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Comparison of the Static and Dynamic Vibrotactile Interactive Perception of Walking Navigation Assistants for Limited Vision People

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ABSTRACT As an effective indication signal, vibration tactile has been widely studied. However, there is still a lack of comparative studies on the use of tactile interaction perception of both static vibration and dynamic vibration as direction indication signals for walking-assistance navigation products for the limited vision. Limited vision people have to perceive the travel environment through nonvisual senses. Besides, vibration and touch can reduce cognitive pressure in complex environments compared with auditory. This study aimed to compare the comprehensive interactive perception of direction indication by both static vibration and dynamic vibration in walking-assistance navigation products for limited vision people. In the tactile interaction perception experiment of static vibration and dynamic vibration, twenty-four participants were involved in the experiment. We measured the direction reaction time, the correct number of direction perceptions, and asked participants to evaluate the degree of perception and perceived comfort in each mode. It can be seen from the results that compared with the dynamic vibration, the static vibration had a higher correct perception numbers ($F = 10.394$, $P = 0.006$) and a shorter reaction time ($F = 5.276$, $P = 0.038$). And participants' perception degree ($F = 21.221$, $P < 0.001$) and comfort degree ($F = 47.692$, $P < 0.001$) in static mode were higher than those in dynamic mode. In conclusion, the static vibration is superior to the dynamic vibration in terms of the comprehensive perception of direction indication. The static vibrotactile interactive perception is preferred as a direct indication signal in the walking-assistance navigation products for the limited vision.

INDEX TERMS Vibrotactile interactive perception, limited vision people, vibration mode, assistance product.

I. INTRODUCTION

Limited vision people suffer in the travel environment. Due to the lack of visual channels, limited vision people have to perceive environmental stimuli beyond their ability, which puts them under additional cognitive strain. To walk safely, the limited vision has to pay more attention to the stimuli of the non-visual environment while walking, which requires them to understand and judge the surrounding environment by using multiple senses, such as auditory and touch. The environmental stimuli for limited vision people mainly include road terrain, vehicle state, people flow, road information, weather conditions and so on. Consequently, the complex environment will consume a lot of their attention resources and increase their cognitive load [1].

Limited vision navigation assistance systems typically use visual substitution technology, perceived through auditory and tactile interfaces rather than vision. [2]–[4]. Auditory instructions are simple for the limited vision to understand and carry out accurately. Although the auditory instructions show obvious usefulness, too many too many of them are likely to interfere with the user's perception of surrounding environmental stimuli, distract attention, and cause dangerous consequences [5]. In a noisy environment, the limited vision people's response to tactile perception is less error-prone than that to the auditory perception. This is because it does not obstruct the user's ability to perceive other environmental events, does not obscure important sound cues in complex environments, and remains easily recognizable under additional cognitive load [6]–[8]. Tactile perception is the most effective way to receive information besides auditory [9]. Therefore, a limited vision navigation device prefers

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to guide the limited vision through tactile prompts to reduce their cognitive load.

The most applicable tactile mode in human-computer interaction is vibrotactile stimulation of which the feedback refers to the skin sensation caused by mechanical vibration at certain frequency [10]. There have been many applications of tactile indication signals in previous studies. Marston *et al.* [11] explored whether the haptic display could guide users to walk along a route, and proved the effectiveness of haptic signals. Flores *et al.* [7] proposed a vibration system in the form of a belt for guiding limited vision people, and experimentally proved that tactile guidance was easier to perceive and process than audio guidance. Rosenthal *et al.* [12] explored the functionality and usability of a vibrotactile system in the form of a belt. In the walking-assistance navigation products for the limited vision, the tactile module often touches the user's head [13], hand [14], [15], waist [7], [12], [16]–[18] or feet [19]. The tactile feedback of waist vibration can liberate users' upper limbs. At the same time, it is relatively flat, stable and concealed, which makes it a promising choice of auxiliary navigation products for the limited vision [17], [20], [21].

A. VIBROTACTILE PERCEPTION

Scholars have long been interested in vibrotactile interactive perception. Huang *et al.* [22] designed a wearable tactile traffic light assistive device. They found that the tactile perception performance of visually impaired people was significantly higher than that of ordinary vision people. Morioka *et al.* [23] studied vibration perception thresholds at four body positions. Cholewiak *et al.* [24] found that the position of the tactile stimulus sites relative to the body and the distance between the sites had a significant influence on the accuracy of tactile positioning and perception. Merz *et al.* [25] proved that implied motion sequence has a significant forward shift effect on the perceived location of tactile stimuli. Kessler *et al.* [6] studied the number of tactors in the direction encoding of the vibrotactile navigation system (usually in the range of 4 to 12). Their experiment used only two tactors to convey the direction information, and the results proved the feasibility. According to an experimental study conducted by Jones *et al.* [26], the smaller the vibration interval, the higher the perceived urgency. Faugloire designed the waist navigation device [27], consisted of 8 vibration motors. Through experiments, the accuracy of the short tactile patterns has been proved to be higher, and the effectiveness of tactile guidance and movement association has been verified. Jones's experiments [28] revealed that by changing the motor activation location, the number of motors become concurrently active, and the time sequence of activation may have an impact on the recognition accuracy of tactile perception. Van *et al.* [29] demonstrated the usefulness of tactile display for direction indication.

Petermeijer *et al.* [30] divided the encoded vibrotactile information into four dimensions: (1) frequency, (2) amplitude, (3) location, and (4) timing (on/off pattern), and pointed out that directional clues can be presented by static vibration and dynamic vibration. In directional guidance, directional indication refers to a product or service that provides users with directional clues through multi-mode feedback or interaction, in this manner to help users make decisions and take action [14]. In the field of automobile driving, the study of Meng *et al.* proved that dynamic vibration warning signal is more effective in automobile collision warning [31]. Petermeijer *et al.* studied the effectiveness of dynamic vibration and static vibration to take over requests in the field of autonomous driving. They compared the accuracy and response time of both modes [32]. Besides, they experimentally proved that the accuracy of static mode is higher than that of dynamic mode, which contradicts Meng's findings. In the field of navigation aids for the limited vision, vibration perception is used as a direction indicator signal, which is able to convey the position information of obstacles to the limited vision. However, it consumes attentional resources to determine the direction of vibration during signal recognition. The common direction indication modes include static vibration and dynamic vibration. The previous studies lacked comparative investigations on different vibration modes under static and dynamic conditions with limited vision people as the research objects. Flores *et al.* [7] proposed a tactile belt for limited vision navigation in dynamic vibration modes. Dura-Gil *et al.* [20] only used the vibration motor at the front of the belt to indicate the direction. They explored the intuitiveness of different vibration modes for the limited vision to indicate the navigation direction under static and dynamic conditions. They also concluded that the static vibration mode may outperform the dynamic vibration mode. However, the study is more subjective because participants evaluate different vibration modes according to their preferences.

B. AIM

As shown in the previous paragraph, although there are many researches on the vibrotactile interactive perception of walking-assistance navigation products for the limited vision, there is still relatively little literature focusing on the study of interactive comprehensive perception of static vibration and dynamic vibration as direction indication signals. This study aims to compare the comprehensive perception of static vibration and dynamic vibration as direction indication signals in the walking-assistance navigation products for the limited vision. We evaluated the comprehensive perception from four dimensions, i.e., the reaction time of static and dynamic vibration, the correct number of direction perceptions, the degree of perception and the degree of perceived comfort under the assumption that the overall perception of static mode is higher than that of dynamic mode, and the comprehensive perception of static vibration is higher than that of dynamic vibration.

II. METHODS

A. PARTICIPANTS

Twenty-four participants with normal vision (twelve women and twelve men) were involved in the experiment at the mean age of 24.4 years (range: 15–35years). All the participants reported normal touch and no tactile disorders. None of them had ever experienced vibrotactile perception before. The experiment time for each participant was 30 minutes with the total experiment time of 12 hours. And each participant took part in the trial after signing the informed consent.

B. APPARATUS

Fig. 1 illustrates the device used in this experiment. The tactile belt system consists of vibration motors, a control box and an elastic belt with an elastic part that fits each person comfortably. The motors have the rated voltage of 3.0V, which are evenly distributed at regular intervals on the front of the belt. The control box offers complete belt control with wireless connectivity and battery power supply, which is in the dimensions of 115mm × 75mm × 55mm. In addition, the control box includes ultrasonic sensors and embedded devices for distance measurement, a Raspberry Pi and its camera, a power supply and a vibration motor drive module.

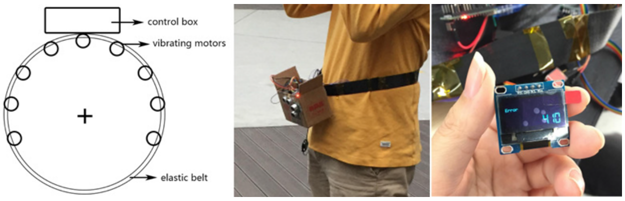

FIGURE 1. Tactile belt system.

Nine vibrating motors were fixed horizontally inside the elastic belt and near the participants' waists. Based on the ergonomic data, the average waistline is set to 73.35cm for Asian men and 65.79cm for Asian women. Therefore, in this device, the initial effective contact circumference of the belt around the waist circumference of the limited vision is set to 68cm. Because tactile stimulation of the contact part between the vibration motors and the human body will affect the body's perception of vibration, the interval of the vibration motors in the elastic belt is equal. The setting of the vibration motors' distance in the experiment is consistent with that recommended by Jones and Sarter [26]. The distance between the vibration motors is set to 50mm, which is larger than the minimum distance required for the human body to distinguish between two vibration stimulus signals. Besides, users can easily perceive and distinguish between any two vibration signals.

The study of Kaaresoja [33] pointed out that the acceptance of a single vibration is higher when the duration is between 50 and 200 milliseconds. Beyond this range, user satisfaction will decrease. Limited vision people usually have better tactile spatial acuity than normal people of the same age [34]. A regular person's reaction time is normally between 0.2-0.5 seconds, and a trained professional can only reach 0.1-0.2 seconds. In this study, the total duration of a single task is set to 0.5 seconds and the single vibration duration is set to 100 milliseconds.

C. STATIC AND DYNAMIC VIBRATION PATTERNS

To let the limited vision focus on the judgement of the direction information of the obstacles in the current scene, the ultrasonic sensors are located in the left front, front, and right front of the device to measure the distance of the obstacle firstly, thereby judging whether the obstacle is within the safe distance. If it is within the safe distance of the limited vision person, the information will be transmitted to the limited vision through vibrating cues in advance, allowing them to focus on the position that poses a risk. In this work, nine vibration motors are used to deliver vibration indication to the limited vision in three different directions, and each vibration in the three directions corresponds to a kind of azimuth indicator information. As shown in Fig. 2, the vibration motors of the three red parts transmit the obstacle information on the left front, the vibration motors of the three green parts transmit the obstacle information straight ahead, and the vibration motors of the three yellow parts transmit the obstacle information of the right front. In that case, there were three static patterns (i.e., 1: left front, 2: straight ahead, and 3: right front) and three dynamic patterns (i.e., 4: left front, 5: straight ahead, and 6: right front).

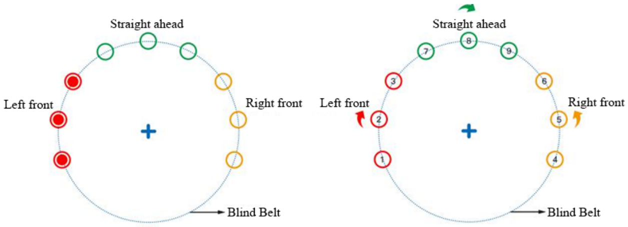

FIGURE 2. Directional vibration prompts in static mode and dynamic mode.

The static vibration mode refers to the stimulation at the same position of the human body [32]. When an obstacle appears within a safe distance in the left front of the limited vision, the three red vibration motors will vibrate simultaneously. When an obstacle appears within a safe distance directly in front of the limited vision person, the three green parts of the vibration motor will vibrate simultaneously. Similarly, when an obstacle appears within a safe distance in the right front of the limited vision person, the three yellow motors will vibrate simultaneously. The static vibration mode in a single task is provided by three pulses (100ms on /67ms off) with the total duration of the task of 500ms.

The dynamic vibration mode refers to the perception generated by a series of stimuli produced by motors at different positions of the human body [32]. When an obstacle appears within a safe distance in the left front of the limited vision, the three red vibration motors vibrate in clockwise order of 1-2-3. When an obstacle appears within a safe distance directly in front of the limited vision person, the three green parts of the vibration motor vibrate in counterclockwise order of 4-5-6. Following the same way, when an obstacle appears within a safe distance in the right front of the limited vision person, the three yellow motors vibrate in clockwise order of 7-8-9.

One motor is activated for 100ms, and an adjacent motor is activated every 67ms, producing the vibration that moves from side to side.

D. PROCEDURE

Prior to the start of the experimental session, participants wore the vibration belt, who were not told the purpose of the study. They should press a direction button provided by the device whenever they felt a vibration feedback. After that, the participants were tested with the vibration device which faced the front as confirmed. When the obstacles set by the researchers appeared in different directions in front of the participants, the vibration device transmitted the position information to the participants by means of different vibration indication signals. They should feel the vibration feedback from the waist carefully, and judge the direction of the obstacles before pressing the corresponding direction button on the device. In this experiment, the left, middle, and right buttons symbolize the obstacle that appeared in the left front, front, and right front, respectively. First, participants were given five minutes to experience and become familiar with different vibration modes. They were then asked to do the following tests: 24 participants were grouped and their dynamic and static vibration tests were in different order. In each experiment, vibration modes in different directions appear randomly to counteract the possible learning effect. Each of the six patterns appeared four times. The experimental software automatically recorded the direction and reaction time reported by participants.

At the completion of the experiment, participants completed relevant questionnaires:

- A questionnaire for evaluating the perception degree of static vibration and dynamic vibration.
- A questionnaire for evaluating the perceived comfort of static vibration and dynamic vibration.

E. STATISTICAL ANALYSIS

The following experimental data are collected in the experiment:

1) REACTION TIME

Reaction time refers to the time between the sending of vibration information by the system and the response of the limited vision person to the instruction information. This study collected the reaction time of static vibration and dynamic vibration mode.

2) VIBRATION PERCEPTION DEGREE

At the end of each experiment, the participants were asked to evaluate their vibration perception by grading the degree from Point 1 to 5 as per the evaluation standard. Specifically, 1 indicates no attention paid; 2 indicates a slight but not obvious perception; 3 indicates a smooth and clear perception; 4 indicates an obvious perception; 5 indicates a strong perception which is difficult to ignore. The higher the score, the better the user's perception of vibration.

3) VIBRATION COMFORT DEGREE

At the end of each experiment, the participants were required to evaluate the comfort of the vibration by grading the degree from Point 1 to 5 as per the evaluation standard. Specifically, 1 indicates that the vibration causes severe and unbearable discomfort; 2 indicates the discomfort produced by the vibration, which can be tolerated reluctantly; 3 indicates that the vibration produces some discomfort but is bearable; 4 indicates that the vibration does not cause any discomfort; 5 indicates that the vibration is more comfortable. In conclusion, the higher the score, the better the user's vibration interaction perception experience.

4) THE CORRECT NUMBER OF DIRECTION PERCEPTIONS

The correct number of direction perceptions were defined as the number of times for the participants to perceive the directional cue of the vibration mode correctly. In the case that the system sent out the directional vibration information, the answer was marked as correct when the participant pressed the button in the correct direction. The more correct numbers, the higher the task performance.

In this paper, the single-factor repeated measurement variance was used to analyse the experimental data. SPSS Statistics 24.0 was used to analyse the experimental data, and all analyses are based on the confidence level of 95%. A small amount of invalid data in the experiment has been eliminated, and a small amount of trial and error operation data have been filled by using SPSS's EM method.

III. RESULT

A. AVERAGE REACTION TIME

The comparison of the average reaction time of the experiment is shown in Fig. 3. The single-factor repeated measures of ANOVA were utilized to determine whether there was a significant difference in terms of perceived time in different vibration modes. Due to the difference between the analysis results and that of the spherical test ($p = 0.003$), the results were corrected by Greenhouse-Geisser. The reaction time of Dynamic A is the longest, i.e., 925.28ms. While the reaction time of Static C is the shortest, i.e., 662.03ms. The experimental data is not significantly different ($F = 1.919$, $P = 0.188$). However, the experimental data shows significant difference among the groups ($F = 5.276$, $P = 0.038$), that is, in the

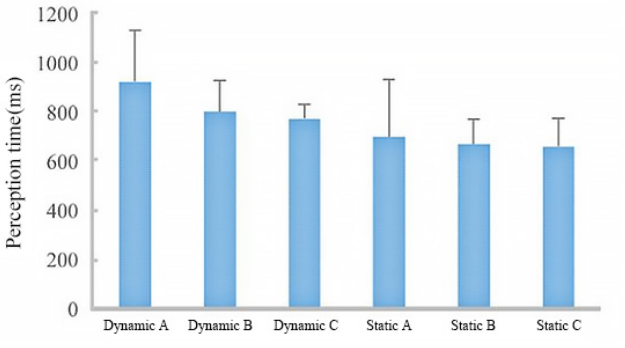

FIGURE 3. Comparison of average reaction time.

direction indication, the reaction time of the dynamic vibration is significantly longer than that of the static vibration.

B. AVERAGE VIBRATION PERCEPTION DEGREE

The comparison of average perception degree is shown in Fig. 4. The single-factor repeated measures of ANOVA were used to determine whether there was a significant difference in terms of average perception degree in different vibration modes. The analysis results were in line with the spherical test (p = 0.269). In addition, theb average perception degree of Static C is the highest, i.e., 4.250 points. At the same time, Dynamic A has the lowest average perception degree at 2.750 points. Though the data does not support its significance (F = 2.074, P = 0.172), the experimental data support the significant difference among the groups (F = 21.221, P <0.001), that is, the average perception degree of static vibration is significantly higher than that of dynamic vibration.

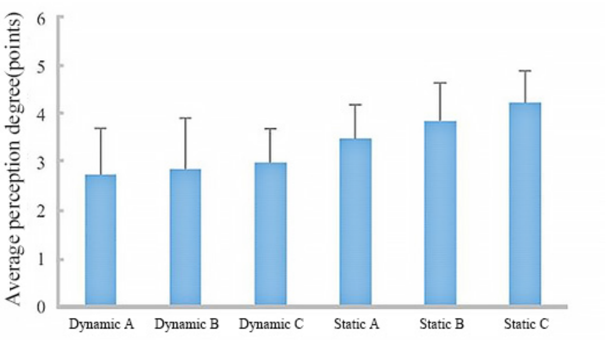

FIGURE 4. Comparison of average perception degree.

C. AVERAGE VIBRATION COMFORT DEGREE

The comparison of average comfort degree is shown in Fig. 5. The single-factor repeated measures of ANOVA were used to determine whether there was a significant difference in term average comfort degree in different vibration modes. The analysis results conformed to the spherical test' (p = 0.382). Besides, the average comfort degree of Static C is the highest, i.e., 4.125 points. Dynamic B has the lowest average comfort degree at 2.625 points. Though the experimental data does not support its significance (F = 0.163, P = 0.693), it supports the significant difference among groups (F = 47.692, P < 0.001). That is, the average comfort degree of static vibration is significantly higher than that of dynamic vibration.

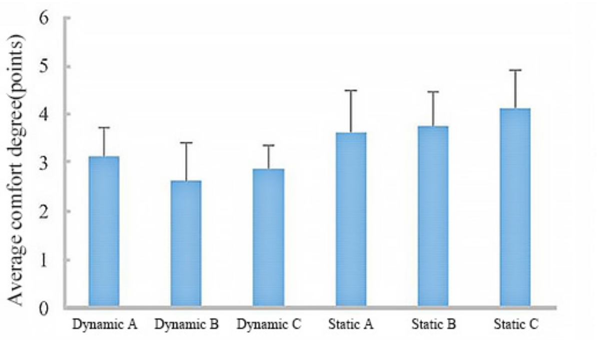

FIGURE 5. Comparison of average comfort degree.

D. THE CORRECT NUMBER OF PERCEPTIONS

The comparison of the correct number of direction perceptions is shown in Fig. 6. The single-factor repeated measures of ANOVA were used to determine whether there was a significant difference in terms of the correct number of direction perceptions in different vibration modes, and the analysis results were consistent with that of the spherical test (p = 0.571). Static B has the highest correct numbers, i.e., 3.500. The correct number of Dynamic B is the lowest, i.e., 2.000. Though the experimental data does not support its significance (F = 0.519, P = 0.483), it shows the significance of the difference between the groups (F = 10.394, P = 0.006), that is, the correct number of perceptions for static vibration perception is significantly greater than that for dynamic vibration perception.

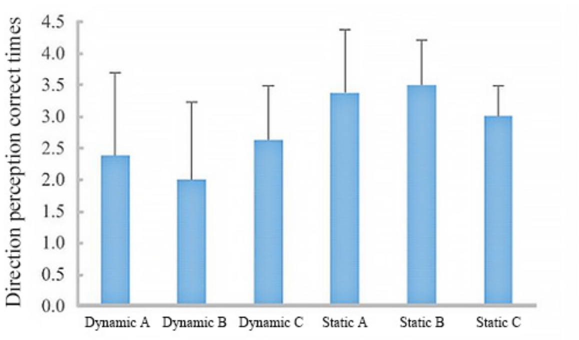

FIGURE 6. The correct number of direction perceptions.

IV. DISCUSSION

This study aimed to compare the comprehensive interactive perception of both static vibration and dynamic vibration as direction indication signals in the walking-assistance navigation products for the limited vision. The results show that in the direction of vibration instruction, dynamic vibration has a significantly longer reaction time than static vibration (F = 5.276, P = 0.038), the average perception degree of static vibration is significantly higher than that of dynamic vibration(F = 21.221, P < 0.001), the average comfort degree of static vibration is significantly higher than that of dynamic vibration(F = 47.692, P < 0.001), and the correct number of perceptions of static vibration is significantly greater than that of dynamic vibration(F = 10.394, P = 0.006). Significantly, the comprehensive interactive perception of static vibration outperformed dynamic vibration, and the experimental results were in line with our predictions.

Compared with the research of Dura-Gil, this study focused on the measurement of the reaction time and the correct number of perceptions of static vibration and dynamic vibration, as well as the comparison of the degree of perception and perceived comfort. The paper compared the two vibration patterns by using both objective analysis and subjective analysis. It concluded that static vibration outperformed the dynamic vibration, thereby compensating for the lack of objective analysis.

Using vibration stimuli as a vehicle driving warning signal, Petermeijer found that the reaction time of static vibration was significantly shorter than that of dynamic vibration, which is contrary to the results of Meng [31], but consistent with our results. As explained by Petermeijer, the dynamic stimulus is almost indistinguishable in the first 200ms, and only after 200ms can the driver feel the movement of dynamic stimulus. Therefore, it takes some time to identify the information indication of dynamic vibration. Although this research is based on a comparative study in the field of car driving, the explanation is also applicable to the field of walking-assistance navigation products for the limited vision. Limited vision people have to consume a lot of attention resources to deal with the complex environment around them when walking. Since it takes extra time to distinguish the transmission of dynamic perception, more attention resources will be occupied. As a result, dynamic vibration will have a longer reaction time than static vibration. Moreover, it is necessary to consider whether the contact area between the vibration motor and the body will affect the perception effect. Bolanowski et al [35] proposed that a larger stimulus area would activate more receptors so that people would be more sensitive to the vibration of a larger area, namely spatial summation. Schmidt et al [36] studied the vibration perception threshold (VPT) of hairy skin, and found that skin sensitivity was improved at both high and low frequencies with the increase of the contactor area. However, larger vibration displacement is required for people with nerve impairment, such as diabetics with decreased tactile sensitivity [37].

In this experiment, the static vibration activated three vibration motors simultaneously, while the dynamic vibration activated three vibration motors in sequence. Therefore, the body contact area of dynamic vibration is smaller than that of static mode. People are more sensitive to vibration perception with larger contact areas. In this case, the perception degree of static vibration is higher than that of dynamic vibration.

In short, static vibration outperforms dynamic vibration in terms of reaction time, the correct number of perceptions, perception degree and perceived comfort. In practice, when faced with complicated environmental information, the direction indication signal of static vibration can reduce the extra cognitive pressure brought by the walking- assistance navigation products for the limited vision to a certain extent.

V. CONCLUSION AND FUTURE WORK

Tactile perception assisted navigation products can effectively reduce the cognitive load of the limited vision in a complex travel environment, and improve the comprehensive perception efficiency. Because there were few comparative studies on tactile interactive perception of static and dynamic vibration as direction indication signals in the research field of walking-assistance navigation products for the limited vision, this study compared the participants' comprehensive interactive perception of static vibration and dynamic vibration when a vibration device was used. Twenty-four participants were involved in the experiment, and comparison was conducted between static vibration and dynamic vibration from four dimensions, that is, reaction time, the correct number of direction perceptions, the degree of perception and perceived comfort. The results show that static vibration was significantly higher than dynamic vibration in three dimensions, i.e., the correct number of perceptions, degree of perception, and perceived comfort. In terms of reaction time, static vibration was significantly shorter than dynamic vibration. In summary, the comprehensive interactive perception of static vibration was significantly stronger than that of dynamic vibration.

Therefore, the conclusions of this study have some implications for the design of tactile interactive perception of walking-assistance navigation products for the limited vision and in related fields. The study is limited by sample size. And more data are required for the research in the future, including more participants from different age groups, to confirm the validity of the findings more accurately. In addition, most studies are based on external hardware, which need additional auxiliary devices. In a recent study, Khusro [38] *et al.* explored the possibility of using smartphones to generate multiple vibrational feedback patterns to reduce cognitive load, and help the navigation of limited vision users without external hardware. Many studies have explored the perception of vibration interaction by limited vision users using touch-screen devices [39]. Due to the mobility of smartphones which are available for complex interactions with limited vision people through vibration and sound, we will explore and evaluate the effectiveness of interactive perception of different vibration modes combined with navigation assistants of smartphones in the future, thereby providing more convenient travel services to visually impaired people.

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