vibration only the left hand A_{left} because of the symmetry of representation.

2.2.1 Method 1: Linear method

Figs. 3a and 3b show the concept of the method 1 (linear method). This method maps the associating phantom sensation point to the combination of the two vibration amplitudes and reflects an intuitively understandable relationship in which the vibration amplitude decreases as the associating point moves away from the actual vibration point. The vibration amplitude is maximum when the phantom sensation point is the same as the stimulus point and the slope of the amplitude change remains constant regardless of the changes in the distance. For example, when the associative point is approached from outside the inter-stimulus points, the amplitudes of the both vibrators are increased, and the amplitude of the vibrator near the associative point is greater than the amplitude of the other vibrator. When the associative point is between the hands, the amplitude of the vibration point with which the associative point approaches increases and the amplitude of the other vibration point decreases. Thus, the model uniquely determines the combination of stimuli based on distance, and the profile of the stimuli is different when folding at the hand position and when passing through the hand position. The two methods described below also have this feature. A_{left} is formulated as follows:

$$A_{\text{left}}(d) = \alpha_1 |d| + \beta_1, \tag{3}$$

where $\alpha_1 = (A_{\min} - A_{\max})/3d_{\text{hand}}$ and $\beta_1 = A_{\max}$. To compare the three methods, the same values for maximum amplitude $A_{\max}$ and minimum amplitude $A_{\min}$ are adopted for all the methods. These amplitudes are empirically selected from a range of previously identified amplitudes where the authors used vibrators to generate the stimuli. The presentation range of the phantom sensation is $d \in \{-2d_{\text{hand}}, 3d_{\text{hand}}\}$, and it was the same for all the three methods (linear, exponential-like, constant methods). Notably, such linearly proportional methods have previous used [13, 22, 29]. In addition, the applicability of those profiles to the presentation of a sense of movement on the outside range has not been investigated.

2.2.2 *Method 2: Exponential-like method*

Figs. 3c and 3d show the concept of the method 2 (exponential-like method). This method, like the linear model, has an intuitive relationship mapping the amplitude of vibrotactile stimulus to the distance between the associating phantom sensation point and the stimulus point. When the phantom sensation point is the same as the stimulus point, the vibration amplitude is maximum and decreases as the phantom sensation point moves away from the stimulus point. However, the slope of the amplitude varies with changes in the distance between the points. Compared with the linear method, the rate of change of the amplitude increases as we move the stimulus point. A_{left} is therefore formulated as follows;

$$A_{\text{left}}(d) = \alpha_2 \beta_2^{|d|/(d_{\text{hand}}\gamma)}, \tag{4}$$

where $\alpha_2 = A_{\text{max}}$, $\beta_2 = A_{\text{min}}/A_{\text{max}}$ and $\gamma = 3$. d_{hand} is constant. A profile similar to this method is found in [21, 30].

2.2.3 *Method 3: Conventional inter-stimulus method*

The concept of the method 3 (conventional inter-stimulus method) is shown in Figs. 3e and 3f. Unlike the methods 1 and 2, this method is a non-intuitive method because this does not have the intuition that

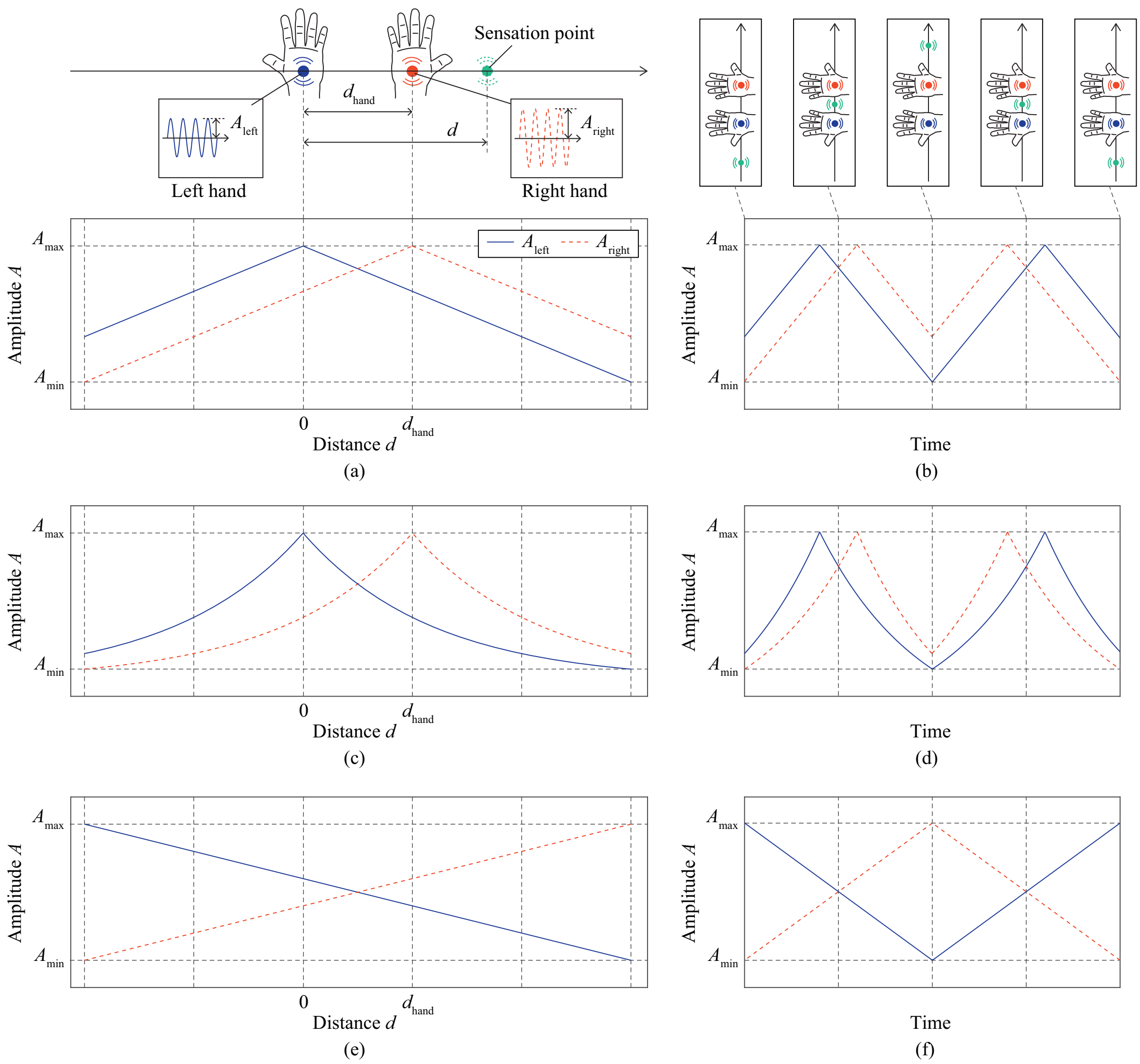


Figure 3. Three types of proposed methods for presenting extended phantom sensation

the amplitude decreases as the distance between the phantom sensation point and the stimulus point increases. The purpose of this method is to compare it with the methods 1 and 2 and the performance is expected to be lower than them. A_{left} is formulated as follows:

$$A_{\mathrm{left}}(d) = \alpha_3 d + \beta_3, \tag{5}$$

where $\alpha_3 = (A_{\mathrm{min}} - A_{\mathrm{max}})/5d_{\mathrm{hand}}$ and $\beta_3 = (2A_{\mathrm{min}} + 3A_{\mathrm{max}})/5d_{\mathrm{hand}}$.

In the conventional method of presenting phantom sensation, highly complex functions such as tangential model [22] and Gaussian model [16] have been observed. In this study, we compare the three methods as an initial verification of the method of presenting extended phantom sensation.

3. Experiment 1

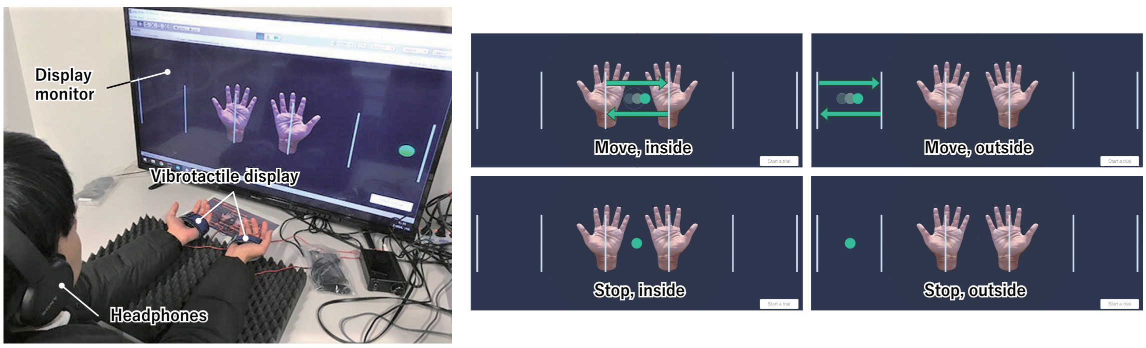
3.1 *Experiment 1-1*

3.1.1 Objective

In the experiment 1-1, participants were asked directly how much movement sensation they felt on each of the outer and inner sides of the inter-stimulus. In addition, the two conditions (with and without a brief visuo-tactile training phase, respectively) were compared in this experiment.

3.1.2 Participants

Eighteen volunteers (aged from 21 to 24 years, all right-handed, and with no history of tactile processing dysfunctions) participated in the experiment 1-1. They were not aware of the purpose of the experiments. Nine participants took part in the experiment with the visuo-only training phase and the remaining nine participated in the experiment with the visuo-tactile training phase.



(a) (b)

Figure 4. Experimental condition in the experiment 1-1. (a) In the training phase, participants experience visuo-tactile information or visuo-only information. (b) Four stimuli ((Move, inside), (Move, outside), (Stop, inside), and (Stop, outside)).

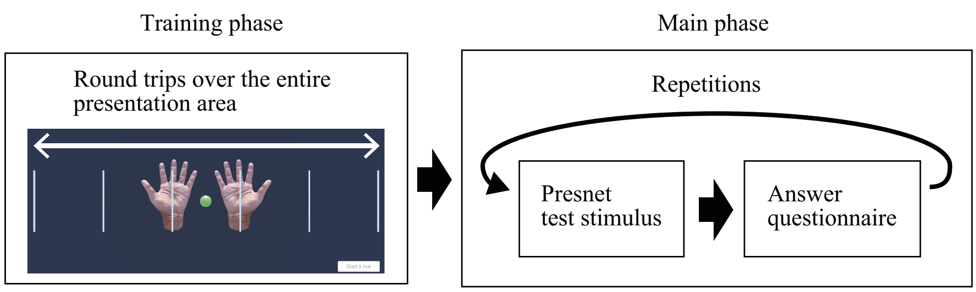


Figure 5. Schematic of the experimental procedure

3.1.3 Apparatus

The apparatus for generating the vibrotactile stimulation is shown in Fig. 4a. The vibotactile stimulation was presented to the palm of the participant's hand using a voice coil actuator (Vp210, ACOUVE LABORATORY Inc.), which enabled the independent control of the amplitude and frequency of the vibrotactile signal [4, 6]. A vibrator was then softly pressed to the palm with the help of flexible belts. The apparatus for generating the vibrotactile stimulation is shown in Fig. 4(a). In this study, we adopted the two-handed vibration stimuli, assuming usual situations where the vibration stimulus is presented from an input interface such as a joypad and VR controller held by both the hands.

The carrier frequency was kept constant at $100\,\mathrm{Hz}$. This frequency is has been adopted by the conventional phantom sensation research [16]. A_{max} and A_{min} employed 4G and 1G, respectively. The acceleration of the actuator is measured using a piezoelectric accelerometer (VS-BV021, NEC TOKIN). The stimuli are continuous vibrations with no intervals, as employed by the conventional researches such as [21, 24, 30]. The effect of the presence or absence of intervals will be an issue for future research.

3.1.4 Procedure

The participants were asked to sit down on the chair and rest their hands on the soft sponge, and the distance between the hands was fixed at $180\,\mathrm{mm}$, as shown in Fig. 4a. The participants were then instructed not to hold the vibrator in the palm of their hands to avoid variations in vibration caused by gripping. They reported that they heard pink noises through their headphones that masked the sound generated by the vibrators.

Fig. 5 shows the schematic of the procedure in the experiment 1-1, which is also adopted in the experiments 1-2 and 2 described later. The sequence shown in Fig. 5 is repeated for each of the three methods. In the sequence, first, the short training phase ($30\,\mathrm{s}$) was conducted. In the training phase, the visuo-only or visuo-tactile stimuli were presented in three round trips over the entire presentation area. Secondly, the main phase was carried out using only vibrotactile stimuli. In one trial, a participant was given one vibrotactile stimuli (8 s) selected from the four stimuli shown in Fig. 4b. In order to reduce the influence of directional differences, the moving stimulus was a reciprocal movement in inside or outside the two hands. The participants were told that stopped and moving stimuli were used as test stimuli but Fig. 4b was not shown. Then, s/he was asked to answer how much the moving sensation at the inside (questionnaire 1) and outside (questionnaire 2) the two hands was felt on a 7-point scale from 0 (no moving sensation) to 6 (very strong moving sensation). Each of the four stimuli were then presented to each participant 8 times. A total of 32 trials were conducted for each method. The first two trials of each of the four stimuli were excluded from the data during the following analysis to reduce the variability of the trials to get used to it with reference to [6]. In total, 96 trials were conducted for each participant. The entire experiment took approximately $40\,\mathrm{min}$. The order of the stimuli and methods were randomized for each participant.

3.1.5 Result

Fig. 6a shows the scores for the moving sensation on the inside with training. The three methods shows relatively high ratings for "move, inside" stimuli compared to the other three. The Friedman test (the method 1: ($\chi^2(3) = 19.74$, $p < 0.001$), the method 2: ($\chi^2(3) = 18.72$, $p < 0.001$), and the method 3: ($\chi^2(3) = 16.77$, $p < 0.001$)) and the post-hoc Wilcoxon signed rank test with Bonferroni correction were conducted. In the method 1, the scores of the inside moving sensation for "move, inside" are significant higher than "stop, inside" ($p = 0.023$, effect size $r = 0.89$) and "stop, outside" ($p = 0.023$, $r = 0.89$). In the method 2, the scores for "move, inside" are significant higher than "move, outside" ($p = 0.023$, $r = 0.89$) and "stop, outside" ($p = 0.023$, $r = 0.89$). In the method 3, the participants perceived significant higher moving sensation on the inside for "move, inside" than "stop, outside" ($p = 0.023$, $r = 0.89$). The results showed that the moving stimuli on inside by the proposed methods with initial brief training was more likely to present the inner movement sensation of both hands than other three stimuli. Therefore, it is suggested that the proposed methods covered the presentation region of conventional phantom sensations.

Fig. 6b presents the scores for the moving sensation on the inside without initial brief training. As in

Fig. 6(a), all three methods tended to show relatively high scores for the "move, inside" stimuli compared to the other three stimuli; however, the scores for the "move, inside" stimuli seem to be small. In the method 1 ($\chi^2(3) = 14.69$, $p = 0.002$, Friedman test), the scores for "move, inside" are significant higher than "stop, inside" ($p = 0.023$, $r = 0.89$) and "stop, outside" ($p = 0.047$, $r = 0.85$). In the method 2 ($\chi^2(3) = 19.05$, $p < 0.001$), the scores for "move, inside" are significant higher than "move, outside" ($p = 0.023$, $r = 0.89$), "stop, inside" ($p = 0.023$, $r = 0.89$), and "stop, outside" ($p = 0.023$, $r = 0.89$). In the method 3 ($\chi^2(3) = 19.33$, $p < 0.001$), the significant difference was observed between "move, inside" and "stop, outside" ($p = 0.023$, $r = 0.89$). The results suggest that the moving stimuli on inside by the proposed methods with initial training are able to present the sense of movement on the inside the two hands and the present methods covered the presentation region of conventional phantom sensations. Although the results suggest that the participants perceived the moving sensation on the inside the two hands even in the no training condition, they also suggest that training facilitates the sensation.

Fig. 6c presents the scores for the moving sensation on the outside with training. The three methods showed a tendency to present the outside moving sensation. In particular, the methods 1 and 2 seems to be superior. The method 1 ($\chi^2(3) = 20.01$, $p < 0.001$) show that the ratings of the outside moving sensation for "move, outside" are significant higher than "move, inside" ($p = 0.023$, $r = 0.89$), "stop, inside" ($p = 0.047$, $r = 0.84$), and "stop, outside" ($p = 0.023$, $r = 0.89$). In the method 2 ($\chi^2(3) = 18.26$, $p < 0.001$), the scores for "move, outside" are significant higher than "move, inside" ($p = 0.023$, $r = 0.89$) and "stop, inside" ($p = 0.047$, $r = 0.84$). In the method 3 ($\chi^2(3) = 21.51$, $p < 0.001$), the scores for "move, outside" are significant higher than "stop, inside" ($p = 0.023$, $r = 0.89$) and "stop, outside" ($p = 0.023$, $r = 0.89$).

Fig. 6d shows the scores for the moving sensation on the outside without training. The methods 1 and 2 were able to present the outside moving sensation without training, although there was a decrease from

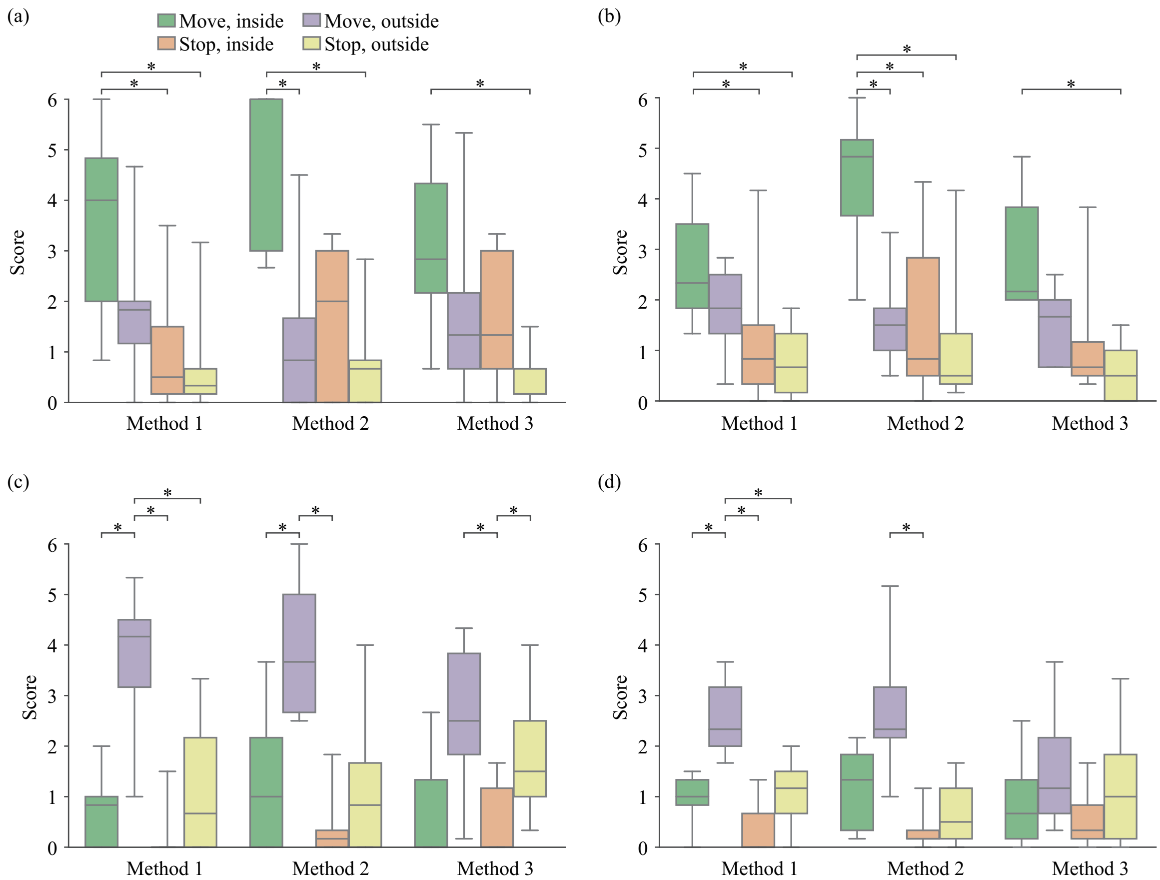


Figure 6. Result of experiment 1-1: Rating score for sense of movement on (a) inside with training, (b) inside without training, (c) outside with training, and (d) outside without training. ∗: $p < 0.05$.

Fig. 6c. On the other hand, the method 3 tended not to present the moving sensation on the outside the inter-stimulus. These trends are supported by the following analyses. The method 1 ($\chi^2(3) = 21.86$, $p < 0.001$) show that the ratings of the outside moving sensation for "move, outside" are significant higher than "move, inside" ($p = 0.027$, $r = 0.89$), "stop, inside" ($p = 0.027$, $r = 0.89$), and "stop, outside" ($p = 0.023$, $r = 0.89$). The method 2 ($\chi^2(3) = 14.93$, $p = 0.002$) show that the scores for "move, outside" are significant higher than "stop, inside" ($p = 0.047$, $r = 0.84$). In the method 3 ($\chi^2(3) = 8.44$, $p = 0.038$), there was no significant difference.

In summary, the results showed that the methods 1 and 2 tended to present both the sense of outer and inner movement. It was also suggested that the sense of movement was clarified by initial brief training, although it was possible to present the sense of movement without training, in the methods 1 and 2.

3.2 *Experiment 1-2*

3.2.1 Objective

In the experiment 1-2, we investigated the extent to which differences in the perception of localization of the moving object can be elaborated.

3.2.2 Participants

Twelve volunteers (aged from 21 to 24 years, all right-handed, and with no history of tactile processing dysfunctions) participated in the experiment 1-2. They were not aware of the purpose of the experiments.

3.2.3 Apparatus

The apparatus in the experiment 1-2 was the same as that used in the experiment 1-1.

3.2.4 Procedure

The basic procedure employed in the experiments 1-2 is the same as in the experiment 1-1 as shown in Fig. 5. For each of the three methods, first, the short training phase (30 s) was conducted. In the training phase, the vibrotactile and visual stimuli were synchronously presented in three round trips over the entire presentation area. Secondly, the main phase was carried out using only vibrotactile stimuli which were different from the training stimulus. In one trial, one vibrotactile stimuli (2 s) was trimmed from the training stimuli as shown in Fig. 7 and provided to a participant. Then, s/he was asked to look at Fig. 7 and answer which cue matched the provided stimulus from a list of numbers from one to eight. Each of the eight stimuli were then presented to each participant 11 times. A total of 88 trials were conducted for each method. The data from the first two trials for each of the eight stimuli were excluded from the following analyses. In total, 264 trials were conducted for each participant. The entire experiment took approximately 60 min. The order of the stimuli and methods were randomized for each participant.

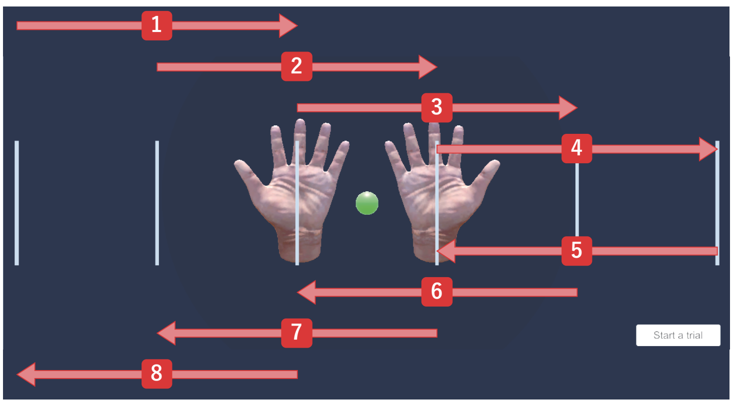


Figure 7. Visual instruction for the participants to answer the cue number in the experiment 1-2.

3.2.5 *Result*

Fig. 8 shows the mean accuracy scores (correct answer ratio) for all 12 participants. Fig. 8a presents the scores for the mean accuracy for all the eight cues. Two significant differences were observed between methods 1 and 2 ($p = 0.010$, $r = 0.79$) and between methods 2 and 3 ($p = 0.004$, $r = 0.84$), which is supported by the results obtained using the Friedman test ($\chi^2(2) = 13.17, p = 0.001$) and the Wilcoxon signed rank test with Bonferroni correction. The results suggest that the exponential-like method (the method 2) is more appropriate for the vibrotactile rendering method to elaborate the perception of localization of a moving object outside the range between the two hands.

Fig. 8b presents the scores for the eight cues. First, to measure the number of discriminable conditions in which the accuracy scores were significantly higher ($p < 0.01$) than the chance level (1/8), the Wilcoxon signed rank test was conducted to compare the scores with the chance level. Notably, the chance level is the probability that the right stimulus will be selected by chance. The results of this test are summarized in Table 1, based on which we conducted that the exponential-like method is more capable of effectively delivering the perception of localization of the moving object as compared with the other two methods.

Second, in Fig. 8b, several significant differences are observed by the results of the Friedman test and the Wilcoxon signed rank test with Bonferroni correction. The differences were observed between the methods 1 and 2 ($p = 0.014$, $r = 0.77$) at cue 1 ($\chi^2(2) = 9.00, p = 0.011$, Friedman test), between the methods 1 and 3 ($p = 0.012$, $r = 0.78$) and between methods 2 and 3 ($p = 0.023$, $r = 0.75$) at cue 4 ($\chi^2(2) = 10.86, p = 0.004$), and between the methods 1 and 2 ($p = 0.004$, $r = 0.85$) and the methods 2 and 3 ($p = 0.003$, $r = 0.85$) at cue 5 ($\chi^2(2) = 14.91, p < 0.001$). Thus, method 2 (the exponential-like method) was shown to be the most appropriate under several conditions.

3.2.6 *Discussion*

The experiment 1-2 showed that the method with an exponential-like profile was superior to the other methods with regard to several aspects. First, the results obtained using the exponential-like method was found to be in good agreement with those in [30], in which the exponential-like function was shown to be effective in the conventional presentation range of phantom sensation. Second, variational tendencies

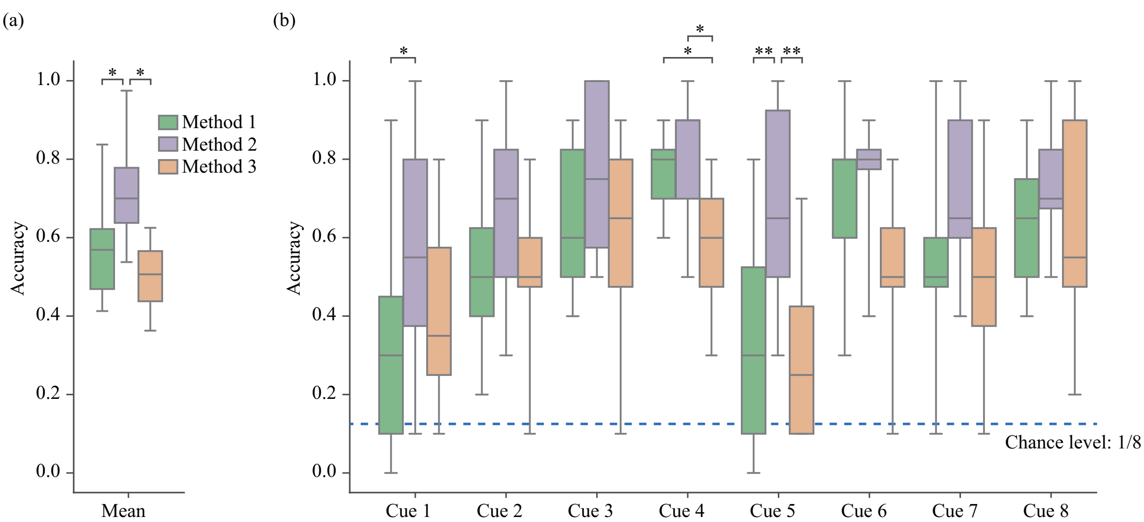


Figure 8. Result of the first experiment: Correct answer ratios for cues 1-8. $*$: $p < 0.05$, $**$: $p < 0.01$.

Table 1. Ratios of discriminable conditions in which correct answer ratios are higher than the chance level in the first experiment

Method	Ratio of discriminable condition
1	6/8
2	8/8
3	7/8

in the exponential-like method was found to be similar to the property of sound waves and radio waves whose intensity decrease in proportion to the square of the distance between the wave generation point and the measurement point. Humans may built internal models that are similar to these physical models.

As can be inferred, method 2 tends to be symmetrical with regard to presentation performance and is more stable than the other methods. A comparison of the accuracy between the symmetrical conditions such as cues 1 and 5 revealed method 2 did not show any significant differences ($p > 0.05$,) thereby demonstrating the symmetry of this method. However in methods 1 and 3, some significant differences ($p < 0.05$) in accuracy were noted between the symmetrical conditions. In terms of the number of cues that differed significantly from the chance level, only method 2 was found to be significantly different in all cues, which further supports the stability of this method.

In exponential-like method 2, the control parameter γ appeared to affect the accuracy and range of presentation. A increase in γ is expected to allow the presentation of the sense of movement over a wider area. Experiments to investigate the effects of γ are required to increase the availability of the method. Therefore, we conducted the second experiment, which we have described in section 4.

4. Experiment 2

4.1 *Objective*

The experiment 2 was conducted to investigate whether the control parameter γ in the exponential-like method affects the presentation accuracy and range of the perceptual moving sensation.

4.2 *Participants*

Ten volunteers (aged from 21 to 24 years, all right-handed, and with no history of tactile processing dysfunctions) participated in the experiments. They were not aware of the purpose of the experiments.

4.3 *Apparatus*

The apparatus in the second experiment was the same as that used in the experiments 1-1 and 1-2.

4.4 *Procedure*

The experimental conditions were the same as those in the first experiment. In this experiment, we compared the four conditions as shown in Fig. 9, with $\gamma = 2,3,4,5$ (equation 4.) Because $\gamma = 3$ was used in the first experiment, the values before and after it were adopted in the second experiment.

The basic procedure in the experiments 2 is the same as Fig. 5. For each of the four conditions, first, the training phase (24 s) was conducted. In the training phase, the vibrotactile and visual stimuli were synchronously presented in three round trips over the entire presentation area. Second, the main phase was conducted. In one trial, one vibrotactile stimuli (2 s) was provided to each participant; then, s/he was asked to answer which cue as depicted in Fig. 10 matched the test stimulus. Each of the eight stimuli was presented to each participant 13 times. A total of 78 trials were conducted for each method. The first 6 out of 78 trials were excluded from following analyses. In total, 304 trials were conducted for each participant. The entire experiment took approximately 70 min. The order of the stimuli and conditions were randomized for each participant to avoid the learning effect.

4.5 *Result*

Fig. 11 shows the mean accuracy scores of the eight participants. Fig. 11a presents the scores for the mean accuracy scores for the six cues. Four significant differences in the results can be observed between $\gamma = 2,3$ and $4,5$ ($p < 0.013$, $r > 0.88$), which is consistent with the results obtained using the

Friedman test ($\chi^2(3) = 24.22, p < 0.001$, Friedman test) and the Wilcoxon signed rank test coupled with Bonferroni correction. These results thus suggest that the conditions $\gamma = 2, 3$ are appropriate for rendering a wide range perception as compared to the conditions $\gamma = 4, 5$. In addition, although no significant difference was identified, performance in the $\gamma = 2$ condition was better than that in $\gamma = 3$.

Fig. 11b presents the accuracy scores for the six cues. First, to measure the number of discriminable conditions in which the accuracy scores were significantly higher ($p < 0.01$) than the chance level ($1/6$), the Wilcoxon signed rank test was conducted for a comparison with the chance level. The results are summarized in Table 2 which support that the exponential-like method is capable of effectively delivering the perception of localization of the moving object over a wide range although there was a significant decrease in performance in the $\gamma = 5$ condition.

Second, there are several significant differences observed in Fig. 11b in the results obtained using the

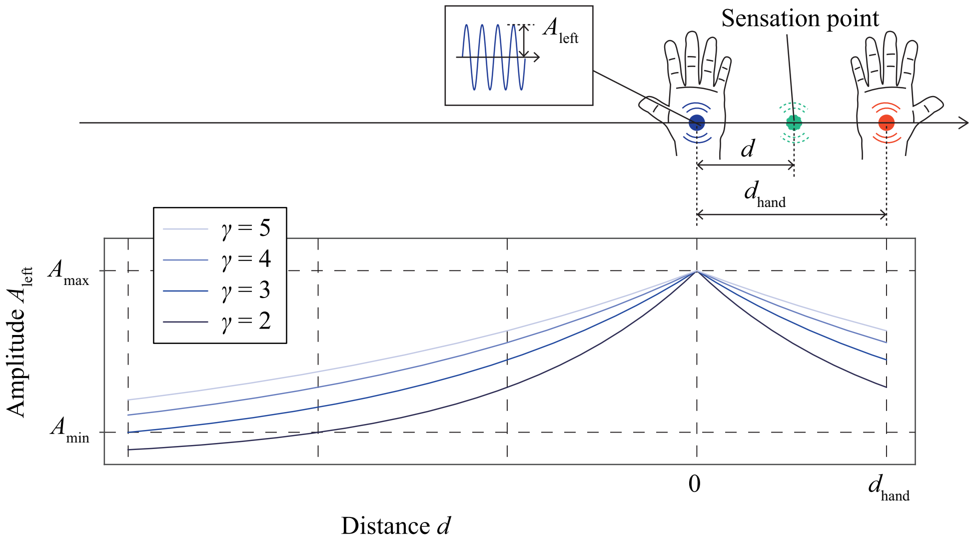


Figure 9. Four types of rendering conditions adopted in the second experiment. Profiles on the right hand side are omitted.

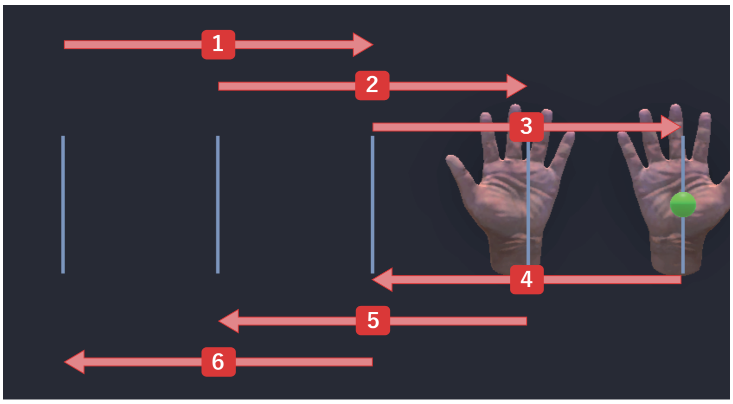


Figure 10. Visual instruction for the participants to answer the cue number in the second experiment

Table 2. Ratios of discriminable conditions in which correct answer ratios are higher than the chance level in the second experiment

Control parameter γ	Ratio of discriminable condition
2	6/6
3	6/6
4	6/6
5	5/6

Friedman test and the Wilcoxon signed rank test with Bonferroni correction. The differences existed were between $\gamma = 2$ and 4 ($p = 0.047$, $r = 0.81$), between $\gamma = 2$ and 5 ($p = 0.023$, $r = 0.85$), between $\gamma = 3$ and 5 ($p = 0.047$, $r = 0.80$,) and between $\gamma = 4$ and 5 ($p = 0.023$, $r = 0.85$) at cue 1 ($\chi^2(3) = 20.38, p < 0.001$), and between $\gamma = 2$ and 5 ($p = 0.023$, $r = 0.86$) and between $\gamma = 3$ and 5 ($p = 0.035$, $r = 0.84$) at cue 2 ($\chi^2(3) = 15.03, p = 0.02$), and between $\gamma = 2$ and 4 ($p = 0.047$, $r = 0.80$), and between $\gamma = 2$ and 5 ($p = 0.023$, $r = 0.84$), and between $\gamma = 3$ and 5 ($p = 0.023$, $r = 0.84$) at cue 6 ($\chi^2(3) = 19.77$, $p < 0.001$).

As described above, although there is no statistically significant difference between conditions $\gamma = 2$ and 3, the results tend to support the suitability of $\gamma = 2$ for presenting the sensations over a wide range.

4.6 *Discussion*

Form the second experiment, it was found that the presentable accuracy varies with changes in the parameter γ of method 2. This tendency may be due to the fact that the ratio of the amplitude change to the distance change varies with γ. The results of the second experiment, in which the perceptual accuracy decreases with increasing γ, support this conjecture.

In addition, there seems to be a trade-off between the range of presentation of the sense of movement and the clarity of the sensation. The minimum amplitudes of both sides are close to zero for $\gamma = 2$. Therefore, when the range of presentation was wider than that of the second experiment, presentation of the sense of movement in the extended area under the $\gamma = 2$ condition appeared to be challenging, whereas, it may be achievable under $\gamma = 3$. However, when $\gamma = 3$, the amplitude change with respect to the change in the distance was smaller than that when $\gamma = 2$; therefore, the overall perceptual accuracy is expected to decrease. Thus, it can be inferred that both the presentation range and perceptual accuracy can change with changes in γ, and that they are in a trade-off relationship with one another.

It is also expected that the presentation performance will vary depending on the travel distance of the stimulus. In order to analyze the localization accuracy of the method in more detail, it is necessary to conduct comparative experiments by changing the range of movement of the stimuli. In relation to this, the present study was aimed at the sense of movement by a moving stimulus, but its versatility can be expanded by investigating whether it can be presented in the case of a stopping stimulus. It seems to be more challenging to perceive a stationary stimulus compared to a moving stimulus.

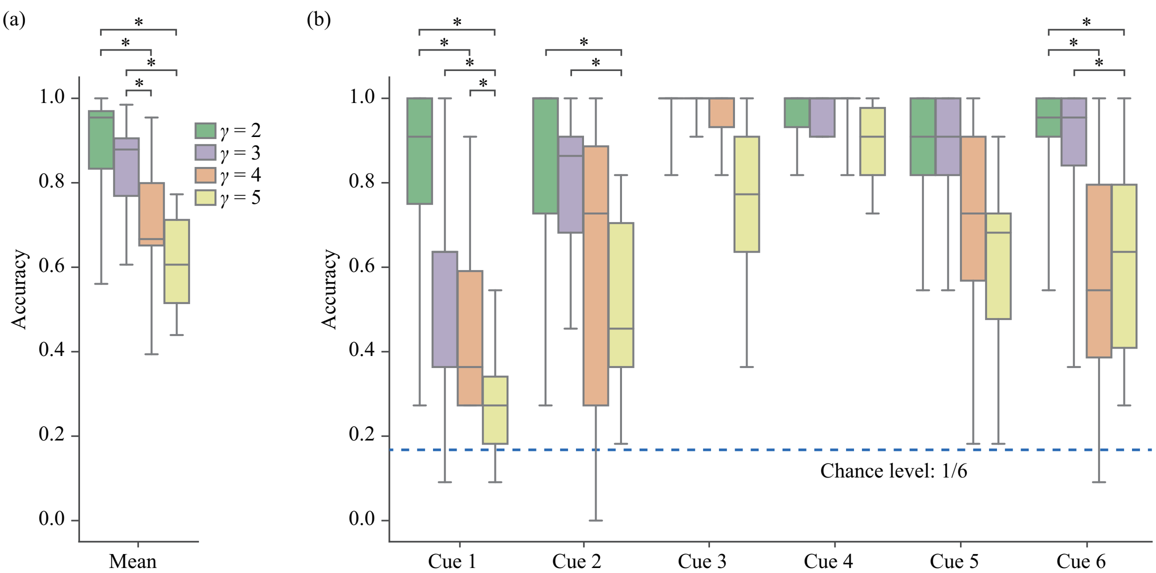


Figure 11. Result of Experiment 2: Correct answer ratios for cues 1-6. $*$: $p < 0.05$.

5. General Discussions

5.1 *Extension to 2D/3D models*

The method with an exponential function-like profile was shown to be effective. This method can be easily expanded to 2D/3D rendering methods without changing the basic characteristics of the equation. Because the vibration amplitude is defined according to the distance between the phantom sensation position and the stimulus position, it is not limited to the number of dimensions, but is determined only by the distance.

However, when extending to 2D/3D methods, the phantom sensation position cannot be uniquely determined based on the vibration amplitudes. For example, in 2D, the phantom sensations positions are linearly symmetrical, which may lead to a decrease in the perceptual accuracy of the moving sensation. To address this, additional vibrators must be placed on the head, legs, arms, or body. In this case, it may be necessary to consider the differences in sensitivity in different areas for effective rendering.

5.2 *Potential applications*

Our proposed model can intuitively perceive the surrounding environment of a user by combining with sensing systems, and can therefore be applied in various fields. In some studies, the system have been developed to only present the directional information. For example, there are systems in which multiple vibrators attached to a belt worn around the waist alerts the user is they are heading in a dangerous direction [9] and in which stimulus to their head using multiple vibrators guides the the user's gaze direction [17]. In the case of tele-operation of robots, there are systems that involve the use of multiple vibrators on the arms to avoid obstacles by indicating the direction of approaching objects [31] and that tell the user which direction in which the manipulator needs to be operated [32]. These therefore provide only directional information and can be improved by the adoption of more informative models such as ours.

Moreover, other researches have used vibration stimuli to indicate direction and distance information by combining two methods for the purpose directional and distance representation. The directional information can be intuitively represented using phantom sensation approach [20] and the single vibration point approach [33], where the correspondence between the direction and the vibration stimulus is easy to understand. These methods may lead to low cognitive load and easy learnability. However, in terms of distance information, these approaches lack an intuition that succinctly links stimulus and perception. In [33], the distance information is proportional to the vibration presentation time. In [20], although the objective was not to deliver the distance information to the user, the vibration was increased with increasing distance. However, the exponential-like method possesses the intuitive characteristic that the vibration amplitude can be reduced as a function of distance. This relationship between the distance and vibration amplitude can be easily understood by everyone. Therefore, by using the exponential-like method, it is expected that intuitive applications can be built for representing the surrounding environment fro users while ensuring low cognitive load and easy learnability.

6. Conclusions

This study extended the conventional vibrotactile phantom sensation method to a novel method for rendering the perception of localization of an object moving in the area outside of the inter-stimulus. For establishing an appropriate mathematical model, we conducted the three experiments. In the experiment 1-1 and 1-2, the three types of methods representing the relationships between the intensity of vibrations applied to the left and right hands and the presentation position were compared in terms of subjective evaluation of the sense of movement and the localization accuracy of movement, respectively. The results showed that the exponential-like method was the most appropriate for effective rendering the perception of localization of an object moving in the area outside the inter-stimulus. This method was additionally investigated in a second experiment to reveal the effect of the parameter on wide range sensation. The results revealed that the presentation accuracy was improved for parameters with large amplitude changes in response to changes in the presentation position. In our experimental conditions, the exponential-like model with $\gamma = 2$ showed the best performance. However, when the presentation range is widened as compared to that in the experiment 2, the presentation accuracy of $\gamma = 2$ model will decrease in the extended area and $\gamma = 3$ model may be more suitable for representing the phantom sensation in the area. Thus, it was inferred that a trade-off relationship existed between the presentation accuracy and the presentation range exists. It is expected that these findings will serve as guidelines to effectively render wide range phantom sensations covering the areas outside the inter-stimulus.

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