以震動觸覺回饋實現三維空間引導系統

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ABSTRACT

由於一些環境因素的干擾，人的視覺或是聽覺通道在接收訊息時，可能會因此超載或是無法傳遞資訊。但是透過觸覺回饋的方式，我們可以在複雜的環境因素干擾下，以不同於視覺和聽覺的方式進行資訊傳遞。使用觸覺回饋的方式進行空間引導時，可以以不顯眼且直觀的方式傳遞方向資訊，將使用者引導至目標位置。在本篇中，我們設計了一個由兩圈震動手環構成的裝置，利用相對稀疏的 8 顆震動馬達產生震動回饋，實現三維空間中 26 種方向的空間引導，並設計了實驗來探討兩個手環之間的有效距離（4、6 或 8 公分），以及在傳遞震動圖騰時的震動方式（單點刺激或動態回饋）。實驗中總共有 36 名受試者參與其中。結果顯示，在 4 公分及 6 公分時，兩種震動方式在統計上有顯著差異。

Author Keywords

震動觸覺回饋; 空間引導; 穿戴式裝置

INTRODUCTION

Humans perceive information through a variety of sensory channels when interacting with the environment, including visual, acoustical, and haptic sensory systems. Besides vision and hearing, haptic feedback can convey information in a more unobtrusive and intuitive way. Through the sensory receptors on the skin, humans feel tactile sense like vibration, pressure, temperature, texture, and so on. Tactile perception can also detect temporal and spatial differences. Due to the environmental factors, vision impairments, or hearing loss, visual and acoustical channels may be overloaded or inaccessible. This overstimulated status causes a ”white noise” effect. In contrast, tactile channels are less overloaded and can receive external information in a complex workspace.

Recently, tactile research has been explored in various fields, like warning systems, navigation systems, tactile displays, tactile feedbacks in virtual reality (VR), and also haptic guidance. Various applications, including learning motor skills [16, 24, 25], virtual reality [23], and rehabilitation systems [9, 10, 11], can use haptic guidance to improve user experience and performance. Haptic guidance not only assists visually impaired persons but also benefits sighted users. For example, haptic guidance can use for car driving warning system directing a driver’s visual attention to time-critical events [5]. During recent years, vibrotactile devices have used in many areas because the easy accessibility, the inexpensive price, and the compact form of vibration motors make vibration become a practical way to convey tactile information. Especially in enhancing spatial awareness, comparing with other stimulation, e.g. exoskeleton [4], vibrotactile stimulation provides an unobtrusive way without getting others’ attention or annoying them, and keep the information confidential; moreover, the tactile channel is generally less overloaded in complex scenarios. With conformity to human body coordinate, the vibrotactile guidance provides an intuitive form of feedback.

Previous studies have worked on finger-worn [7] and wrist-worn vibrotactile directional guidance for hands. While comparing between the fingertip and the wrist, the latter provides sensitivity [1, 2], sensing area, and social acceptability. To enhance the dimensions of spatial guidance, the larger surface area on the wrist, for example, allows the larger amounts of vibration motors to put on than the amounts of vibration motors on the fingertip. Furthermore, the opportunity of embedding in wrist-worn devices, e.g., smartwatches, provides a timely and reasonable way to let the tactile feedback become a part of our daily life.

Wrist-worn vibrotactile devices, however, used to be studied for notification systems [5], such as the single vibrotactor wrist-worn display which producing different durations of vibration patterns as a notification message [14] or vibrotactor localization in a gird of motors on the wrist [1, 13]. The conventional patterns of directional guidance for hand usually become a low-resolution, small set of target directions (4 to 7) [9, 24, 25, 30], and one- or two-dimensional type. High-resolution directional guidance has received less attention. Hong et al. [6], for example, has studied 32 directions in one wristband, which contains 4 or 8 motors, and used ”phantom sensation” to generate directional stimulation. However, it contains only two-dimensional directions. The absolute movement error of $\sim 25°$in interpreting and executing on the directional haptic signal is indicated in this paper. This result also indicates the resolution on the wrist when interpreting the directional haptic information. To enhance the performance of spatial guidance and quickly trace the path in the environment, three-dimension directional patterns are needed.

In this study, we use two low-fidelity (4-motor) wristbands to achieve high-resolution three-dimensional spatial guidance (26 directions). To determine the effective distance between the two vibration-bands and the appropriate vibration feedback, thirty-six participants involved in the controlled lab experiments with three different distance (4cm, 6cm, and 8cm) and two different vibration feedback (vector-like directional motion feedback and point stimulus). Participants in this experiment need to interpret the designed vibration stimulus and choose the corresponding direction they felt.

In this paper, we present the design of spatial guidance system using two low-fidelity vibrotactile wristbands. The experiment explores the effectiveness of the distance between two vibrotactile wristbands (4cm, 6cm, 8cm) and the different vibration feedback (vector-like directional motion feedback, and point stimulus) with 26 vibration patterns. Each pattern can represent different spatial direction. With these patterns, we can achieve three-dimensional spatial guidance.

RELATED WORKS

Vibrotactile feedback in different parts of body

Vibrotactile feedback has been successfully designed for various parts of human body and different aspect of purposes, including the *shoulder* pad vibrotactile display [26], tactile navigation belt around *abdomen* [3], and vibrotactile display on the *arm* and *back* [15, 8]. The vibrotactor has also been applied to the *wrist* or the *forearm* in the form of armbands [24] and been mounted on the *fingertip* to transmit visual information, which is directly obtained from the camera on the fingertip, by haptic perception [7]. Some studies actuate even larger parts of the body by wearable vibrotactile suit [16].

Besides other parts of the body, we are more interested in the wrist-worn devices. For general purpose, Chen et al. [1] have done tactor localization using the 3x3 grids of vibration motors on both dorsal and volar side of the wrist, concluding that only two motors could be reliably distinguished on either the dorsal or the volar side. Another study has also been conducted to determine the suitable spatial configurations of vibrotactile displays on the forearm near the wrist [17]. Lee et al. [13] revealed that different parameters, such as tactor type, sensory saltation, and locus of stimuli will affect the performance of transmitting tactile information using 3x3 grids of tactor on the wrist. Other applications, such as delivering the alphanumeric character [15], enabling eyes-free interaction for a wristwatch [19], producing alerts to on-the-go users [14], and also motion guidance [9], are all enhancing the interactivity and expressiveness of wrist-worn vibrotactile devices.

Vibrotactile Guidance

Regarding vibrotactile guidance, in general, three different types of guidance can be divided.

Attentional guidance

Vibrotactile cues can be used to redirect a user's visual spatial attention. With the vibrotactile warning signal, directing the visual attention to the critical location can be highly effective in the car driving scenario [5]. Another study also has shown that the response time with haptic cuing was significantly faster, as compared to the condition without haptic cuing [21]. All of these are showing that the vibrotactile signal can successfully guide the user's attention and reduce the response time when the critical event happened.

Motion and posture guidance

Vibrotactile feedback has also been employed in motion guidance or posture adjustment. To enhance motor skills learning and training, vibrotactile guidance, for instance, has been applied to guide the misalignment of joint angle. With the real-time vibrotactile feedback, novice violin players can have effective improvement in learning good postures and bowing technique [28]. Follow-up study also finds that half of those subjects continued to show improved bowing technique even when they no longer receive vibrotactile guidance feedback [29].

In 2007, Lieberman [16] has focused on the wearable robotic system using vibrotactile feedback for upper limb motion control. In his work, the 5 degrees of freedom (DOF) robotic suit, which contained two 4-motor bands around the wrist and the elbow, was designed to assist students while they tried to learn motor skills without teachers' physical guidance. This vibrotactile motor task guidance is applied to the joints angle and shows a decrease in motion errors and an acceleration in learning rate. The similar configuration has been applied to stroke rehabilitation for helping patients reaching desired movements with 4-DOFs movement guidance [10]. For static posture, HAPI Bands [22], with user-worn bands around the wrist, the elbow, and the waist, has used the joint misalignment from a target pose to correct 15-DOFs of the upper-body. In 2012, Schönauer et al. [24] propose three 4-motor bands on the wrist to encode motion speed and 7 different directions for motor learning in 3D directional movement. Another configuration used 6-motor and tactile illusion to generate 8 directional information cues for upper extremity motion guidance [9].

Spatial guidance

Besides, vibrotactile feedback has been successfully used in guiding human operators toward a target position. This feedback is found to be useful when actors need to interact with the virtual objects and can also be used to guide actors in the virtual studio [31]. Also, vibrotactile devices are used in supporting marksmanship [18]. In some scenarios, the spatial frame of reference is disturbed, such as spatial disorientation [20], altered-gravity environment [27], and also virtual and augmented reality environment [12].

While our focus is on wrist-based spatial guidance, most of the works, as mentioned above, are studied in directing the whole body movements. Other related works include a few wrist-worn devices [25, 30]. Most of these works in wrist-based are using a 4-motors type of wristband with a small set of directions (4 to 6) and most of these achieve only two-dimensional spatial guidance.

In 2006, Schätzl et al. [23] study vibrotactile feedback in spatial acuity of different parts of the arm (wrist, elbow, and upper arm) and the effectiveness in a different division of the arm's perimeter (4, 6, and 8 areas). The results of this study are going to use in VR system. In 2008, Sergi et al. [25] designed the forearm orientation guiding system using one 4-motor wrist-bracelet to indicate 4 different directions (north, south, west, and east), which is used to complete 2D directional guidance, in the VR environment. In 2011, follow up Schätzl's work, Weber et al. [30] have compared the wristband configuration with four and six motors and evaluated the user's ability to perceive vibration signal in one of pre-defined directions, move their arm, according to the vibrotactile feedback, and reach the target position. Experimental conditions in this study include two different set of vibrotactile directions (4 and 6) and verbal instruction ("up", "down", "left", or "right"). Results show that verbal instruction required less time to complete the translation task in this relatively simple task. Participants also report the difficulty to distinguish the vibrotactile translational cues. All these works examined on low-resolution 2D spatial guidance with a small set of directions.

In 2016, followed up Weber's work, Hong et al. [6] evaluate 32 different vibrotactile directions using 4 and 8 motors in one wristband for 2D guidance. In this work, the absolute movement error is about 25°in interpreting and executing on the directional haptic signal. This result also indicates the resolution on the wrist when interpreting the directional haptic information. With only one vibrotactile band, spatial guidance is limited to 2D directional movement. To enhance the performance of spatial guidance and quickly trace the path in the environment, three-dimension directional patterns are needed. For our work, we use two low-fidelity (4-motor) wristband to achieve three-dimensional spatial guidance with 26 different directions.

APPARATUS AND METHOD

We implement the custom experimental system with two vibrotactile wristbands connected to an Arduino Mega microcontroller and a Unity program as an interface for presenting the experimental tasks and communicating with the Arduino. For each trial, the participants interpret a directional vibration pattern, which we randomly give from the pre-defined 26 directions, and choose a corresponding direction from the 26 directions we gave. During the study, the participants are asked to keep the wrist in the position without rotating the wrist.

Physical prototype design

Motors and layout

The two wristbands, Figure 1, use a total of 8 motors, with 4 motors in each band, around the wrist. The motors, which we choose to generate tactile stimulus, are 10-mm Precision Microdrive 310-117, circular Eccentric Rotation Mass (ERM) type, with rated operating voltage 3V and flat design, which is easily integrated into wristbands. Following a previous study [13], we attach a hemispherical plastic cap with 4mm diameter to each vibration motor to create precise stimulus from using a smaller contact area.

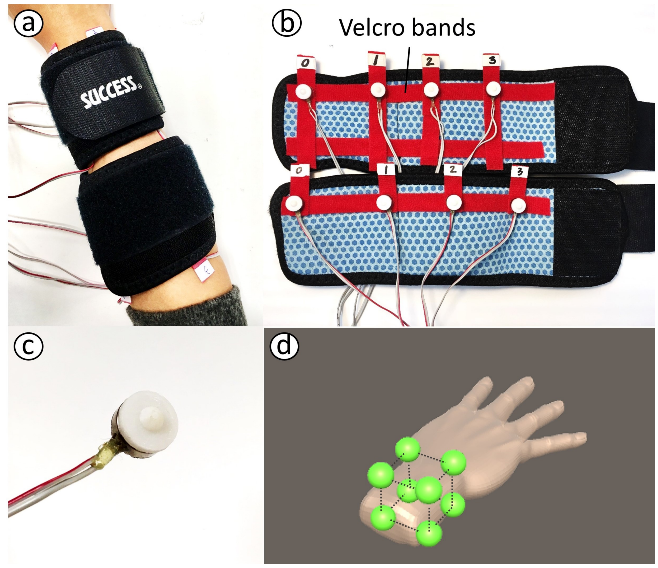

Figure 1: The devices and motors for our experiments. (a) The vibrotactile wristbands worn by a participant. (b) The details of vibrotactile wristbands and the arrangement of motors in the wristbands. (c) The motor with plastic caps. (d) The layout of 8 motors on the wrist. Each green sphere in the figure represents a vibration motor.

Besides the conventional layout of 4-motor vibrotactile wristband, which places the motors on the up, down, left, and right side of the wrist, we decide to place two motors on the dorsal and two motors on the volar side in each wristband, as shown in Figure 1d, which has been used as the form of wrist-worn tactile display on the dorsal side of the wrist [15]. The layout of vibrotactors is a cuboid and becomes more intuitive to map the spatial direction on to the vibration motors. The detail of the design of vibrotactile spatial patterns will be discuss later.

Design of wristbands

With the non-uniform shape of the wrist and the variation of different wrist size, we design an adjustable vibrotactile wristband, which can easily arrange the motors' placement and fit for most of the participants. To ensure proper contact with the skin, a sports wrist guard is worn on the top of Velcro bands, which connect between motors and the wrist guard and can easily rearrange the layout of motors. To reduce the effect of vibration, which is transferred along the band, we choose the wrist guard made from thick fabric.

Figure 2: The label of each motor. (a) Dorsal side (b) Volar side

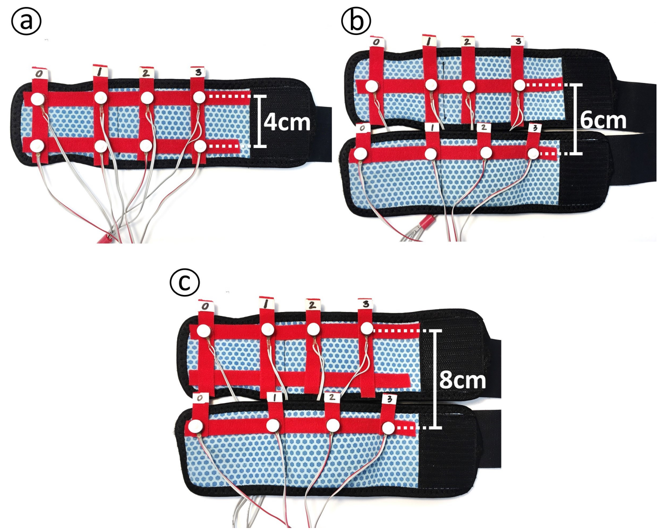

Figure 3: The arrangement of motors and the vibrotactile wristbands worn by the user. (a) The form of 4cm distance. (b) The form of 6cm distance. (c) The form of 8cm distance.

Furthermore, to guarantee the correctness of motor layout, which has two on the volar side and two on the dorsal side for every 4 motors, as we mentioned above, we label the motors with a different number, which can see clearly outside of wristbands, Figure 2. To cover the all vibrotactors in three different distance (4cm, 6cm, and 8cm), we use one wrist guard to cover all 8 motors in the form of 4cm distance, Figure 3a, and two wrist guards in the form of 6cm and 8cm distance, Figure 3b and c, with adjusting the Velcro bands distance inside the wrist guards. The custom vibrotactile wristbands can, therefore, fit different distance forms and different participants.

Directional patterns design

To produce three-dimensional vibrotactile spatial guidance, we conduct 26 different directions to satisfy our purpose, see Figure 4. Our design relies on a phenomenon called *phantom illusion*, which simulates a single vibration between two vibrotactors, when the tactors are placed closely together. To map the target direction and the vibration motors, if the direction exactly matches a motor, then the vibrotactile pattern of that direction actuates only one motor. For another direction between two vibration motors, the vibrotactile pattern actuates two motors simultaneously. For the direction between four motors, the vibrotactile pattern then actuates four motors concurrently. Following this design principle, we conduct 26 different vibrotactile directional patterns, each expressing different direction, for our layout of 8 motors.

Haptic feedback

Intensity

The amplitude and frequency of the motors, which are affected by the voltage, are controlled by the pulse-width-modulation (PWM) signal produced by the Arduino board with different voltage. In the ERMs, a higher voltage is corresponding to a higher amplitude and frequency. Because the vibration frequency is not a critical issue in precisely locating a phantom illusion [2], providing the independent control of frequency is not a necessity in our design. The range of vibration amplitude in the experiment is between 1.8g to 2.5g, and the corresponding vibration frequency is between 220Hz to 250Hz.

To ensure the same intensity of perceived vibrotactile perception in different locations of the skin, we conduct a simple sensitivity test with eight participants from our lab. In each form of distance, we use the right motor on the volar side of the wrist in the first wristband with fixed 4.0V as the reference motor. Then, we choose one of the 7 remaining motors of the wristbands as the compared motor. Therefore, we vibrate the reference motor and the compared motor respectively. Increase the voltage of the compared motor continuously from an absolute weaker perceived intensity compared with the reference motor, and then record the threshold, where the participant first reports a weaker perceived intensity of the reference motor compared with the other one. Then, we decrease the voltage of the compared motor until the participant feels a stronger intensity of the reference motor and record this intensity. The process repeats 4 times for each remaining motors. An average intensity is computed from the recorded intensity.

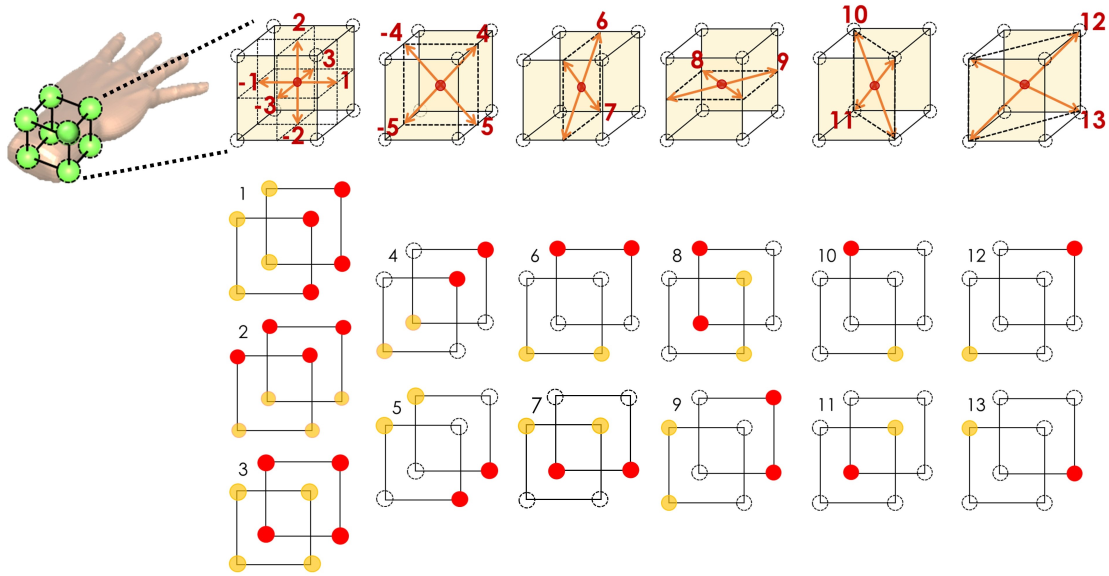

Figure 4: The designed vibration patterns of 26 directions. Each number represents specific direction. The negative number is the opposite direction, e.g. -1 is the opposite direction of 1. Each sphere represents one motor. Motion Feedback: The vibration pattern of the positive number is from the yellow motors to the red motors. The vibration patterns of the negative number is from the red motors to the yellow motors. Point Stimulus: The positive direction actuates the corresponding red motors simultaneously. The negative direction actuates the opposite yellow motors.

Each distance form of wristbands has to complete the sensitivity test once to decide the absolute intensity of each motor. In the 4cm distance form, because of the close distance between two vibrotactile wristbands, we only perform the sensitivity test on the motors of the front wristband and apply the result of this sensitivity test to the motors of the second wristband. In the 6cm and 8cm form, we complete the sensitivity test separately on the motors of the second wristband, and apply the sensitivity test result of the 4cm distance form to the motors of the front wristband.

Directional feedback

Due to the close distance, eg. 4cm, between two wristbands, the localization of different motors in different wristbands may be confused with only *point stimulus*, Figure 5b, as most of the previous works had been used, when using the device in the complex workspace. Because of the lack of reference point for each vibration, it becomes difficult when identifying which wristband the motor is actuated in. We design the *motion feedback* for each vibrotactile directional pattern, as shown in Figure 5a, where the opposite motor will vibrate separately as a reference point of the original actuated motor.

In addition, with the motion feedback, the vibration patterns provide with more directional information without confusing compared with the original point stimulus, which may mislead the participant to incorrect direction because of the less information provided, see Figure 6.

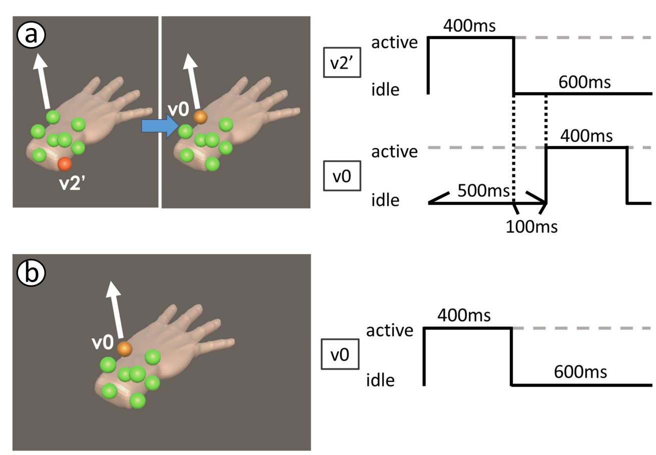

Figure 5: Illustration of directional feedback and active duration of motors. (a) Motion feedback (b) Point stimulus

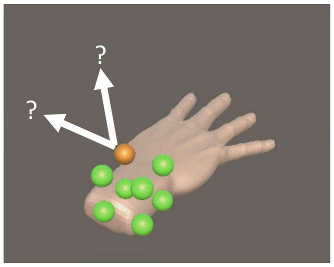

Figure 6: Directional ambiguity of point stimulus.

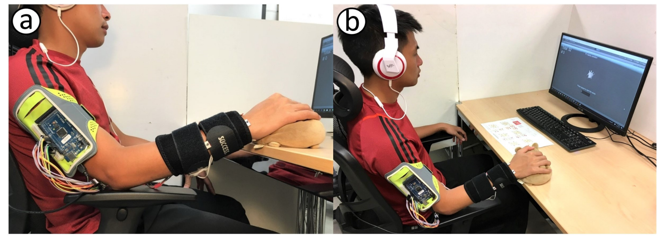

Figure 7: (a) Wrist position during the experiment (b) Environmental setup.

The active duration of vibration is 400ms, as Figure 5 shown, and the intermediate idle duration, which is used to separate two vibrations in motion feedback, is 100ms.

Distance pilot study

In order to find the effective distance between two vibrotactile wristbands, we conduct a pilot study of recognition accuracy in the pre-defined 26 vibrotactile directions with motion feedback for three different distance (4cm, 8cm, and 12cm). Each study of distance is completed with six participants. The procedure of this pilot study is the same as the procedure we will describe later. The result shows that 4cm distance has 72.25% recognition accuracy, 8cm has 91.03% accuracy, and 12cm has 94.46% accuracy. According to the result of recognition accuracy in this pilot study, we are interesting in the accuracy of 6cm distance, which is in the middle of 4cm and 8cm. Based on this point, we determine to conduct our experiment with three distances, 4cm, 6cm, and 8cm, and two kinds of directional feedback, motion feedback and point stimulus.

PARTICIPANTS

We recruit 36 participants (18 males) from various department of our university aged from 20 to 30 years old in order to find the effective distance between two wristbands and suitable directional feedback (motion feedback or point stimuli) for each distance. In this study, only right-handed participants are recruited, and the prototype device is all worn on their right hands. In each form of distance, 12 participants are included. Each participant completes two experiments in one of three distances with the motion feedback and the point stimulus. The time interval between two experiments for each participant is above three days in order to balance the learning effect between two tests.

PROCEDURE

In this study, the two experimental conditions, motion feedback and point stimulus, are presented in counterbalanced order for each distance. For each experiment, we place the wristbands on the participant's right hand in corresponding distance, rearrange the layout of motors as Figure 1d, and adjust the tightness of wristbands to be comfortable. Before the experiment begin, all vibrotactile directional patterns are fully explained to each participant, including represented directions, design method of each pattern, directional feedback, and the layout of motors. After the explanation, each motor vibrates separately in order to check the correctness of layout. Some adjustments of motors might need if the participant perceives an inaccurate layout of motors. During the study, we do not control the placement of the participant's arm, but ask the participant to keep the posture without rotating the wrist, and keep the wrist without contacting with the table, as shown in Figure 7a. A sheet of schematic vibrotactile directions is provided to the participant in order to select the corresponding direction during the study. The participant is asked to wear a headset playing pink noise to block the noise caused by the vibrators. All experimental setup is shown as Figure 7b.

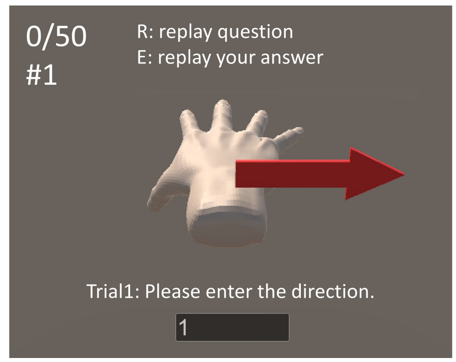

Figure 8: The interface of the experiment. The red arrow represents the input answer form the participant.

Each experiment includes 26 different vibrotactile directional patterns. For each trial, the program randomly plays one of 26 directions. The participant can replay the vibration as many times as they want. We do not limit the respondent time. After the participant inputs the answer, in the training phase, the trial will show the correct answer; otherwise, next trial will be started directly. In the training phase, the participant can replay the wrong answer and thus compare with the correct one for each trial if the respondent direction is incorrect. In the testing phase, the participant will not know the correct answer for each trial during the testing. The interface of the experiment is shown in Figure 8.

Each participant completes 52 training trials in training phase: each direction in pre-define 26 vibrotactile patterns will be selected twice; the order of all directions is randomly sorted. The recognition rate in training phase needs to be above 50%, and then the participant can attend the next testing phase. This threshold is used to confirm the participant is fully understanding about all vibration patterns. The testing phase contains 78 trials: every 26 directions we defined will be repeated three times; the randomize order of directions is applied to per participant. During the testing trials, participants are asked to replay each trial as less as possible and complete each trial quickly and accurately.

In the training phase, there is no break between trials. After the training is completed, a short break about 10 minutes is provided. During the testing phase, there is a five minutes break after every 26 trials. The time of each break can be extended according to the condition of each participant.

EXPERIMENT DESIGN AND HYPOTHESIS

The experiment is designed to find the *effective distance* of two wristbands and the *suitable directional feedback* for each distance with our pre-defined vibrotactile directional patterns. With a single factor, which is *motion feedback* or *point stimulus*, we use the within-subjects design in each form of distance. The presenting orders of two directional feedback are fully counterbalanced and are randomly assigned to each participant.

Our hypotheses are:

H1: *With the larger distance between two vibrotactile wristbands, the accuracy of recognition of the 26 vibrotactile directional patterns will increase.* Because the separation between two wristbands becomes larger, the distinction between the wristbands will also become clearer. Without the confusion among the wristbands, the recognition of the vibrotactile directions produced by the wristbands will, therefore, more accurate. As the hypothesis, we want to find the effective distance between two wristbands.

H2: *The recognition of vibrotactile directions may be improved when we use the vector-like motion feedback rather than original point stimulus, especially in small distance between two wristbands.* The lack of vibration reference may be the reason for the incorrect judgment of different vibrotactile directions. The motion feedback composes of two sequential vibrations: the first one is the opposite vibration, as the reference point, and the second one is the original vibration. The two vibrations construct a vector-like vibration signal and thus provide more directional information than the original point stimulus.

DATA AND ANALYSIS

All the answers during the trials were logged. The recognition rate is computed according to these answers. During the experiment, we have a threshold, which is 50%, for the training trial to sift out our target users. Only those who can pass the threshold in the training phase can attend our next testing phase.

Distance	Motion Feedback (SD)	Point Stimulus (SD)	T-test
4cm	80.24% (7.74%)	70.95% (10.51%)	0.0124
6cm	80.19% (14.13%)	69.58% (9.87%)	0.0048
8cm	88.47% (6.28%)	82.95% (4.84%)	0.0522

Table 1: Average recognition rate and result of t-test in different distance.

Each participant completes 52 training trials and 78 testing trials. For each distance, the time for a participant to complete all procedures and trials in one condition, which is motion feedback or point stimulus, is about one and half hour. One participant in 6cm motion condition reports sensitivity fatigue after the testing phase. Due to the smaller wrist circumference she has (13cm) comparing with other participants (average 14.5cm for our female participants), the intensity of motors may needs adjustment for her. According to these reports and concern, we decide to classify her as an outlier in this experiment and thus exclude from our analysis. Two participants in 8cm point stimulus condition are outliers using Tukey's fences:

$$[Q1 - k(Q3 - Q1), Q3 + k(Q3 - Q1)]$$

where Q1 is lower quartile, Q3 is upper quartile, and k is 1.5, indicating an outlier.

A two-way mixed ANOVA reveals that there are statistically significant differences between the mean recognition rate of different feedbacks, with $F(1, 33) = 12.862$, p-value < 0.05, and $\eta_p^2 = 0.28$ (strong effect). In other words, if we ignore the distance of wristbands, the recognition rate still varies significantly according to different feedback modes. Moreover, there is not a statistically significant interaction between the distance and the directional feedback, with $F(2, 33) = 0.167$, p-value $= 0.847 \gg 0.05$, and $\eta_p^2 = 0.010$. According to the result of ANOVA, there is significant main effect of the distance on the recognition rate, with $F(2, 33) = 5.452$, p-value $= 0.009 < 0.05$ and $\eta_p^2 = 0.248$, which is a strong effect. With a Tukey HSD test, there is not a statistically significant difference between 4cm and 6cm, with p-value $>$ 0.05. However, there are significant differences between 8cm and the other two distances. The mean recognition rate of 8cm is higher than that of 4cm and that of 6cm.

For the conditions in each distance, we use a two-tailed paired t-test to analyze the data. The paired t-test will indicate whether two conditions in each distance have a

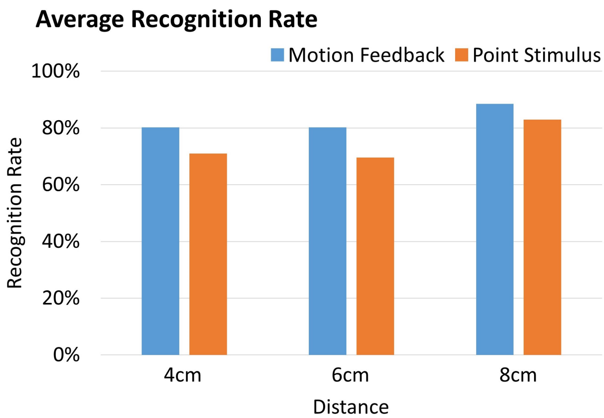

Figure 9: The average recognition rate of motion feedback and point stimulus in different distance form.

significant difference or not. The average recognition rates for each condition in the different distance are shown in Table 1. The standard deviation and p-value of t-test are also indicated in the table.

RESULTS

Recognition Rate

According to the result in Figure 9, the average recognition rate in motion feedback condition is higher than the one in point stimulus condition for each distance. This lower recognition rate in point stimulus may be caused by the direction ambiguity from point stimulus, see Figure 6. The results of paired t-test comparing the two conditions in each distance have statistically significant difference in 4cm (paired t-test, p-value $= 0.0123 < 0.05$) and 6cm (paired t-test, p-value $= 0.0048 < 0.05$), but the result in 8cm does not have statistically significant difference (paired t-test, p-value $= 0.052 > 0.05$), see Table 1.

The different results imply that the effect of recognition improvement caused by the motion feedback is decreasing when the distance between two wristbands is getting larger. Also, the t-test result in 8cm is on the borderline of statistical significance ($p < 0.05$). This result also indicates that with larger distance above 8cm between two vibrotactile wristbands, the difference of recognition rate between two conditions, motion feedback and point stimulus, might be smaller, and the direction ambiguity caused by point stimulus might be compensated by the distance between the wristbands.

Cross-type error

According to the number of actuated motors, the 26 vibration patterns can be divided into three types, as shown in Figure 10. Thus, the error can be classified into *cross-type error*, where the error occurs in a different type of direction compared with the type of correct direction, and *within-type error*, where the error occurs in same type of correct direction.

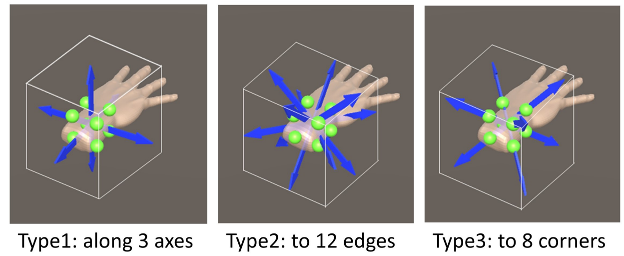

Figure 10: Three types of directions.

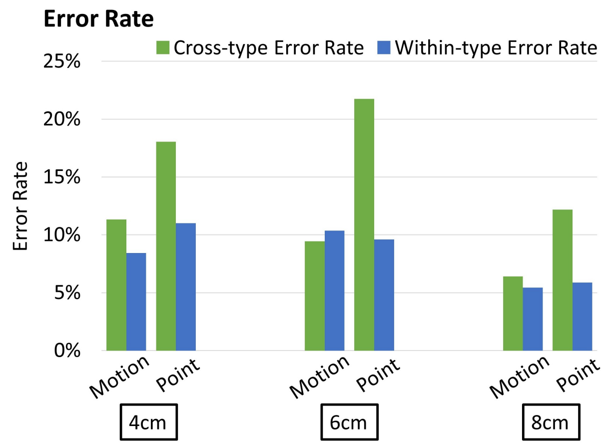

Figure 11: Cross-type error rate and within-type error rate of motion feedback and point stimulus in different distance form.

As the Figure 11 shows, in point stimulus, there is a higher error rate caused by cross-type error compared with motion feedback. This difference may be caused by the direction ambiguity when using point stimulus.

Angular error

The definition of angular error is the angle between correct direction and incorrect answer. During the experiment, most of the angular error happened below 90 degrees, as shown in Figure 12. Because the angle of adjacent directions in different direction type is smaller than that in same type, this result is also consistent with the average higher cross-type error rate compared with the within-type error rate. In motion feedback, the amount of error, which happened below 90 degrees, are lower than that in point stimulus.

DISCUSSION AND CONCLUSION

With the different distance between two vibrotactile wristbands, the average recognition rate for our 26 directional vibration patterns is higher with motion feedback than with point stimulus, but only in 4cm and 6cm, these two feedbacks have statistically significant differences according to the results of the paired t-test. Due to these results, using motion feedback in 4cm and 6cm may be

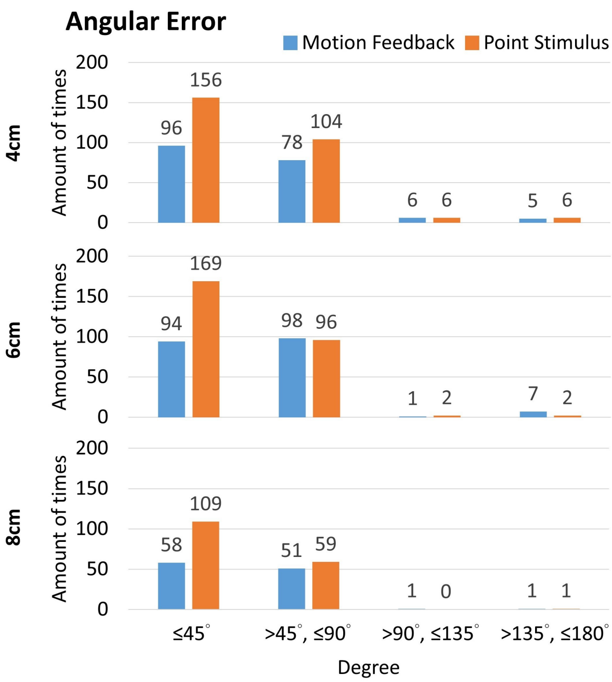

Figure 12: Angular error of different distance form.

more suitable when receiving directional vibration patterns on the wrist compared with only point stimulus. In the 8cm distance, there is no statistically significant difference between these two feedbacks. Moreover, the t-test result in 8cm is on the borderline of statistically significant differences (p-value = $0.052 > 0.05$). As reported by these results, we expect that the difference between two feedbacks might decrease when the distance becomes larger.

We analyze the cross-type error rate and the angular error for each feedback and distance. The results reveal that there are a higher cross-type error rate and a larger amount of angular error under 90°occurred in the point stimulus than the one occurred in the motion feedback. The reason for this result may due to the direction ambiguity caused by the point stimulus. With the motion feedback, this ambiguity can be reduced by providing additional directional information.

As the training threshold (recognition rate $> 50\%$) we designed to sift out our target users in this experiment, there are a few participants (three participants in 4cm, three participants in 6cm, and two participants in 8cm) we excluded according to the threshold. These participants might need additional time to get used to the device or the vibration patterns. Due to the limited time in the experiment, we have to exclude them from our testing phase.

In our design, we embedded ERM vibrotactors in each wristband. According to the feedback from the participants of the study, some of the participants perceived a residual vibration during experiments. The reason for this residual vibration may due to the limitation of the type of motors, which has a longer response time. While the response time of our motors is about 100ms, a linear resonant actuator (LRA) might be useful in the further experiment. LRA offers a shorter response time, which indicates a clearer tactile feedback, and allows for independent control of amplitude and frequency. A future experiment might need to be done to test this type of motor is suitable for our design.

In future work, a real-world task should be tested to investigate the performance of our design. With continuously directional feedback, the update rate of directional guidance and the delimiter between each directional pattern will affect the recognition of direction and the consuming time of guidance. For the guiding system, an angular error tolerance should be considered to reduce users' confusion during the guidance. With continuously vibrotactile feedback, a potential sensory adaptation is another concern. Furthermore, a crossmodal guidance is also a potential option for reducing the time of guidance.

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