Designing a 2 × 2 Spatial Vibrotactile Interface for Tactile Letter Reading on a Smartphone

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Abstract. In this paper, an eyes-free tactile reading system on a smartphone is proposed. This system adopts 2 × 2 flat vibration motors that are attached to the back of a smartphone, and a spatial tactile feedback will be generated and applied to the palm while the user holds the device. The tactile reading of 26 English letters was designed using spatial vibration codes. The hieroglyphs of English letters and their order of writing strokes were borrowed to minimize the tactile code learning curve for users. Numerous user experiments were conducted to tune important design parameters, such as distance between motors and vibration times. Results showed that a 3-cm distance between motors and a 200-ms vibration time are appropriate for designing an efficient system. The accuracy of tactile letter reading was 84.6%, time was 976.9 ms per letter, and the system can provide an efficient tactile reading technique for users in an eyes-free interaction.

Keywords: Spatial vibrotactile · Tactile interface
Empirical studies in interaction design · Tactile reading

1 Introduction

Smartphones are becoming an important computing platform in our daily life. However, smartphone touchscreens inherently lack tactile feedback compared with the conventional physical keyboard; hence, the interaction is generally susceptible to high errors and hardly supports eyes-free interactions [1]. The vibration motor provides linear tactile feedback and vibrates the entire device although this vibration motor inside the smartphone can provide tactile feedback to enhance interaction on a smartphone. The single vibration motor only supports a vibration on/off scheme to convey tactile codes; therefore, the dimensions of tactile coding design are limited [2].

In this paper, we propose a multiple vibration motor system that provides spatial vibrotactile feedback for a smartphone. The system adopts 2 × 2 flat vibration motors that are attached to the back of a smartphone. The spatial tactile feedback will be generated and applied to the palm while the user holds the device, as illustrated in Fig. 1.

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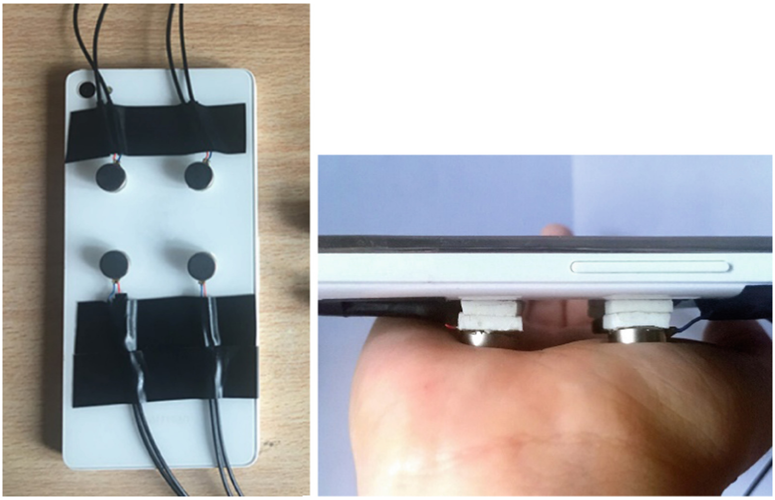

Fig. 1. System prototype. Four flat vibration motors attached to the back of the smartphone. The motors contact with palm while holding the device.

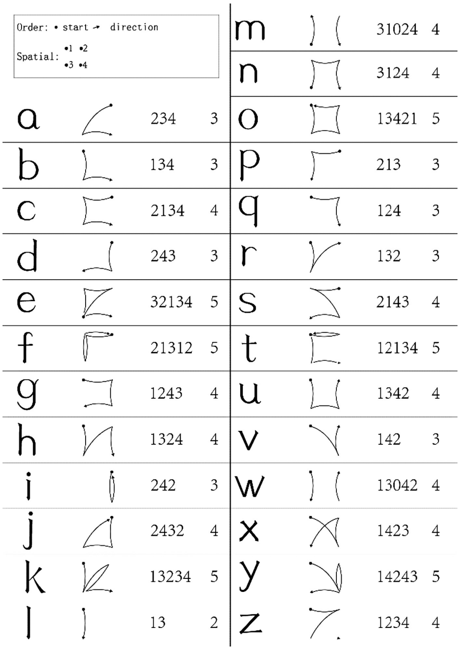

Fig. 2. Tactile codes of the 26 English letters.

We empirically investigated the parameter design in terms of efficient motor distance, appropriate vibration time, and vibration switching time between actuators to improve the usability of the prototype. These factors are important in designing an effective tactile interface with time efficiency and high user perception accuracy [3]. Moreover, we implemented a tactile letter code system for tactile reading of English letters based on the prototype design. The hieroglyphs of English letters and their order of writing strokes were borrowed to minimize the learning curve, as depicted in Fig. 2. A user experiment with nine participants was conducted to evaluate the performance of the tactile reading system. The results showed that the overall perception accuracy of tactile letter codes is 84.6%, and the mean time for presenting a letter is 976.9 ms. The system can provide an efficient tactile reading system for users in an eyes-free interaction.

2 Related Works

2.1 Single Vibrator Tactile Design

A single vibrator was widely used for designing non-visual tactile message on smartphones. The different vibration on/off patterns can be encoded to convey tactile codes and carry Morse or braille codes to deliver character information. For example, Rentala et al. [4] achieved the tactile reading method on a touchscreen mobile device, which expresses the raised and lowered information of six braille dots consequently through the tactile feedback in processing "rhythmic" patterns to be able to read tactile braille. Al-Qudah et al. [5] improved the design by encoding the braille with the vibration rhythm and Morse code to increase the tactile reading performance. These authors showed that the average reading speed can reach up to 855 ms per character, and the reading accuracy is approximately 71%.

However, the problem with these methods was that the linear tactile feedback with single vibrator only supports a vibration on/off scheme to convey tactile codes. Therefore, the dimensions of tactile coding design are limited to code vibration on/off intervals in the different patterns. In addition, the linearity of tactile feedback in the timeline is typically difficult for users to catch up, thereby resulting in low perception accuracy. The user experience on tactile information acquisition using a single vibrator is frequently reduced because of these problems.

2.2 Spatial Vibrotactile Design

To enhance expressiveness, previous studies have adopted multiple vibrators to deliver spatial vibrotactile information. For example, SemFeel [2] designed a five-vibration motor system in a cross shape attached to the backside of a smartphone. The system could generate different spatial patterns of vibration, such as position notification, linear, and circular messages. The experimental results showed that users can distinguish 11 patterns with 65.8%–93.3% accuracy in 2.19–2.95 s per pattern. The parameter design was not discussed in their work, although the system can generate different spatial patterns. For example, the physical distance between vibrators and the sensory saltation times between vibrators were not given. However, these parameters are important in designing an efficient tactile reading system.

In EdgeVib [3], a wrist-worn smartwatch with 3 × 3 and 2 × 2 multiple vibration motors was implemented; the distance of the vibrators were 1.5 and 3 cm, respectively. The vibration periods of a running vibration were 500 ms, and the interval between vibrators was 100 ms. The user experimental results showed that the 2 × 2 layout of vibration motors outperform the 3 × 3 layout in terms of recognition rate and time efficiency. Therefore, a spatiotemporal vibration pattern that uses a 2 × 2 layout and unistroke patterns that represent characters were adopted to implement tactile reading. The user experiment results showed that the system recognition rate is 85.8%. The results of wrist perception can hardly be generalized to a palm in a smartphone-holding situation because different body positions demonstrate distinct sensitivities to tactile feedback, although the design parameters have been considered in this study [6]. For example, Lee [7] revealed that the sensory saltation and locus of stimuli can affect the performance of information transfer.

Therefore, carefully tuning the design parameters related to the distance and vibration time of motors remains crucial. This open question motivated us to design an efficient spatial vibrotactile interface for implementing tactile reading on a smartphone.

3 Prototype Design

The prototype system is exhibited in Fig. 3. Four flat XY1027L vibration motors were attached to the back of a smartphone. The working voltage of the vibration motors was 3 V, and the current was 100 mA. The diameter and thickness of the motor are 10 and 2.7 mm, correspondingly. The Arduino Uno was used to control the vibrations.

The vibration motors were elevated with a spongy for approximately 5 mm raise that easily contacts with the palm while the user holds the device, as presented in Fig. 4. The spongy can reduce the vibration noise and cache the knock with the solid surface of the smartphone.

4 Parameter Tuning

The design has two important parameters, that is, the distance between vibration motors and the appropriate timing for vibration stimuli and switching between vibration motors. These parameters are crucial to user recognition for tactile codes.

We conducted a user experiment on six university students who were majoring in digital media technology to refine these parameters. Their mean age was 20.3 (19–21), and three respondents were male.

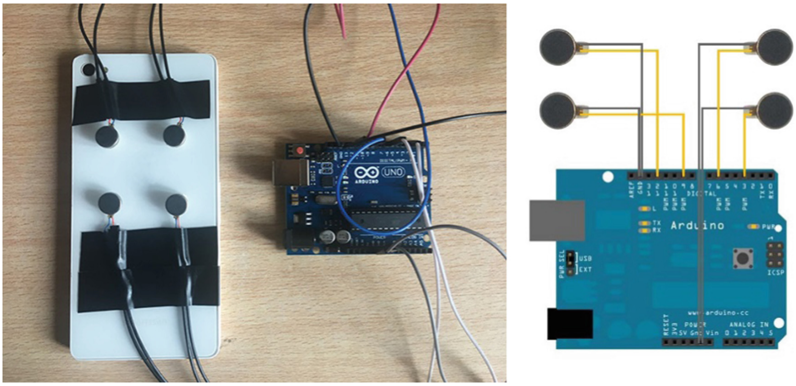

Fig. 3. Prototype designs. Four flat vibration motors were attached to the back of a smartphone. The Arduino was used to control the vibrations.

4.1 Vibrator Distance

The experiment was conducted in the laboratory. A PC was used to send a control command to the Arduino and generate vibration patterns to the vibrators.

The apparatus and experimental environment are presented in Fig. 5.

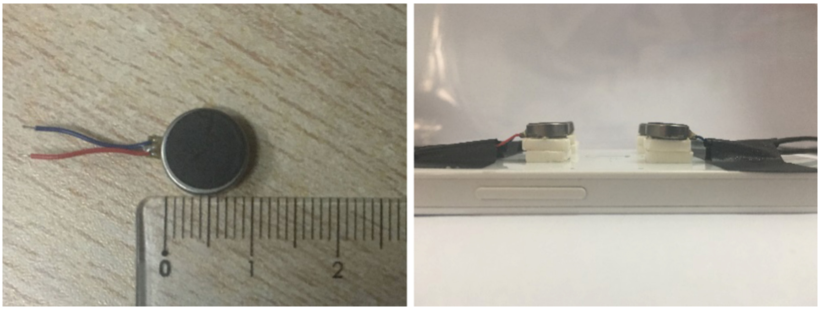

Fig. 4. Size of the vibration motor and spongy was used to raise the motors.

Procedure: The experimenter explained the system function and allowed the participants to hold the device on the right hand to perceive the different vibrations generated by each vibrator. The experimenter will change the vibrators in different distances, that is, 2, 2.5, 3, and 3.5 cm, and explain to participants that the experiment was aimed at examining the appropriate distance for obtaining a favorable recognition accuracy. The formal experiment started after approximately 10 min of familiarizing themselves with the system.

The experimenter provided the participant with the device, which was set to a predefined vibrator distance (2, 2.5, 3, or 3.5 cm). The experimenter then sent a random position (up–left, up–right, down–left, and down–right) of vibration stimuli to the device using the PC. The participants perceived the stimuli and reported to the experimenter the relative position of the vibrator that generated the vibration. The perception correctness of the participant was recorded to calculate the accuracy of the various vibrator distances.

Each different vibrator distance had six random stimuli. The total test trails were as

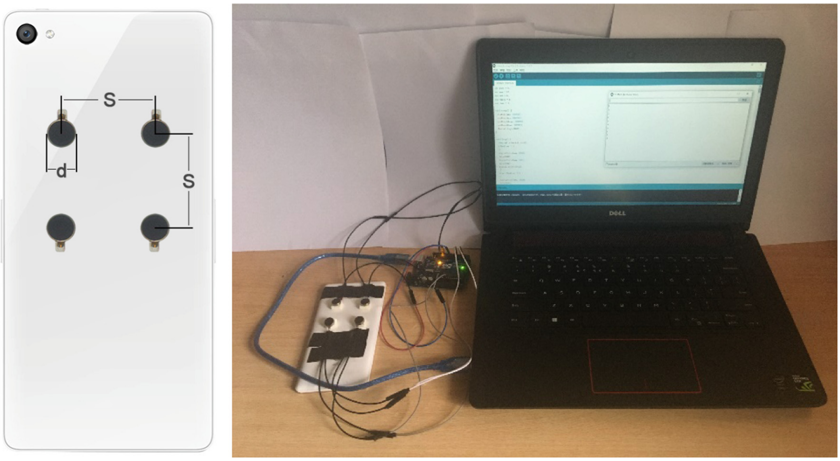

Fig. 5. Experiment apparatus. The PC was used to control the experiment procedure.

follows: 6 stimuli × 4 distances × 6 participants = 144.

Result: The experiment result is displayed in Fig. 6. The perception accuracy increases when the distance between vibration motors is large. The 3-cm distance is appropriate for users to obtain a high perception accuracy because no significant difference exists between 3 and 3.5 cm; the t-test is $p = 0.182$. The t-tests on other distances are: 2 cm versus 2.5 cm, $p = 0.013$; 2.5 cm versus 3 cm, $p = 0.038$.

4.2 Vibration Times

In this user experiment, we tested different vibration times and combined various intervals between the motors to find the appropriate parameters for achieving a high perception accuracy. We aimed to find the minimal vibration time T and vibration interval I that user can perceive and simultaneously guarantee a favorable perception accuracy.

The apparatus and participants are respondents in the previous experiment session.

Procedure: The participants were encouraged to join this experiment after the previous experimental session. The combinations of T = 75, 100, 125 ms; and I = 150, 175, 200 ms conditions were tested. In each condition, six random sequences of stimuli were generated by the device. These sequences, which were e, f, k, o, t, and y, were

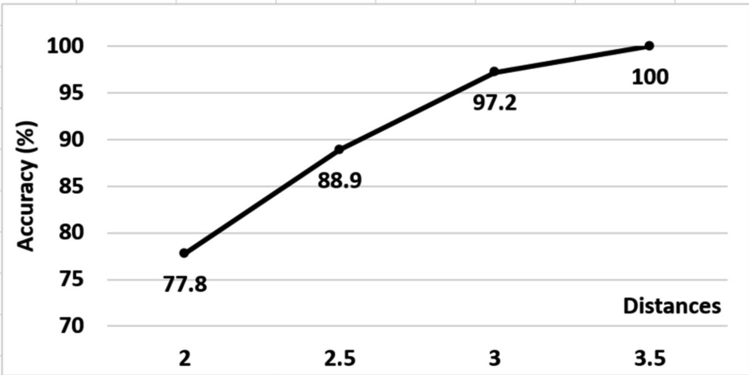

Fig. 6. Result of perception accuracy for different vibration motor distances.

letter codes that are illustrated in Fig. 2. These stimuli were selected because they had five strokes and were the most complex stimuli in our letter code design.

Participants were allowed to familiarize themselves with the six stimuli in different *T* and *I* conditions for 10 min. In the formal test, the experimenter sent a vibration code to the device, and the participants perceived and reported to the experimenter the exact sequence of the vibrations generated by the device. The result was recorded as correct if the participant reported the same vibration code to the code the experimenter sent.

The total test trails are as follows: 3 vibration times $T \times 3$ intervals $I \times 6$ stimuli × 6 participants = 324.

Result: The results are depicted in Fig. 7. The perception accuracy reached the highest value with mean = 91.7% when the vibration time T > = 100 ms and interval I = 200 ms. The t-test exhibited a significant difference between I = 175 and I = 200 ms when p = 0.001.

5 Tactile Letter Code Perception

We designed tactile letter codes after tuning the appropriate parameters to implement tactile reading on a smartphone (Fig. 2). The codes were designed based on the strokes while writing the lowercase letter. The number of vibrations and their switches was reduced as much as possible. The minimum number of vibrations is two (such as letter l), and the maximum vibrations (i.e., letters e, f, k, o, t, and y) are five. A user experiment was conducted to evaluate the performance of the tactile letter perception.

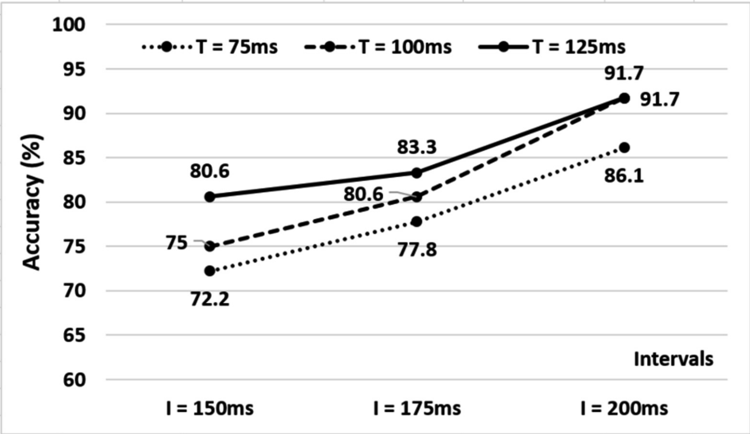

Fig. 7. Result of the perception accuracy for different vibration times and intervals.

5.1 Experiment

Nine university students were invited to participate in the experiment. Their mean age was 20.5 (19–22), and four were male. In the experiment, the 26 letters were presented to the nine participants randomly, and they reported their perceived letters to the experimenter for correctness check. The participants were allowed to familiarize themselves with the system for 5 min, and the formal experiment lasted for approximately 10 min.

5.2 Result

The final results are presented in Fig. 8. The overall accuracy of perception on the 26 letter codes is 84.6%.

We calculated the accuracy of the different numbers of vibrations. Figure 9 illustrates that the accuracy was higher than 88.9% when the number of vibrations is less than five. The accuracy dropped to 57.4% on 5 times of vibrations (the letter codes of e, f, k, o, t, and y). The ANOVA (Analysis of Variance) indicated no significant difference on 2, 3, and 4 times of vibrations, but a significant difference was found between 4 and 5 vibrations.

6 Discussion

In the tactile display design, we adopted the 2 × 2 shape of vibrators and tuned the parameter design. However, other shapes of a tactile display, that is, cross shape design, should also be considered [2]. In the future, we will compare the current design with other tactile displays and explore their differences.

In the letter code perception experiment, 2, 3, and 4 vibration codes showed a higher recognition performance than the 5 vibration codes. Thus, we will optimize the

	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	no
a	9																										
b		9																									
c			9																								
d				9																							
e					9																						
f						7															1						1
g							7												1								1
h								8																			1
i									7	1																	1
j							1			6																	2
k											5														1		3
l												9															
m													7	2													
n														9													
o															4					1					1		3
p																9											
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t										2										4					1		2
u																					8		1				
v																						9					
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y										1									1						2		5
z																										9	

Fig. 8. Confusion matrices of letter code perception.

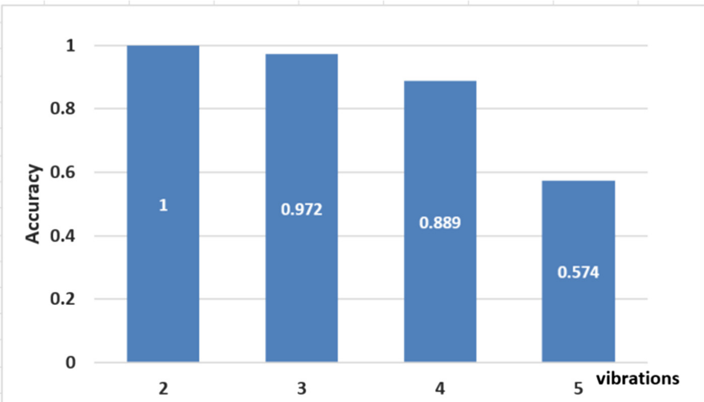

Fig. 9. Accuracy of the different numbers of vibrations.

low-accuracy letter code design, that is, e, f, k, o, t, and y, and avoid using 5 or more vibrations in the future work.

In the tactile code design, we only adopted a single vibration at a time; future work should also consider the simultaneous vibrations generated on the multiple vibrators [7].

7 Conclusion

We learned that the relative locus of vibrators and the number of sensory saltation can affect the performance of a tactile display through a series of experiments. Based on our findings, our recommendation for an efficient tactile reading system on a 2 × 2 tactile display is to use temporal patterns with sensory saltation and limit the number of saltations to less than five.

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