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Design and Implementation of a Semantic Information Expression Device Based on Vibrotactile Coding

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Abstract: In recent years, research on new technologies for expressing and exchanging information through tactile vibration has been the focus of researches. In this paper, by choosing a suitable coding scheme and a vibrating motor arrangement, we designed a device to express semantic information through vibrotactile. Three types of experiments were designed to test the usability of the encoding scheme and the device. Firstly, the vibration intensity was experimented when designing the encoding scheme, and the results showed that the encoding scheme was better with Braille units of 0.2 and 0.3 vibration intensities. In addition, the learning experiment and sentence recognition accuracy experiment were carried out to verify the usability of the device. The learning experiment results show that subjects were able to memorize Braille characters with an accuracy more than 90%, and to recognize a Chinese character (consisting of two Braille cells) with an average of 90.8% accuracy. The sentence recognition accuracy test experiment results show that the average recognition rate of the three poems used for the test was 93.33%. The device can be used for semantic information expression and touch-reading of Braille, and it can realize the reading experience of paper Braille.

Keywords: vibrotactile coding; tactile perception; vibrotactile experiments; semantic information expression device

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1. Introduction

In daily life, in addition to sight and hearing, haptic is an important information acquisition channel for human beings [1]. When sight and hearing are limited in conditions such as in dark or noisy environments, relying on the tactile sense to acquire or convey information becomes extremely efficient [2–4]. Braille, as one of the most common forms of tactile communication used by people with hearing and sight impairments, is also the basis for their use of tactile expression [5–7].

Vibrotactile technology is the most widely used technology in the field of haptic expression [8,9]. A haptic expression device about information is a tactile stimulus that is applied to the human skin in order to feedback specific information to the user. Vibrotactile technology uses vibratory stimuli, such as mechanical vibrations generated by micro-motors, solenoids, voice coils, piezoelectric crystals, etc. [10], which are delivered to the surface of the user's skin at a low frequency, and the user perceives and interprets the information expressed by the vibratory stimuli.

In order to perform vibrotactile expression of Braille information, domestic and foreign researchers have developed various tactile expression devices [11,12], which are briefly categorized here as the direct-contact and body-worn types. Body-worn devices belong to the "Body-Braille" system [13,14], which can be placed on the surface of any part of the body, and the user is able to passively access Braille information. This means that the user can keep their hands free while understanding the Braille information, even if the device is a glove, and performing other things with their hands does not affect the acquisition of Braille information. Direct-contact devices, on the other hand, use fingers to touch the surface of the device directly to obtain Braille information. It does not allow keeping the hands free like a body-worn device, but it is more suitable for Braille reading. Since paper Braille is initially read with the finger, it is easier and quicker for the user to learn how to use the device.

Most of the body-worn devices for semantic information acquisition are gloves and wristbands. In 2017, Savindu designed a BrailleBand [15], in which six motors in three bands correspond to a Braille cell to read the Braille information with its vibration. However, its reading speed and reading accuracy are related to the character gap, and the accuracy increases but the reading speed decreases when the character gap increases. In the same year, based on finger Braille (the index, middle, and ring fingers of both hands correspond to the six dots of the Braille characters, and the vibrating device is set on these six fingers), Oliver designed a glove for Braille communication [16], where the Braille information is delivered to the glove, the corresponding finger vibrates, and the subject interprets the information and inputs it into a cell phone program. However, the experiment only tested whether the device could correctly transmit and express Braille information, and the results showed that the correct transmission could be carried out. Based on this and a variety of assistive technologies, in 2020, Oliver upgraded the device with integrated sensors and actuators [17]. Non-blind subjects were tested to be able to read two types of Braille words with 68% and 75% accuracy.

As for direct-contact devices, the earliest vibrotactile expression device appeared in 1970, Braille printers for the blind designed by Bliss et al. [18], which was the first device used to help blind people with text reading. The device enlarged and imaged letters on an array, and controlling the vibration of motors in the array resulted in a vibrating tactile image that the user could touch-read, but the range of readability was only 92–98%. Since then, because of the emergence of touchscreen phones, designing vibrotactile interactions based on the phone has become a very common means [19–21]. The first time the vibration function of the phone was utilized for Braille tactile reading was realized in 2009 [22], where the user crossed his finger over the screen of the phone to feel the concave and convex vibration information of the six-dot Braille for reading. However, it was not widely used because it required another special piezoelectric sensor device on the phone. Later, Al-Quadah et al. improved the device on this basis, using the law of vibration of the cell phone and the Morse code to encode Braille, which made the application of Braille reading by phone wider [23], but the recognition accuracy of Braille is low, only 71%. In addition, in the category of direct-contact devices, there has been a lot of research on vibrotactile keyboards in recent years [24–26], and most of the keyboard devices are used in conjunction with Braille displays to realize human-to-human communication. For example, Aqel [27] designed an electronic Braille reading and writing device that uses six vibrotactile actuators (a.k.a. keyboards) to represent a Braille cell, which is used for both sensing vibrations and inputting Braille characters. However, it still contains errors in reading and takes a relatively long time to read.

The above are some studies of the two types of devices, and the device discussed in this work belongs to the direct-contact device of the two types of devices. The device uses the index and middle fingers for touch-reading, as the fingers have a higher tactile sensitivity from a psychophysical point of view [28]. In addition, this device can touch-read one Braille cell at a time, which improves reading efficiency. This coding scheme is designed with reference to the "Chinese Common Braille Scheme", which is the most suitable Braille scheme for Chinese characters after a long period of research and exploration, modification and improvement by experts.

Vibrating motors are arranged according to the distribution of Braille cells in order to achieve the maximum similarity with paper Braille so as to match the user's reading habits to the greatest extent. Moreover, research at home and abroad on using vibrotactile coding to express Chinese Braille is relatively scarce, and most of it focuses on English Braille. Therefore, the main research goal of this paper is to use vibrotactile to encode Chinese

Braille, and to design a device that allows users easy and convenient interpretation of the semantic information contained in the encoding, so that visually impaired people or people in complex environments (e.g., darkness or noisy environments) can use the device to read the Chinese text and obtain the information contained in the text without any barriers.

The main work of this paper is as follows:

- Testing out the appropriate vibration intensity and designing a suitable vibration coding scheme.
- Several days were spent for subjects to learn Braille and device usage [29].
- Evaluate the usability of the device, mainly in terms of Braille recognition accuracy.

2. Hardware Design

The main control chip chosen for the hardware circuit is STM32F103ZET6, the voltage regulator chip is SPX1117, and the ULN2803 eight-way NPN Darlington connection transistor is used for driving. The vibrotactile expression of this device uses flat button-type vibration motors with a diameter of 8 mm and a thickness of 3 mm, using 100 vibration motors arranged in a 10 × 10 array, with a 1 cm spacing between motors both horizontally and vertically, as shown in Figure 1.

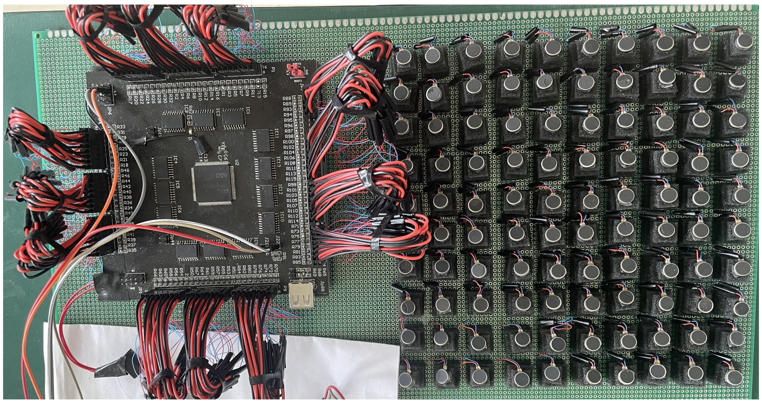

Figure 1. Physical drawing of the device. The right half is an array of 100 motors arranged as 10 × 10. The left half is a core control circuit module that controls the vibration of the motor.

This device is a direct-contact device, and the user obtains the Braille information by directly touching the vibration motor with their fingers (all the experiments in this thesis were performed by touching and reading with the index and middle fingers). For the control of the vibration motor, pulse width modulation PWM is used to control the vibration intensity of the motor by modulating the duty cycle of the square wave; the expression of the Braille information is realized based on the coding scheme by controlling the vibration points and vibration intensity of 100 motors through a computer program.

2.1. Overall Design

The general scheme is as follows: first, the Braille information to be expressed is encoded in advance on a computer and set into the device. Second, the user is required to learn how to use the device and familiarize themself with the vibration form before using the device. Finally, the accuracy of Braille recognition is tested by the subjects who touch the device to perceive its vibration form and interpret the Braille information expressed by the device based on their previous Braille learning experience. The block diagram of the system design is shown in Figure 2.

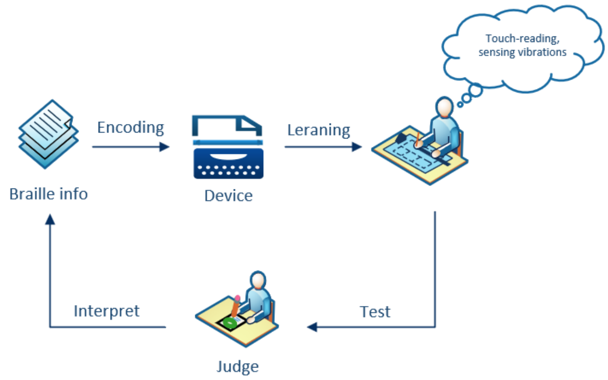

Figure 2. Framework diagram for the design of the system program. It is divided into the following steps: 1. Braille information is coded into the device. 2. The user learns the Braille and the device. 3. Testing the recognition accuracy. 4. The user interprets the Braille information.

2.2. Vibration Coding Design and Experimentation

Designing of a suitable coding scheme is needed to express the exact Braille information on 100 motors by suitable vibration position and vibration intensity, so it is necessary to conduct a vibration intensity test and vibration position recognition accuracy test.

2.2.1. Vibration Intensity Perception Test Experiment

The purpose of this perceptual experiment was to select a vibration intensity that would be strongly felt by the subject without discomfort. Before starting this experiment, a pre-test was conducted to find a suitable range of vibration intensity for the experiment.

In the pre-test, it was found that when the duty cycle was 0.2, the vibration was just able to be perceived, and when the duty cycle was 0.7, the motor was obviously hot and accompanied by numbness, so the vibration intensity range selected for the experiment was 0.2–0.6.

Then, in the formal test, the duty cycle interval can be set to 0.1, so there were 0.2, 0.3, 0.4, 0.5, 0.6 a total of five vibration intensities for the test. A total of 10 school students (five males and five females) were recruited, all of whom were right-handed and did not have any problems with tactile perception, and none of the subjects performed similar experiments prior to the start of the experiment.

In order to prevent the vibration motor and the human body contact when the subject's force is not uniform, which results in biased experimental results, before the test, the vibration motor was taped to the fingers of the test subject, as shown in Figure 3, so that the vibration motor was in contact with the skin but did not produce extrusion. This was performed ensure that the vibration was clearly perceived by the subject and to avoid limiting the vibration amplitude of the motor.

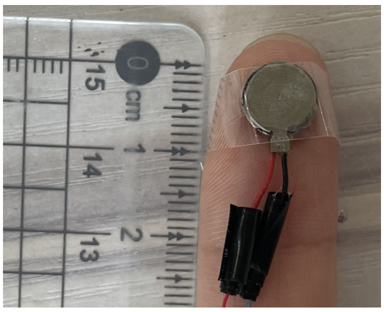

Figure 3. Diagram of a vibration motor tied to a finger.

Since vibration produces a numbing sensation, this experiment was divided into two parts: one was the vibration sensation test and the other was the numbing sensation test. Both use the rating method, a total of seven levels, from zero to six indicating that the vibration or numbness was gradually strong. To ensure the accuracy of the experimental results in the vibration sensation and numbness test, the vibration intensity of the first sequential enhancement of the experiment was measured. Then, the vibration intensity was weakened sequentially. Finally, a random vibration intensity was assigned. Subjects perceived the vibration and numbness for rating and recording. Each vibration intensity was rated three times in the experiment, and a total of 30 levels were recorded for 10 subjects; then, the mean value of the levels recorded for each vibration intensity was calculated.

The experimental results are shown in Figure 4. The condition required for suitable vibration intensity is that the vibration sensation is strong, but the numbness should not be strong. It is a matter of finding the value with the largest difference between the two. The difference between the vibration sensation and the numbness was calculated as 1.3, 1.8, 1.1, 1.3, 0.9, and the larger differences were 1.3 and 1.8, which corresponded to the vibration intensities of 0.2, 0.3, and 0.5. However, the numbness of 3.8 was too high when the vibration intensity was 0.5, so this vibration intensity was discarded. The final vibration intensity chosen was 0.2 or 0.3.

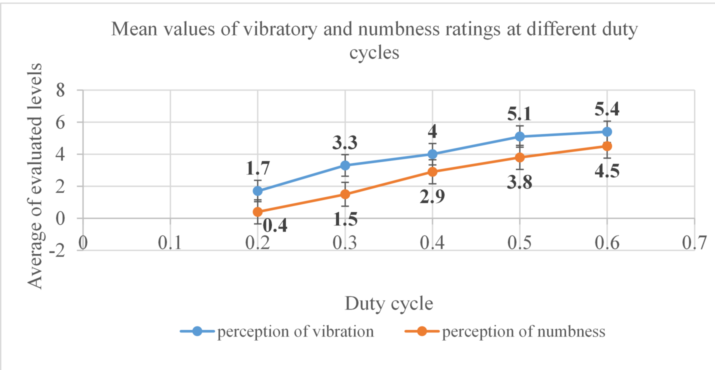

Figure 4. Mean values of ratings of vibratory and numbness perception for different duty cycles. The horizontal coordinate represents the duty cycle (indicating vibration intensity), which was chosen to range from 0.2 to 0.6 for the test. The vertical coordinate represents the average of the subjects' ratings for the five vibration intensities.

In addition, since the perception of vibration is also affected by the vibration duration and the vibration interval time, excessively long or excessively short vibration duration and vibration interval may make the subjects' ratings of vibration sensation inaccurate. After testing, the optimal vibration duration was chosen to be 350 ms and the vibration interval time to be 300 ms.

2.2.2. Vibration Position Recognition Accuracy Test

In order to help the user to judge the vibration position and to improve the accuracy of the user's identification of vibration positions, comparative experiments were carried out. A comparison experiment was carried out using one vibration intensity and two vibration intensities (one strong and one weak) for six dot positions, and the final vibration intensity scheme adopted was determined by the subjects' accuracy in identifying the vibration positions.

In the experiment, a total of 24 vibration motors of 3 × 8 were selected, and their vibration modes were set as one-point vibration, two-point vibration, three-point full vibration, and full non-vibration, and the permutations and combinations were carried out. Eight columns of motors were divided into (a), (b), and (c) three large groups and eight groups, as shown in Figure 5. The vibration of each group was touch-read with the index finger during the experiment.

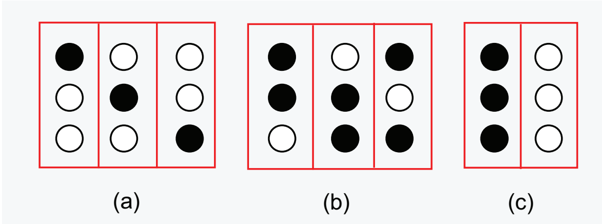

Figure 5. Eight vibration modes. Black dots indicate vibration, white dots indicate no vibration. (**a**) One-point vibration. Divided into three groups. (**b**) Two-point vibration. Divided into three groups. (**c**) Three-point full vibration and full non-vibration. Divided into two groups.

Ten subjects wore headphones and blindfolds to exclude interference (the experimental scenario is shown in Figure 6). The experiment was conducted with one vibration intensity, which was set by the experimenter to 0.3. Eight sets of vibrations were presented to the subjects sequentially, then in reverse sequence, and finally randomly in a disrupted sequence. Subjects touch-read and then recorded the points, a total of 10 people × (8 groups in order + 8 groups in reverse order + 8 groups random) = 240 experiments. Every time a touch-reading was performed, the subject needed to rest their fingers for 30 s to avoid numbness of the fingers that would affect the results of the experiment. The two vibration intensity experiments were conducted in the same way, except that the vibration intensity was adjusted to 0.2 for Rows 1 and 3, and 0.3 for Row 2 (similar to Figure 7b). The vibration position recognition accuracy of the two experiments are shown in Figure 7a.

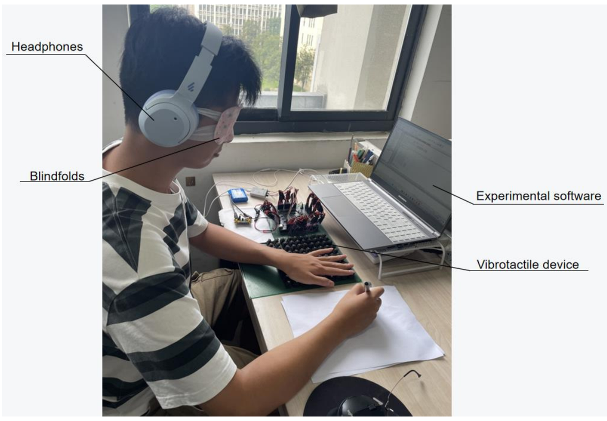

Figure 6. Vibration position recognition accuracy test. Subjects would wear headphones and blindfolds while touch-reading the device. At the end of the touch-read, blindly note down the information read.

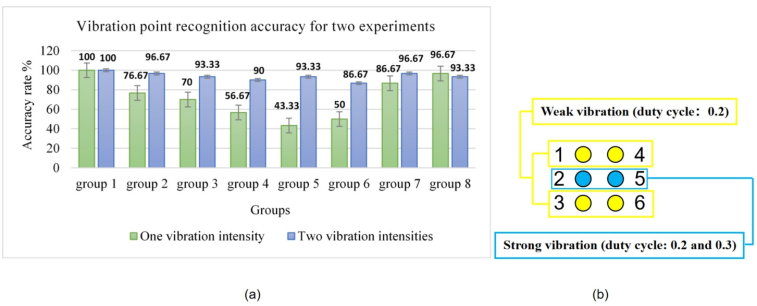

Figure 7. (**a**) Vibration position recognition accuracy for two experiments. The horizontal coordinate represents the 8 vibration modes (seen in Figure 5), and each vibration mode represents a group; the vertical coordinate represents the subject's touch-reading accuracy for the 8 vibration modes. (**b**) Two types of vibration intensities. Rows 1 and 3 are strong vibration and Row 2 is weak vibration.

When a Braille cell has only one vibration intensity, the average recognition accuracy is only 72.50%, while the average recognition accuracy reaches 93.75% when two vibration intensities are strong and weak. In Group 8, where all three points were not vibrating, the results should have been at a 100% touch-read accuracy, but the results were biased by the numbness of the fingers. In addition, in the experiment, it was found that the tactile sensitivity of the fingertip was the highest, while the vibration felt in the joint part of the finger would transfer the vibration sensation to the fingertip, and the tactile sensitivity of the position between the fingertip and the joint was low. As a result, two vibration intensities were selected for the encoding scheme of this device, as shown in Figure 7b.

2.2.3. Encoding Scheme

Considering that the audience of this device is visually impaired people or people who need to eliminate audio-visual interference, the tactile encoding scheme is based on the common Blair Braille (as shown on the left side of Figure 8, the Braille bumps are indicated by the dot number) and is designed in accordance with the "Chinese Common Braille Scheme". It applies to the use of Braille in official activities, public services, etc., throughout China. It stipulates the rules for writing the national common language in Braille, including consonant characters, vowel characters, tone characters, punctuation marks, as well as spelling rules, tonal rules, etc. The spelling rules in the specification are the following: syllables are usually composed of consonants, vowels, and tones, and they are spelled sequentially, such as the spelling of the Chinese character "美", as shown in the figure below.

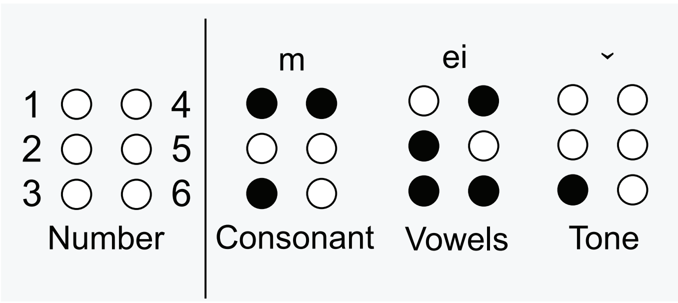

Figure 8. Braille characters. The left is the Braille dot number (a Braille cell) and the right is the spelling of the Chinese character "美".

However, in order to reduce the amount of memory required for the subjects to learn Braille and to reduce the complexity of using the device so as to increase the user's efficiency, and because of the special characteristics of the Chinese language, the removal of tones, punctuation marks, etc., does not affect the reading of sentences. Therefore, only the consonant symbols and vowel symbols in the "Chinese Common Braille Scheme" and the spelling rules of these two symbols are selected for the experiment. It should be emphasized that the tactile patterns tested and coded are the same as those used by the blind in China, but only simplified, without affecting the reading of Braille.

The black color on the Braille character is the raised dot, which corresponds to the device the vibration position indicates the Braille raised dot and the non-vibrating dot position indicates the white dot. Based on the above two experiments, Row 2 of a Braille cell was set to strong vibration, and Rows 1 and 3 were set to weak vibration in order for the user to obtain the exact vibration dots.

3. Learning Process

Since the participants are all people with normal vision and hearing, and have never learned Braille or used a similar device before, they need to learn basic Braille and familiarize themselves with the device before testing.

A total of 10 students (5 males and 5 females) with an average age of 23.4 years were invited to participate in the experiment, which required the use of the index and middle fingers for tactile vibration perception. All of them did not have any tactile perception problems. They had not been exposed to Braille or similar devices or experiments before participating in the experiment. Headphones and blindfolds were worn to eliminate distractions during the experiment (see Figure 6).

3.1. Braille Learning

Participants learned Braille by memorizing the dots corresponding to each Braille character and could learn to use the device only after they achieved the required percentage of correct memorization.

3.1.1. Learning Material

The learning materials refer to the "Chinese Common Braille Scheme" and focus on the consonant and vowel characters within the book.

3.1.2. Learning and Testing Procedure

There are 50 consonant and vowel characters, and the main learning task for the participants is the dots of the Braille characters and the Braille corresponding to the dots. Participants were given five days, during which they studied 10 Braille characters each morning and selected 5 of the 10 Braille characters to dictate in the afternoon. Participants had to achieve a 90% correctness to learn the new Braille characters the next day; otherwise, they needed to consolidate their learning again that evening until they were able to achieve the required rate of correctness. After the 5 days of learning time, participants were tested on the 6th day on the memorization rate of all 50 Braille characters, and when the correct rate reached 80%, they were allowed to proceed to the device usage study; otherwise, the whole group spent another 2 days consolidating the learning.

3.1.3. Results and Discussion

After five days of learning and training, each participant was tested on being able to memorize Braille characters correctly at 90% or more, allowing them advancing to the next step of learning device usage.

3.2. Device Usage Learning

The main purpose of this section was to familiarize participants with the use of the device as well as to test out whether participants could recognize the information conveyed by the vibration, the approximate length of time it took participants to recognize and record the vibration information, thus preparing for the next step of validating the feasibility of the device (whether the device could be used to read long sentences).

3.2.1. Learning Material

The Chinese characters used for learning and testing of device usage refer to the "Seven Sound Summary", which is considered to be one of the two earliest surviving Phonologies, and an important source for the study of Phonology and the Chinese phonetic system from the Northern and Southern Dynasties to the Song Dynasty (between the 430s and the 1280s). The top two rows of the "Seven Sound Summary" were chosen for study and testing. Referring to Table 1, a total of 36 Chinese characters were used, with the first 24 characters used for the study and the last 12 characters used to test the effect of the study, with each 12 characters forming a frame.

Table 1. Thirty-six characters selected from the top two rows of the Seven Sound Summary.

Frame 1				
Consonant	**Points**	**Vowels**	**Points**	**Chinese Characters**
b	12	ang	236	帮
p	1234	ang	236	滂
b	12	ing	16	并
m	134	ing	16	明
f	124	ei	2345	非
f	124	u	136	敷
f	124	eng	3456	奉
w	136	ei	2345	微
d	145	uan	12456	端
t	2345	ou	12356	透
d	145	ing	16	定
n	1345	i	24	泥
Frame 2				
Consonant	**Points**	**Vowels**	**Points**	**Chinese Characters**
zh	34	i	24	泥
ch	12345	e	26	彻
ch	12345	eng	3456	澄
n	1345	iang	1346	娘
j	1245	ian	146	见
x	125	i	24	溪
q	13	ün	456	群
y	24	i	24	疑
j	1245	ing	16	精
q	13	ing	16	清
c	14	ong	256	从
x	125	in	126	心
Frame 3				
Consonant	**Points**	**Vowels**	**Points**	**Chinese Characters**
x	125	ie	15	邪
zh	34	ao	235	照
ch	12345	uan	12456	穿
ch	12345	uang	2356	床
sh	156	en	356	审
ch	12345	an	1236	禅
y	24	ing	16	影
l	123	ing	16	零
x	125	iao	345	晓
x	125	ia	1246	匣
y	24	ü	346	喻
l	123	ai	246	来

3.2.2. Experimental Description

This device has 100 vibration motors (10 rows and 10 columns); a Braille cell needs 3 rows and 2 columns of a total of 6 motor compositions. In order to achieve a better learning effect, two Braille cells need to be arranged in a row for touch-reading. As shown in Figure 9, the number of Braille cells that can be displayed on the device each time is 12, and a total of six Chinese characters can be read out.

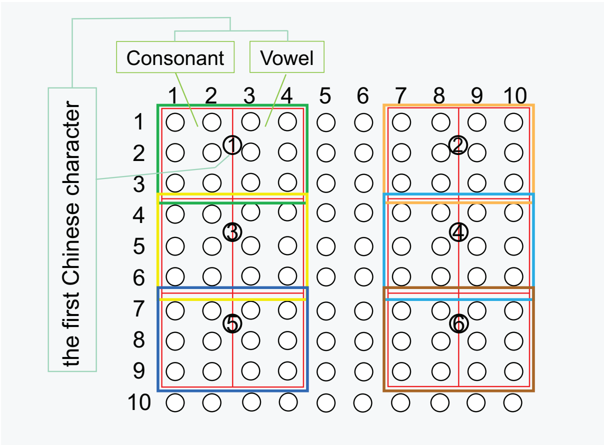

Figure 9. Braille cell arrangement on 100 motors. a Braille cell needs 3 rows × 2 columns of a total of 6 motor compositions. Taking the first green frame as an example, the first 3 × 2 motors in the green frame represent the consonant and the second 3 × 2 motors represent the vowel. The consonants and vowels are combined to form a Chinese character, and each color of the large frame represents a Chinese character, which is marked with a serial number in the figure. Subjects were able to touch-read a total of 6 Chinese characters in order from left to right.

3.2.3. Learning and Testing Programs

The learning process was divided into four phases and is expected to take five days.

- Day 1: Learn to touch-read 18 consonant characters;
- Day 2: Learn to touch-read 32 vowel characters ;
- Day 3: Learn to touch-read 12 Braille characters in the first frame;
- Day 4: Learn to touch-read 12 Braille characters in the second frame;
- Day 5: Test experiments using the 12 Chinese characters in the third frame.

The learning of the device usage focused on familiarizing the participants with the vibration pattern of the device and training their touch-reading speed. Because of the presence of homophones, for the learning of Chinese characters, participants were only required to pronounce the pinyin of the Chinese characters, and a recognition rate of 85% was required.

On the fifth day, 10 participants were tested for familiarity with the device and accuracy in recognizing individual characters using the last 12 characters. Two experiments were conducted: the first experiment was on the accuracy of Chinese character recognition, and the second experiment was used to test the participants' familiarity with the device and the Braille characters, i.e., to test the total time spent on touch-reading and recording the 12 Chinese characters. The two experiments were conducted simultaneously. The experimenter entered the 12 characters into the device twice, and the subjects touch-read them with one hand and recorded them with the other.

3.2.4. Results and Discussion

The experimental results of the recognition accuracy of Chinese characters are shown in Figure 10.

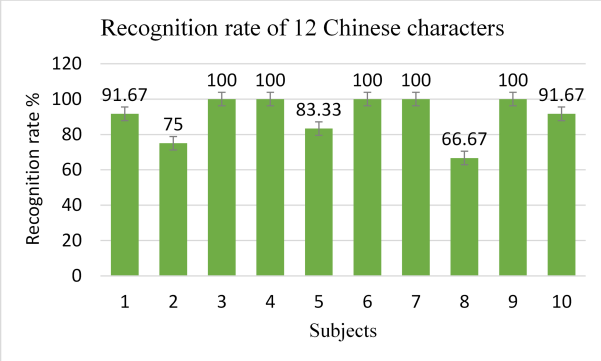

Figure 10. Recognition rate of 12 Chinese characters. The horizontal coordinate indicates 10 subjects. The vertical coordinate indicates the recognition rate of 12 Chinese characters by 10 subjects.

The average recognition rate of 12 Chinese characters by 10 subjects was 90.8%.

The results of the total time taken by the subjects to touch-read and record the 12 Chinese characters are shown in Figure 11.

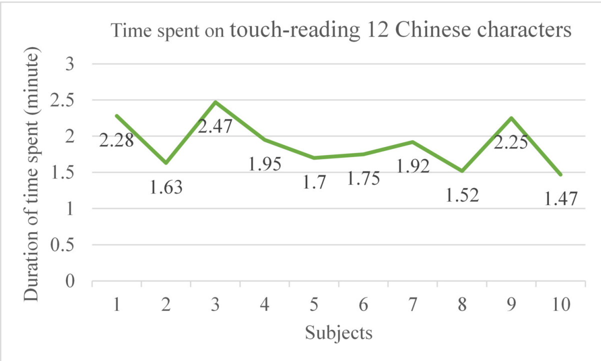

Figure 11. The total time taken by the subjects to touch-read and record 12 Chinese characters. The horizontal coordinate indicates 10 subjects. The vertical coordinate indicates the time taken by the subjects to recognize 12 Chinese characters.

The total average time taken by the 10 subjects to touch-read the 12 Chinese characters was 1.894 min/person, which means that the total time taken to touch-read and record each Chinese character was about 9.47 s. Then, in the next Braille recognition accuracy experiment, the duration of touch-reading of 12 Chinese characters can be limited to make a more accurate assessment of the usability of the device.

4. Braille Sentence Recognition Accuracy Test

The final experiment was to evaluate the device's feasibility and test whether the device could be used to touch-read long sentences.

4.1. Test Material

This device can display 12 Braille cells in one input, which means it can display six Chinese characters. In China, there are a lot of six-word ancient poems. Therefore, three six-word poems were selected for the Braille recognition accuracy test: "水至清则无鱼", "待到繁花落尽" and "醉里挑灯看剑". The corresponding consonants and vowels are "shui, zhi, qing, ze, wu, yu", "dai, dao, fan, hua, luo, jin" and "zui, li, tiao, deng, kan, jian". All three verses were selected from the students' textbooks, and they were randomly chosen from all the ancient poems in the textbooks as test materials. We should mention here that the first and the third poems in the students' textbooks are required to be learned by heart, and the second one is only required to be read familiarly.

4.2. Experimental Process

Before the experiment started, the experimenter input six words into the device beforehand. The subjects rested for one minute after each touch-read of the six words to prevent numbness of the fingers due to relatively long vibration from affecting the test results. During this minute, the experimenter input the second or third poem. Immediately after the experiment began, the 10 subjects recorded the corresponding consonant and vowel on white paper for every two Braille characters (one Chinese character) that they touch-read (there was no need to write down the Chinese characters, as there were homophones).

In addition, based on the conclusion that the total time for touch-reading and recording each Chinese character was 9.47 s obtained from the test experiment above, the time for the subjects to touch-read and record each line of the poem (6 Chinese characters) was limited to 1 min in this experiment (10 s $\times$ 6 Chinese characters = 60 s = 1 min). The motor was kept in vibration during this 1 min period for the subjects to continuously interpret the Braille characters. At the end of the test, the experimenter collected the papers recorded by 10 subjects and counted the accuracy of their recognition of the 3 poems.

4.3. Experimental Results

The results showed that 8 out of 10 subjects could accurately recognize the complete three poems, and only two subjects could recognize two complete poems, the first and the third one, and the second one could only be partially recognized or recognized with wrong Chinese characters. The recognition rates for the three poems were 100%, 80%, and 100%, with an average recognition accuracy of 93.33%. It was proven that the subjects can recognize Braille with high accuracy in a limited time, and the device can be used for Braille sentence touch-reading with high feasibility.

5. Discussion

In this paper, three types of experiments were conducted to explore the degree of usability of the device. The first one was the testing of the vibration intensity and the accuracy of vibration position recognition when selecting the vibration encoding scheme. The objectives were to find the vibration intensity that is suitable for the device and can be used without discomfort, and to allow the user accurate recognition of the vibration position as well as the increase in the speed of Braille reading, respectively. The results of the former test showed that 0.2 and 0.3 were the vibration intensities that were comfortable for the user. Since there were two suitable vibration intensities, a comparison experiment was conducted on the latter. A comparison was made between using only one vibration intensity (0.3 was chosen) and two vibration intensities on a Braille cell to see which option participants used to achieve higher recognition accuracy for Braille vibration dots. The result of the test showed that the recognition accuracy was only 72.50% when one vibration intensity was used and 93.75% when both strong and weak vibration intensities were used. Thus, the final encoding scheme was chosen to include both strong and weak vibration intensities.

In short, for users with different levels of Braille, in order to simplify the user time of learning how to use the device and to increase the efficiency of its use, the device was designed with a coding scheme that uses only consonant and vowel symbols as the spelling rules for the Chinese characters and omits the tone symbols (the absence of the tones does not affect the reading of the Braille sentences). For users with different tactile sensitivities, the Braille cells were designed to have two vibration intensities to increase the user sensitivity to vibration. The intensity of the vibration was tested to be clearly perceived by most people and produced only a small amount of numbness. However, if there is a user with very low sensitivity, we will specially customize a device to suit their vibration intensity based on their perception threshold.

The second type of experiment was a test experiment in which participants learned about Braille and device usage. The learning process was set up because the selected participants were sighted school students who had never been exposed to Braille before.

The Braille learning phase took five days, and then the subjects' rate of memorization of Braille characters was examined. The test results showed that each participant's memorization rate was 90% or higher, indicating that the subjects could carry out the device usage learning process. In this process, the subjects spent five days learning the vibrotactile expression of the device's consonant characters, vowel characters, and 36 Chinese characters. In total, 12 of the 36 Chinese characters used to test the learning outcomes were tested for recognition rate. The result was 90.8%, which indicated that the users were familiar with the device and Braille characters.The next task was to evaluate the usability of the device through Braille recognition accuracy test experiments.

However, to limit the subjects' touch-reading and recording time, the test of time spent was conducted along with the recognition rate test. The results indicated that the approximate duration was 9.47 s per Chinese character. However, this result tends to be subjective and cannot be used in the evaluation of reading speed. In addition, the participants learned the Braille characters and the device usage for only 5 days each, which is biased toward short-term memory. And the subjects had different learning efficiency and memory rates. Therefore, it is possible to improve recognition accuracy and reading speed with practice.

It is also worth noting that Braille learning and device usage learning are both part of the learning process. In accordance with the general principles of memory consolidation [30] and the distributed practice approach [31], participants spent a limited amount of time studying each day and continued learning for a period of time, rather than engaging in long periods of intensive training. This is extremely effective for tactile language learning and was felt by the participants. Subjects responded that there were instances of memory confusion during the learning process, but this was largely mitigated by the presence of a consolidated learning procedure. In addition, a few subjects felt that the motor-to-motor spacing was a bit large and relatively uncomfortable to touch-read. However, in the experiment, most subjects felt that the spacing was appropriate. Therefore, no modification of the spacing was implemented in the subsequent work.

In the final Braille sentence recognition accuracy experiment, we chose poems as the test material. However, there are potential limitations to this experiment. The experimental results may be affected by the associative properties and the amount of knowledge reserve of the subjects. Some subjects who were familiar with the poems were able to recognize the complete poems when they touch-read two or three characters, while others, who were unfamiliar with the poems, needed to spell out the poems after touch-reading all of them. The result was that the average recognition accuracy of the three verses was 93.33%. Hence, human knowledge and associative properties affected the accuracy of Braille touch-reading and even the speed of touch-reading.

Compared to other body-worn and direct-contact devices, In terms of recognition accuracy, the mobile phone (direct-contact device) in [23] had an only 71% accuracy for Braille recognition, and the gloves (body-worn device) in [17] had 68% and 75% accuracy. This device is able to achieve an average recognition accuracy of 93.33% for sentences, which is a significant improvement in accuracy. After familiarizing themselves with the device, those who are proficient in reading paper Braille can even touch-read with both their right and left hands, and their reading efficiency can be further improved. In terms of device ease of use, other devices split the six dots and set the order or tactility of the six dots to represent the Braille cell (such as the glove in [5]). However, this device does not need to separate the six dots. The user can read the six dots in one touch as if they were reading paper Braille, which is the biggest advantage of the device. Moreover, this device is used without any visual or auditory assistance at all (for example, compared with literature [6]). Its method of use is also very simple and easy for the user to operate. Last but not least, in terms of economic value, the cost of producing this device and the cost of the materials used is low (compared to the previously mentioned mobile phones [23], keyboards [27], gloves [16,17], etc.). Paper Braille books are bulky and expensive; this device can achieve similar functions to paper Braille reading, but the acquisition price is not high.

6. Conclusions

The device discussed in this paper is a vibrotactile expression device for reading Chinese Braille. It uses a 10 × 10 array of vibrating motors that are divided into rows similar to paper Braille to offer the user the most familiar usage experience. In addition, the design of the vibrotactile encoding scheme is based on the "Chinese Ordinary Braille Scheme", where the appropriate vibration intensities are 0.2 and 0.3. In a Braille cell, the appropriate vibration scheme is that the setting of the vibration intensity to 0.3 for Line 2 and 0.2 for Lines 1 and 3. Finally, poetry is chosen for the feasibility validation and testing of the device. The results show that the average recognition accuracy for long sentences is 93.33%, and this accuracy may be further improved as the user becomes accustomed to the device.

However, there are still limitations with the current device. The problem of recognizing Braille characters involves the user's familiarity with Braille. The subjects spent only a few days learning Braille, and they were not able to fully master the Braille characters. Therefore, the issue of the generalizability of the conclusions needs to be further considered.

In addition, future research will be carried out in the following aspects: first, we need to further optimize the coding scheme and explore more vibrotactile coding. For example, we need to increase the variety of coding schemes and extend them to encoding Braille characters (e.g., numbers, letters, etc.) other than Chinese characters. In addition, this device was also tested with recognition accuracy rate of patterns at the very beginning (circles, squares), so it is perfectly feasible to increase the variety of coding schemes. Second, we need to invite a larger, more diverse group of participants—blind people, people with normal vision and hearing, but put them in complex circumstances such as dark, noisy environments, etc., —to conduct the study, thus optimizing the range of applicability of the device. Third, we need to explore the optimization of the device's functionality and the expansion of its applications, such as the addition of voice input functionality and communication functionality, enabling the device to be used for information acquisition and exchange in fields such as virtual reality, augmented reality, Cosplay of Counter-Strike, etc.

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