Localization Performance of Multiple Vibrotactile Cues on Both Arms

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Abstract—To present information using vibrotactile stimuli in wearable devices, it is fundamental to understand human performance of localizing vibrotactile cues across the skin surface. In this paper, we studied human ability to identify locations of multiple vibrotactile cues activated simultaneously on both arms. Two haptic bands were mounted in proximity to the elbow and shoulder joints on each arm, and two vibrotactile motors were mounted on each band to provide vibration cues to the dorsal and palmar side of the arm. The localization performance under four conditions were compared, with the number of the simultaneously activated cues varying from one to four in each condition. Experimental results illustrate that the rate of correct localization decreases linearly with the increase in the number of activated cues. It was 27.8 percent for three activated cues, and became even lower for four activated cues. An analysis of the correct rate and error patterns show that the layout of vibrotactile cues can have significant effects on the localization performance of multiple vibrotactile cues. These findings might provide guidelines for using vibrotactile cues to guide the simultaneous motion of multiple joints on both arms.

Index Terms—Localization performance, vibrotactile cues, correct rate, location identification, perception, simultaneous activation of multiple cues

1 Introduction

Skin is a unique sensor of a large area, impling a big potential for using the body surface as a means of conveying information to human operators [1], [2], [3]. It is fundamental to know the human ability to identify the locations of multiple vibrotactile cues activated simultaneously on the skin. This knowledge can not only enhance the understanding of haptic perception, but may also provide guidance for designing vibrotactile display systems [4] and multi-joint motor skill learning platforms utilizing vibrotactile cues.

A specific motivation behind this study is to explore the feasibility of using vibrotactile cues to guide simultaneous motion of multiple joints. This study can be useful for learning multi-joint motor skills [5], [6]. Typical examples of these tasks include Gymnastics, Yoga, Tai Chi and other sports involving multiple joints coordination, in which motions of multiple joints need to be coordinated [7]. For example, in Tai Chi, the motion of the shoulder should precede the motion of the elbow in specific patterns, and arms and/or legs should move in a synchronous way.

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The above motivation originates from two fundamental questions that need to be addressed. First, the perception capacity of the vibrotactile signal, i.e., how many vibrotactile cues can be simultaneously perceived at a sufficiently high correct rate, and how the locations of these cues may influence the perception accuracy. Second, the performance of motor control assisted by haptic cues, i.e., how accurately and how fast human can execute a commanded motion of multiple joints based on multiple cues simultaneously presented at different locations on the body surface.

In this paper, the first question is addressed. Specifically, the objective is to measure the human ability to identify locations of multiple vibrotactile cues presented simultaneously on both arms.

Our long-term goal is to explore effective haptic feedback to enhance motor skill learning in Tai Chi. The movement of Tai Chi is complicated, which requires coordination of the joints of the arms and legs. We begin our study by investigating the coordination of two arms. In our early experimental study presented here, we consider only the motion of the elbow and shoulder in order to keep the mental work load under the participants' control.

1.1 Related Work

A number of studies have already been conducted to explore the performance of skin in perceiving vibrotactile cues in parallel, including numbers and locations of multiple cues simultaneously presented on the body [2], [8], [9], [10].

The study on the numerosity judgments of tactile stimuli provides a basis for exploring the localization performance of multiple cues. Gallace et al. [2] systematically studied the numerosity judgments including the number of stimuli, and duration and intensity of the vibration to explore the possible limitations on cognitive processing of tactile stimuli distributed over the body surface. They found a monotonic relationship between the number of the tactors activated and the perception performance measured. Wentink et al. [9] measured the perceptual performance of vibrations at different frequencies and locations on one upper leg, as well as the ability of subjects to estimate the locations and the number of stimuli in an array. Their results illustrate that sequential stimulation is more suitable for feedback than simultaneous stimulation. They also found that the most sensitive locations for providing the haptic feedback are the medial and posterior sides of the leg.

The localization performance of the vibrotactile cues on both arms has been explored in several studies. Roger et al. [10] explored the ability to localize the vibrotactile stimuli on a linear array of tactors on the forearm. The influences of a number of stimulus parameters were studied, including the frequency and location of the stimulus sites. They found that stimulus frequency produced much less effect on localization performance than expected. For those stimulus sites proximal to natural anchor points, such as the wrist, elbow and shoulder, they exerted an overwhelming influence on tactile localization accuracy. Contrary to the opinion from Piateski et al. [11], Ian Oakley et al. [12] believed that the forearm as a site for the display of vibrotactile cues was superior to the torso.

To test whether the localization accuracy on the upper limb varies with location (hand, wrist, and forearm), Cody et al. [13] found that acuity was greater in the transverse than longitudinal axis. Additionally, acuity was greater on the dorsal surface at the wrist than either at the hand or forearm locations in the longitudinal axis, supporting an enhancement of resolution at joints (anchor points).

Furthermore, the perception differences between the left and right arms were also studied. Lakatos et al. [14] studied the time-distance relations in shifting attention between locations on one's body, and found that subjects took longer time to respond to the locations on the left, as opposed to the right, side of the body. They explained that such chronometric differences may be related to differences in the lengths of the afferent neural pathways and to the size of cortical area devoted to the representation of individual body locations.

To the best of our knowledge, limited studies have explored the localization performance of multiple vibrotactile cues activated simultaneously on both arms. In this paper, we mainly focus on two questions as follows:

1. How does the number of activated cues affect the localization performance?
2. How does the spatial layout of the simultaneously activated cues influence the localization performance? For example, whether the performance is different for symmetrical and non-symmetrical distribution of vibrotactile cues on both arms?

Answers to these questions will be useful in developing future haptics-assisted motor learning systems involving coordination between the joints on both arms.

1.2 Contributions of This Study

The contributions of this paper can be summarized as:

1. We measure the correct rate of localizing the vibrotactile cues distributed on both arms. The experimental results indicate that the number of simultaneously activated cues has a significant effect on the localization correct rate. The performance deteriorates to a surprising low level when the number of simultaneously activated cues is equal to or above three.
2. For a given number of simultaneously activated cues, the ranking of the correct rate is obtained with regard to different layouts of the activated cues. Based on this ranking, we identify the layouts with low correct rates, and the possible reasons are given considering the effects of several key parameters, including symmetrical/non-symmetrical distribution, left and right arms, forearm and upper arm, and dorsal/palmar side of the arm, etc.

The remainder of this paper is organized as follows. In Sections 2 and 3, we introduce the method and results of the experiments. In Section 4, the possible psychophysical reasons leading to the perception error are analyzed, and the implications of the findings for designing wearable vibrotactile devices are discussed. Conclusions and future work are presented in the last section.

2 Method

2.1 Participants

Ten participants (S1-S10, 3 females and 7 males) participated in the experiment. Their ages ranged from 22 to 35 with an average age of 26. All of them reported no haptic perception abnormality. All participants gave written consent to participation in the study. The participants were compensated RMB 60 Yuan (about $10) after the experiment.

2.2 Experimental Setup

Two vibrotactile bands were worn on the arms of the participants. The bands were located in close proximity to the elbow and shoulder joints. In each band, two eccentric rotating mass (ERM) motors (NFP-C1020BME, Need-For-Power Motor Co., Ltd, China) were mounted on the inner and outer parts of the arm. The motor is 10 mm coin type with a nominal voltage DC 3.0 V and 61 mA current. The nominal rotational velocity is 14000 ± 3000 rpm. The locations of the motors on the arms were illustrated in Fig. 1a.

The rational of our experimental design was based on the following practical situation: the forearm or upper arm cannot move in two opposite directions at the same time for motion guidance. On perceiving a cue, participants were instructed to rotate his/her elbow or shoulder joint in opposite directions, e.g., when the inner motor on the upper arm was activated, the shoulder generated an extension motion of the shoulder joint [5], [15]. Consequently, the two motors on the same vibrotactile band never simultaneously vibrated. All eight motors were coded by a number for the convenience of analysis. In the following sections "13" means simultaneous vibration of motor "1" and "3".

The motors produced vibrotactile cues at around 250 Hz, which was reported to be the optimal frequency for skin detection and in particular for the upper limb [4], [10]. The vibration amplitude of the motor was adjusted by changing the value of PWM as described in [16]. According to the

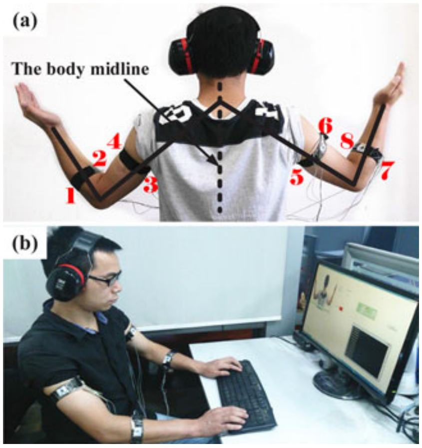


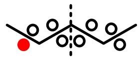
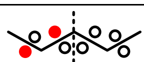
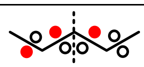
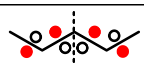
Fig. 1. Experimental system. (a) Graphical user interface. (b) One participant during the experiment.

online feedback from the participant in the calibration experiment, a voltage value was identified as the best if it could be clearly and comfortably perceived by the participant. The range of actual operating voltage is from 3.5 V to 4.0 V. Measured by a laser vibrometer (LV-S01-SF, Sunny Intelligent Technology Co., Ltd., China), the actual vibration frequency of the ERMs for different participants is different, which ranges from 234 Hz to 254 Hz. The vibration magnitude remained the best value calibrated individually for each participant throughout the experiment.

The participants were instructed to sit in a comfortable posture facing a visual display as shown in Fig. 1b. In order to avoid fatigue and reduce the cognitive load of participants, the locations of the eight motors on the arm were displayed on a graphic user interface, which provided a visual aid for the participants to map between the motors' code and their locations on the two arms. The distance between the participants and the visual display was about 0.5 m, so the participants could clearly see that the motor locations marked on their arms were displayed on the monitor.

During the experiments, a pair of head-mounted earmuffs (Peltorh10A, 3M Inc. US) was used to mask distracting ambient noises, so as to help the participant to concentrate on the perception task. On the desk was placed a response keyboard, through which the responses were recorded by pressing the targeted keys on the keyboard. All

TABLE 1
Number of Combinations of Activated Cues in Each of the Four Conditions

Condition	Number of combinations (N_k)	Examples for the layouts
C1(one cue)	8 cases ($C_4^1 \cdot 2^1$)	
C2(two cues)	24 cases($C_4^2 \cdot 2^2$)	
C3(three cues)	32 cases($C_4^3 \cdot 2^3$)	
C4(four cues)	16 cases($C_4^4 \cdot 2^4$)	

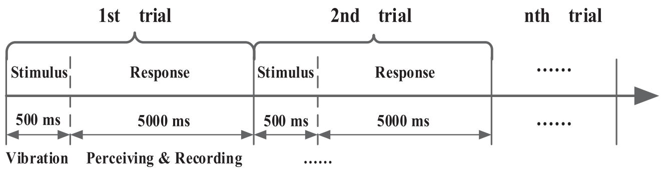


Fig. 2. Time allocation during each trial (2nd trial, nth trial).

the locations of the motors activated simultaneously were recorded regardless of the input sequence of these codes in one trial. The participants were free to perform the input operation using the fingers from either one hand or both hands.

A progress bar was displayed on the computer screen to show the time left. If no response was provided within the time duration, the trial was considered as a failure.

2.3 Experimental Procedure

As shown in Table 1, there were four conditions for the number of simultaneously activated vibrators, i.e., one/two/three/four vibrating cues. For each condition, the number of combinations for the layout of the cues was 8, 24, 32 and 16. The total number of all combinations was 80. For each combination, 3 trials were performed. Therefore, 240 trials were conducted for each participant.

The experimental procedure was divided into three blocks, and each block was comprised of 80 trials arranged in a random sequence of the combinations. There was a 5-minute break between the two blocks to avoid fatigue.

Before the formal experiment, a pilot experiment was performed for participants to get familiar with the mapping between the location of the motors and their codes. In the beginning of the experiment, the vibrating magnitudes of the eight motors were calibrated individually for each participant to ensure easy and reliable perception of vibration at all locations. The participants were provided with sufficient number of trials on each motor location until they were able to accurately report the code of the activated motor within the required time duration. They were informed that the maximum number of the simultaneously activated motors is 4. The participants were instructed to identify which motors were vibrating and then click on the numeric keys on the keyboard according to the codes of these motors within the allowed duration.

Each trial lasted for about 5.5 seconds, consisting of duration for vibration, perception and recording. Allocation of the time allocation for each trial was shown in Fig. 2. For each participant, it would take about 7 minutes and 20 seconds to finish a block. A trial began with motor vibration, which lasted for 500 ms, and the following 5 seconds are for the participants to response.

The time duration of each trial was selected based on the previous studies by Lakatos et al. [14]. They measured the adjusted reaction time (RT) for subjects to respond to the tactile stimulus while shifting their attention between right and left wrists. Their results reveal that the average RT was 393.4 ms. In the experiment conducted by Gallace et al., the time limit of the response time was 4 sec [2]. According to these studies, the allowed response time for one trial was set as 5,000 ms in our experiments.

2.4 Definition of Correct Rate

For each of the four conditions (Table 1), the average correct rate of localization performance was defined as

$$\eta_k = \frac{\sum n_{ij}}{MN_k} \times 100\% \ , \quad i = 1, 2, \ldots, M \ ; \ j = 1, 2, \ldots, \ N_k \quad (1)$$

where k refers to the number of activated cues ($k = 1, 2, 3, 4$), and n_{ij} refers to the score of a trial. It was counted as 1 if both the number and location of vibration cues were correctly identified within the allowed response time. Otherwise, it was recorded as 0. And

$$N_k = C_4^k \cdot 2^k \quad (2)$$

refers to the number of cue combinations for each of the four conditions. As shown in Table 1, the value of N_k is 8, 24, 32 and 16 for the four conditions, respectively. In the above Eqn. (1),

$$M = N_p \cdot N_r \quad (3)$$

refers to the total number of trials for each given cue combination. N_r refers to the number of the trials for a given combination. In our experiment, three repetitive trials were performed for each combination. N_p refers to the number of participants. There were ten participants in our experiment.

For each location, the average correct rate of localization performance under the four conditions was defined as

$$\eta_k^s = \frac{\sum a_{ij}}{MR_k} \times 100\% \ \ , \ i = 1, 2, \ldots, M \ ; \ j = 1, 2, \ldots, \ R_k \quad (4)$$

Where, s refers to the motor code, and a_{ij} refers to the score of a trial. It is recorded as 1 if a vibration cue at a specified location was successfully perceived and recorded within the allowed response time. Otherwise, a_{ij} was recorded as 0. $R_k = C_3^{k-1} \cdot 2^{k-1}$ refers to the number of the combinations for the specified location. Under the four conditions, the value of R_k is 1, 6, 12 and 8 respectively, and is the same for all the eight locations.

For all four conditions, the average correct rate of localization performance for a specified location was defined as

$$\gamma_s = \frac{\sum \eta_k^s}{4} \ , \ k = 1, 2, 3, 4 \quad (5)$$

3 RESULTS

In this section, results of correct rate under each condition are compared with respect to the number of activated cues as well as the location of individual sites. Furthermore, the ranking of the correct rate with respect to the combination of the activated cues are obtained to reveal the recommendable spatial layouts of the vibrotactile cues in terms of the perception performance.

3.1 Correct Rate versus the Number of Vibrotactile Cues

Fig. 3 shows the average value and the standard deviation of the correct rate of localization performance calculated according to Eqn. (1). The average correct rate monotonously decreased when the number of the activated cues increased. The correct rate was 62.9 percent for two activated cues, 27.8 percent for three activated cues, and even lower for four activated cues.

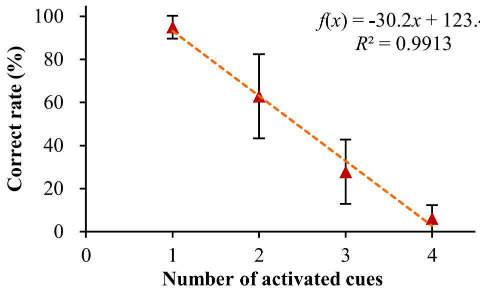


Fig. 3. Localization correct rate with respect to the number of the activated cues.

The data obtained was fitted by a linear function with respect to the number of simultaneously activated cues. The analysis of the goodness-of-fit shows that the R^2 value was 0.9913, indicating that the linear model could precisely describe the correct rate with respect to the number of activated cues.

One-way analysis of variance (ANOVA) was also performed to check the statistical difference in the correct rate between four conditions. The results show that there were significant differences among the four conditions as a within factor ($\mathrm{F}(1.636, 11.449) = 56.993$, $\mathrm{p} < 0.05$). Fractional degrees of freedom were due to the Greenhouse-Geisser correction when Mauchly's Test of Sphericity shows that the assumption of sphericity had been violated. Post-hoc multiple-comparison tests using Bonferroni method revealed significant differences across all pairs of conditions except C2 versus C3. We show all the combinations under four conditions in an extra Appendix, which can be found on the IEEE Xplore Digital Library at http://ieeexplore.ieee.org/document/8013825/.

3.2 Rankings of Correct Rates Among Layouts

For a given number of activated cues, the variability of localization performance in different spatial layouts of the activated cues was analyzed. Under each of the four conditions, we obtained the ranking of average correct rates among different combinations of activated cues as shown in Fig. 4.

For the condition of one activated cue as shown in Fig. 4a, the correct rate for most locations was over 90 percent, except for the cases ("2", "3"), which had a relatively lower correct rate between 80-90 percent. However, comparing to the correct rate of two, three and four activated cues as shown in Fig. 3, the correct rate in these two cases was still much higher.

For the condition of two activated cues, the ranking of correct rate among all combinations is shown in Fig. 4b. More than half of the combinations had a correct rate lower than 70 percent, and the correct rate of the three combinations ("25", "58" and "23") was less than 50 percent. Several observations can be obtained based on statistical analysis. First, the correct rate was higher when the two cues were located on both arms, e. g. "16", "35" and "17", rather than on a single arm, e. g., "24", "57" and "13". The difference in the correct rate between the two cases is significant ($\mathrm{F}(1, 9) = 10.946$, $\mathrm{p} < 0.05$). Second, when the two cues

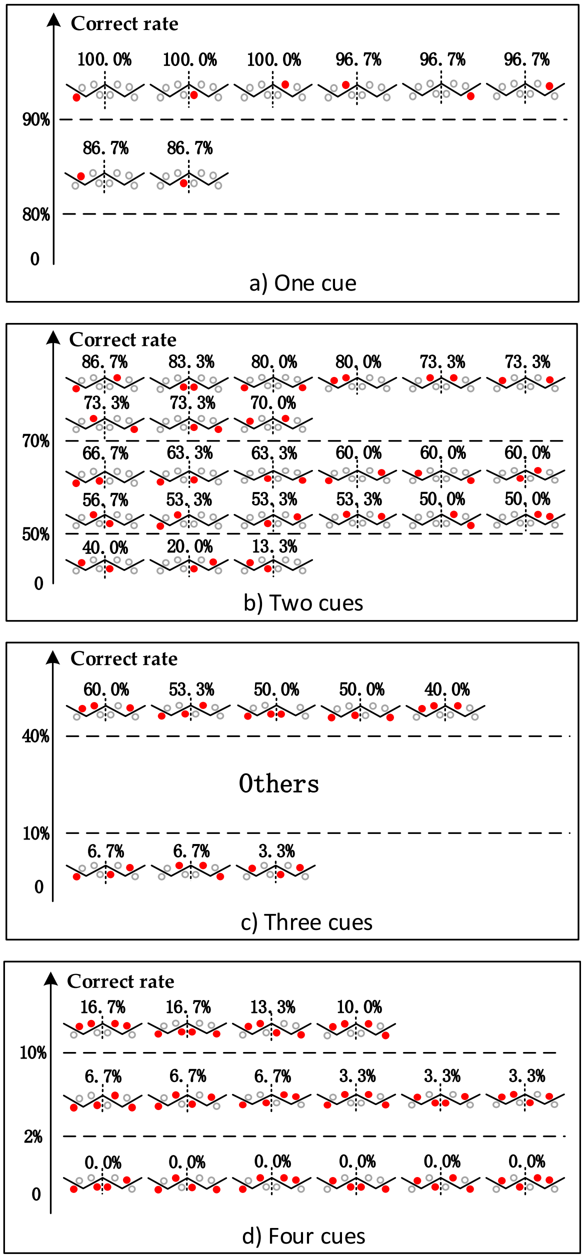


Fig. 4. Ranking of the localization correct rate among different spatial layouts of activated cues.

were located on the two arms, the correct rate was higher when the layout of two cues was symmetrical rather than asymmetrical with respect to the body midline. One-way repeated measures ANOVA analysis of the correct rate showed significant difference between the two cases ($F(1, 9) = 15.176$, $p < 0.05$). Finally, when the two cues were located on the same arm, the correct rate was higher when the two cues were located on the same side of the arm (i.e., both cues were on the dorsal side) rather than on the opposite side. ANOVA analysis of the correct rate showed significant difference between the two cases ($F(1, 9) = 25.686$, $p < 0.05$).

For the condition of three activated cues provided with an extra Appendix, available in the online supplemental material, the combination sets with the best and worst performance are shown in Fig. 4c. The correct rate for only five of the 32 combinations was above 40 percent. Apart from the "136", the four combinations, "248", "135", "137" and "246" with higher correct rates in the ranking had a common feature that all activated cues were located on the same sides of both arms (either dorsal or palmar side). Furthermore, for those combinations having the correct rate less than 10 percent, one common feature was that the two activated cues are located on the two opposite sides of a single arm.

For the condition of four activated cues, the highest correct rate happened in the two combinations, "1357" and "2468". The common feature of these two combinations was that all activated cues were located on the same side of both arms. Furthermore, for the symmetrical layouts, the correct rate was higher when the four cues were located on the same sides of the two arms (i.e., "1357" and "2468") rather than on the two opposite sides (i.e., "1467" and "2358").

TABLE 2
Error Pattern Analysis: Illustration of Actual Location and Its Corresponding Reported Locations

Multi-cue condition	Actual locations	Reported locations (replication trials)
2 cues	"25"	"257"(3),"2"(2),"258"(2),"15"(2),"157"(2)
	"58"	"57"(5),"67"(5),"68"(4),"5"(3)
	"23"	"13"(9),"3"(5),"14"(4)
3 cues	"158"	"157"(6),"168"(4),"15"(3),"18"(3)
	"467"	"468"(8),"46"(6),"47"(4)
	"258"	"25"(6),"268"(6),"257"(4),"267"(3)
4 cues	"1358"	"1357"(7),"245"(3),"138"(2)
	"1457"	"147"(4),"245"(3),"246"(3)
	"1468"	"146"(7),"2468"(4),"246"(4)
	"2357"	"1357"(5),"1367"(2),"235"(2),"135"(2)
	"2367"	"368"(4),"2368"(3),"236"(3),"248"(3)
	"2368"	"146"(5),"2367"(2),"368"(2)

3.3 Error Patterns

In order to thoroughly investigate the reasons for wrong perception, we further analyzed those combinations with the lowest correct rate (Fig. 4). Table 2 lists the combinations along with the corresponding wrong reports. The number of the wrong reports is shown in the brackets.

Comparing the actual location with the reported location, we found two error patterns. First, most errors occurred between the two motors located within the same haptic band. For example, "58" were perceived as "57", while motor 7 and 8 were located in the same band. Similar situations occurred for other combinations such as "23", "158", "1358", etc. Second, most errors resulted from overestimation or underestimation. For example, "25" was reported as "257" or "2", and similar situations occurred for other combinations such as "258", "1468", etc. Underestimation grew more remarkable as the number of the activated cues increased.

3.4 Correct Rate of Individual Location

Fig. 5a shows the mean and standard deviation of the correct rate of each location under the four conditions computed by the metrics defined in Eqn. (4). Furthermore, as shown in Fig. 5b, the mean and standard deviation of the correct rate of each location for all the four conditions could be derived using the metrics defined in Eqn. (5). In Fig. 5,

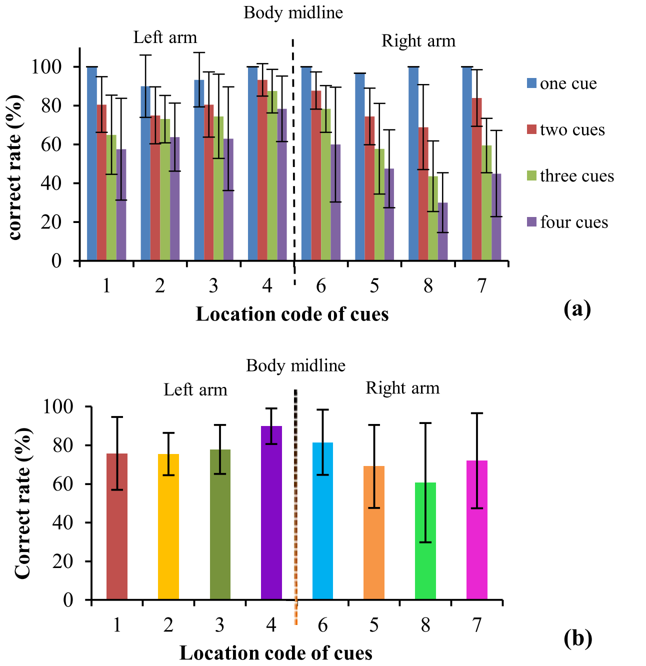


Fig. 5. Localization correct rate at each individual location. (a) Correct rate under each of the four conditions. (b) Average correct rate of the summation from all four conditions.

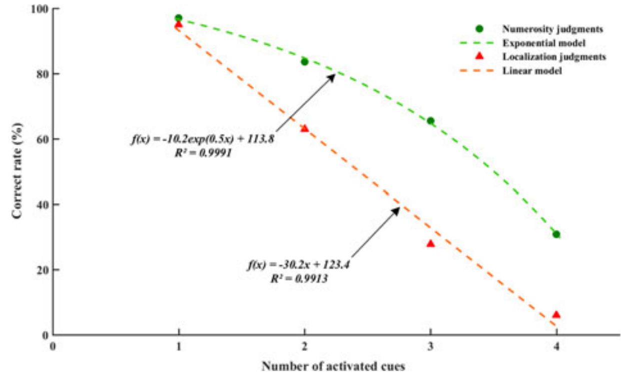


Fig. 6. Comparison between localization and numerosity correct rate with respect to the number of the activated cues.

the order of the location codes was intentionally arranged symmetrically with respect to the body midline, so as to compare the localization performance between the left and the right arm.

The performance at each individual location could be observed from the results. For each one of the four experimental conditions, pairwise comparisons (8 levels) were performed using Bonferroni statistics to analyze significant effects of ANOVAs. No significant difference is shown between the eight sites under the condition of one-cue with $F(2.230, 20.074) = 1.988, p > 0.05$. Fractional degrees of freedom were due to the Greenhouse-Geisser correction when Mauchly's Test of Sphericity shows that the assumption of sphericity had been violated. Post hoc multiple-comparison tests show the difference is not significant between eight sites under the condition of one-cue, because a single vibration stimulus is very easy to be perceived for each site. In contrast, there was significant difference between the eight sites under the condition of two-cues with $F(3.614, 32.530) = 3.077, p < 0.05$, under the condition of three-cues with $F(3.727, 33.547) = 7.262, p < 0.05$, and under the four-cues condition with $F(3.771, 33.937) = 5.326, p < 0.05$.

The difference between the left and the right arm could be also revealed through the results in Fig. 5. For the condition of one activated cue, the correct rate of all locations on the right arm was slightly higher than that of the corresponding symmetric location on the left arm (except "7" versus "1"). For the other three conditions of multiple vibrotactile cues, the correct rate of all locations on the right arm was lower than that of the corresponding symmetric location on the left arm (except "7" versus "1" under the condition of two cues). Furthermore, in terms of the fluctuation for individual locations on both arms, standard deviation values at each location were presented in Fig. 5.

Comparing the forearm and upper arm, the localization performance of the upper arm was better than the forearm. Eight sites were divided into two parts by the upper arm and the forearm in order to use one-way repeated measures ANOVA analysis. Overall, the correct rate of the locations on the upper arm (i.e., "3", "4", "5", "6") was higher than that of the forearm (i.e., from "1", "2", "7", "8") as shown in Fig. 5. One-sample Kolmogorov-Smirnov Test shows that the distribution complies with the normality assumptions during statistical testing. ANOVA analysis shows the significant difference ($F(1, 9) = 8.212, p = 0.019$) between the forearm and upper arms.

For the condition of one activated cue, the difference of localization performance between the dorsal and palmar side was studied by comparing the average accuracy of each location on the dorsal side ("1", "3", "5"and "7") and the corresponding location on the palmar side ("2", "4", "6" and "8"). One-way repeated measures ANOVA analysis indicated no significant difference ($F(1, 9) = 0.897, p > 0.05$) between the two sides. Therefore, it seems feasible to deploy the motor at either dorsal or palmar side of both arms for the condition of one activated cue.

Moreover, the correct rate of location "4" was always the highest for all conditions, while that of location "8" was always the lowest except for the condition of one cue. This is an interesting issue to be studied in the future work.

4 Discussion

4.1 Numerosity and Localization Performance

As there is a close relationship between numerosity and localization performance, we computed the numerosity performance with respect to the different number of vibrotactile cues, and compared it with the localization performance.

As shown in Fig. 6, for the four conditions, the average correct rate of numerosity performance is 97.08, 83.61, 65.52 and 30.83 percent. The correct rate dropped sharply with the increase in the number of activated cues. The correct rate of numerosity performance was fitted by an exponential function with respect to the number of the simultaneously activated cues. The analysis of the goodness-of-fit showed that the R^2 value was 0.9991, indicating that the exponential model could accurately describe the correct rate with respect to the different number of activated cues.

This result of numerosity performance is consistent with that of previous studies measured by error metrics rather than correct rate [3]. This consistency validated that the parameters used in our experiment, such as the duration of the tactile stimuli and the allowed reaction time, are reasonable for measuring the perceptual performance of human subjects.

As shown in Fig. 6, it is clear that the more the number of simultaneously activated cues is, the larger the difference between the numerosity performance and the localization performance is. This gap indicated that the task of localization is much more challenging than the task of numerosity, especially for perceiving the locations of multiple activated cues.

4.2 Effect of Spatial Layouts on Localization Performance

For the condition of two cues, our experimental results indicated that the distribution of the cues within one arm or between two arms made a significant difference. When the two cues were located on two arms, the correct rate was significantly higher than the case when both the cues were located on a single arm. This result is consistent with the findings from the tactile perception experiment by Lakatos et al. [14]. In their experiment, subjects had to determine as quickly as possible whether an air stimulus had been received at one of the eight symmetric locations from arms and legs. They found it took subjects more time to shift attention between the locations on the same side of the body, as compared to those on the different sides.

Another important finding is about the symmetrical effect of the location layouts. When the two cues were located on both arms, the correct rate of all the combinations with symmetrical layouts were significantly higher than those with asymmetrical layouts.

Another finding is that the distribution of the cues on the same side of the arm is different from that on the opposite side. For the condition of two cues, experimental results indicated that the correct rate of the combinations whose cues were located at the same side of the arm, such as “24” and “57”, was significantly higher than those whose cues located on the opposite sides, such as “23”and “58”. Similarly, for the condition of three and four cues, the correct rate of the combinations whose cues were located at the same side of both arms, such as “248” and “2368”, were better than those on the opposite sides, such as “247” and “2358”. The possible reason for this side-dependent effect might be an important research topic.

However, there is not yet a common criterion or an objective reference to categorize the correct rate of vibrotactile perception. Only 50 percent could be taken as a watershed for ranking categories of correct rates among layouts, but it is too rough for presenting the correct rate. In order to accommodate as many combinations as possible, while highlighting the best and worst combinations, we divided the correct rate levels as shown in Fig. 4. It is expected that a more reasonable success rate rating method could be put forward based on requirements from specific motor tasks.

4.3 Analysis of Error Pattern

Analysis of error patterns revealed that underestimation and overestimation were two important factors leading to the error of localizing multiple activated cues. The experimental results indicated that underestimation increased as the number of presented stimuli increased, while overestimation decreased as the number of stimuli increased. The underestimation occurred frequently under the conditions of multiple activated cues, especially when the number of activated cues was four. For instance, over 25 percent participants reported the combinations “1468” as “146”. This result is consistent with the findings of Gallace et al. [2], who found participants tended to underestimate, rather than overestimate the number of tactors activated.

Another error pattern was also revealed. Most confusion occurred between the two motors are located within the same band. In other word, the reported location and the actual location were opposite within the same vibrotactile band. There are two possible reasons for this error pattern.

One reason could be the small distance between the two motors. Sofia and Jones studied surface wave propagation during vibrotactile stimulation, and found that the surface wave was markedly attenuated at the distance 8 mm from the motor, but even at the distance 24 mm the amplitude was still above the perceptual threshold [17]. Thus, we could not deny the possibility that the two closely located cues might cause confusion, resulting in the perception error. Although this type of masking effect might decrease with the increase of the interstimulus distance, the value of the distance threshold is still controversial [11], [18], [19]. Cha et al. [20] found that the separation of two vibrating stimuli on arms should not be less than 20 mm. On the contrary, the results from Roger’s experiments demonstrated that a physical separation of 25 mm was insufficient to provide very accurate identification of seven locations along the surface of the forearm [10]. Barghout et al. [21] illustrated that the two-point discrimination threshold ranges from 38 mm to 40 mm.

The other reason might be the band linking the two motors. Few studies have discussed this issue, except for Cha et al. [20]. They used a soft band to link motors, but the soft band still became a little stiff when it was bundled on an arm. It seems unavoidable that the vibration of one motor would be delivered to the adjacent motor, and then resulted in perception confusion. Therefore, in the future, we plan to develop separate bands that are capable of mounting vibrators at the dorsal and palmar sides of a given longitudinal location of an arm.

4.4 Analysis of the Difference between Individual Locations

A comparison of the localization performance between the left and right arms shows that the left arm performed better with multiple vibrotactile cues, while the right arm performed better under the one-cue condition as shown in Fig. 5a. When more cues were involved in the vibration, the difference between the left and right arms tended to be greater.

The difference in the localization performance between the two arms might be due to limited working memory [22]. Considering the cognitive process during the perception task in our experiment, the participants first concentrated on detecting both the location and the number of vibrating cues, then mapped those vibrating cues into the code of corresponding locations, and finally reported the locations within the given time constraint. Although the visual clues of the codes and the practice before the formal experiment helped to decrease the memory and cognitive load, the workload of working memory might still be heavy, and thus influenced the localization performance in the case of multiple cues. Our observation was that most participants could not help memorizing the code of vibrating motors from the left arm to the right arm. As the participants were required to provide the response within the allowed time constraint, it might be possible that the participant could not recall the cues on the right arm because of limited working memory.

This result is consistent with the previous findings on visual perception of multiple cues [23]. When the number of the visual stimuli presented exceeds a certain value, and when sufficient time is not available for observers to accurately count all the items presented, the participants stopped counting and started to use a less accurate 'estimation' procedure instead. This could partially explain the error patterns observed in our experiment.

4.5 Implications for Designing Wearable Devices

The correct rate found for the different layouts of vibrating cues could provide several important guidelines to design wearable device with vibrotactile cues. First, based on the influence of cues number on the localization accuracy, the number of cues simultaneously presented on both arms should not exceed two if a high accuracy of localization is required. For some applications requiring three or more cues, it is advisable to adopt those layouts having a high localization performance. Second, for those applications that require two vibrotactile cues simultaneously presented, it will be preferable if their distribution is symmetric. Third, when the number of cues is greater than two, other vibration strategies should be considered such as adopting sequential stimulation instead of simultaneous activation of multiple motors [9].

The analysis of the error patterns between the actual and reported locations on the arms provides important insights to improve the design of vibration patterns. If it is unavoidable to employ three or more vibrotactile cues for a certain design, it is advisable to avoid using the same vibration parameter (i.e., frequency, amplitude and wave form) for the two motors within the same band, and thus to avoid possible interference between dorsal and palmar sides.

One simple solution is to employ different vibration patterns for the two motors within the same band. For example, diversified patterns of vibration might be used for the location of "1" and "2", such as incorporating different frequency, amplitude, and duration of sustained vibration, so as to produce better discrimination accuracy. However, this may also increase cognitive load as more vibration patterns need to be perceived and memorized. Therefore, the effect of these methods needs to be validated by more rigorous studies.

In this study, we adopted the convenient method of subjective calibration for determining the intensities of vibrations for each tactile stimulus. It remains an open question to explore the influence of intensity on perception accuracy. As Hwang et al. [24] suggested, the psychophysical magnitude functions of the perceived intensity are rarely reported, in part because of the difficulty of conducting exhaustive psychophysiological measurements. Even though they built a robust model for the perceived intensities of mobile device with the two independent variables of frequency and amplitude, the optimal perceived intensity of coin vibration motors remains in question for the wearable devices.

However, one of the limitations in our study is that the possible spurious effects about limb motion were not addressed. The absence of the condition with limbs movements makes it unclear whether a participant could follow the tactile instructions displayed on his/her limbs simultaneously while moving. The position of the body can also influence the localization of the tactile cues [25], [26], [27]. When tactile cues are used to guide the movement of limbs, the interaction between the movement and the vibration could be introduced as a potential factor to be investigated further. Previous studies have shown that movement and tactile stimulations can interact even if they don't come from the same location on the body and particularly between the two arms [28], [29]. Therefore, when tactile cues is used to guide the movement of limbs, it is necessary to examine the interaction between movement and vibration cues. One future research topic is to add a new condition to the current experimental study. The participants could be required to move their arms in a slow motion, and the response to the vibrotactile cues from different combinations of locations could be examined.

5 Conclusion and Future Work

In this paper, we explored the perceptual performance of identifying the location of vibrotactile cues on both arms to understand how it changes with the number and layout of multiple vibrotactile cues. The implications of the result from this study for the design of wearable vibrotactile devices were summarized. Furthermore, the possible psychophysical reasons for misperception of the stimuli location were analyzed.

The results indicate that the localization performance decreased by a linear function with respect to the number of simultaneously activated cues, while the numerosity performance related to the number of the activated cues by an exponential function. Generally, for the multiple vibrotactile cues with the same vibration signal, our experimental results suggest that the localization of more than two simultaneously activated cues imposes a great perceptual challenge for human participants.

Further analysis of different layouts of vibrating cues and errors patterns reveals that the layout of multiple cues produces a significant effect on the localization performance. In the case of two cues, the correct rate, of which the two cues were located on both arms, was higher as compared to that on a single arm. When the two cues were located on two arms, the correct rate of symmetrical layouts (with respect to the body midline) was higher than that of asymmetrical layouts. Furthermore, when the two cues were located on a single arm, the correct rate, of which the two cues located on the same side of the arm (e.g., both cues on the dorsal side) was higher as compared to that on the two opposite sides.

In the study of tactile perception, it is desirable to consider the superimposed effect of several factors, such as stimulus waveform, stimulus duration, body location, contact area, skin temperature, the presence of other masking stimuli, and age [4]. In our experiment, the vibration magnitude and frequency of the motors were kept constant. Therefore, a large space exists for future exploration.

In this paper, the motors adopted were not sufficiently accurate as the amplitude and the frequency cannot be independently controlled. In the next step, we plan to build a new system with better vibrotactile motors such as Linear Resonant Actuators (LRAs) to produce more accurate tactile stimuli with the high performance motors, more diversified temporal patterns of vibration could be produced on each location, and thus we may compare the effect of different temporal codings for motion guidance involving multiple joints.

Another future topic is to study the performance of multi-joint motor control assisted by haptic cues, i.e., how accurately and how fast human can execute a commanded motion of multiple joints based on multiple cues simultaneously presented at different locations on the body.

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