Design and Evaluation of Tactile Number Reading Methods on Smartphones

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***Abstract*—In this paper, we propose two active tactile texture interaction methods enabling eye-free tactile number (0–9) reading on a variable-friction surface for a smartphone equipped with a TPad device. We employ four discriminative stripe-based tactile textures to represent different numbers, namely, 0, 1, 2, and 5, and combine them with the other numbers. For the first interaction method, we adopt simple left/right slider motion gestures (LRSM), and for the second, we utilize up to down slider motion gestures (UToDSM). We examined the interactive efficiency, recognition accuracy, and user-subjective satisfaction of both techniques. We also compared the two methods with an approach that converts a variable-friction perception into a typical vibrotactile perception. Our results indicate that UToDSM leads to the highest interactive efficiency and achieves a high recognition accuracy.**

Keywords—tactile interface; tactile number; tactile reading; user study; human computer interaction

I. INTRODUCTION

Touchscreens have become a prevalent means of smartphone interaction. Users can interact and obtain information from their smartphones primarily through visual and auditory channels. However, this is quite difficult for people who are visually or hearing impaired. In addition, in certain cases, it may be inconvenient for the user to view the screen or hear a voice on a smartphone in a noisy environment.

A tactile interaction technique provides a novel solution for non-visual and non-auditory interaction. In addition to tactile reading, eye-free tactile-based interactions are quite valuable for certain applications [1-3].

The vast majority of research on haptic surfaces has been conducted using vibrotactile devices and dynamic friction tactile devices. Vibrotactile technology is a mainstream approach that can produce significant, strong vibrational feedback through a vibration motor equipped in a smartphone. However, a defect of such technology is that it can be noisy when used. In contrast, technologies based on frictional tactile feedback have emerged in recent years, including Tpad [4, 5]. A TPad device can control the friction between the surface and the user's fingertip through low-amplitude, high-frequency (ultrasonic) vibrations of the surface [4]. Compared to vibration technology, TPad can provide a richer and more flexible tactile pattern, with lower noise. Thus, with a frictional tactile device, it is possible to obtain information by encoding messages into a tactile pattern. However, reading on a smartphone using tactile feedback remains a challenging task.

In this paper, we propose two novel methods for reading tactile numbers on a smartphone using TPad. We start from the tactile number with friction based technology to provide a basic solution for more information tactile reading.

The contributions of this paper include the following: We first propose two tactile number reading methods that use finger sliding on a TPad. We then describe the encoding of the numbers 0 through 9 as tactile texture patterns. Finally, we evaluate the two methods as compared with a vibrotactile perception method.

II. RELATED WORKS

A. Tactile Feedback Devices

Vibration-based approaches have been successful to the point of being widely commercialized. The main haptic interaction technology used to produce vibration is achieved through the assembly of a vibrating motor in a mobile phone. By adjusting and combining the parameters of the vibration intensity, frequency, pulse, and rhythm, vibration-based devices can provide different tactile feedback [6, 7]. A characteristic of a vibration-based device is that it can provide clear and strong tactile feedback; however, the method inevitably produces unwanted noise [2].

Variable friction technology is a method for producing force-based haptics, including Tpad [4]. The variable friction effect of TPad is achieved through the ultrasonic vibration of the surface [5], which occurs according to the tactile texture rendered and the position of the finger on the screen. As a technical feature, it can offer extremely fast response times (27.5 ms), frictional feedback to the fingertip, and a lower amount of noise. The highest friction state occurs when the vibration amplitude is zero (represented by black on the tactile texture), and the friction level steadily decreases as the vibration amplitude increases (represented by gray until a white color appears on the tactile texture). By adjusting the dynamic friction coefficient through a tactile texture pattern, it can simulate different haptic textures on a mobile phone screen. In current researches, Mullenbach et al. explored affective communication through variable-friction surface haptics [8] and Birnholtz used variable-friction tactile display technology for awareness information [9].

B. Tactile Reading Method

The main methods of tactile reading on a mobile phone include passive and active interaction.

With passive interaction, Rantala et al. and AI-Qudah et al. proposed a method for presenting braille characters on a mobile device [10, 11]. They encoded braille into rhythmic haptic feedback in the time domain. These methods achieve a high reading efficiency with a character reading speed of up to 797.7 ms for each cell. However, the high learning costs of such methods often require a long period of pre-study to become familiar with distinguishing the different haptic coding patterns.

In an active interaction method, Jayant et al. introduced an active interaction method called V-Braille [12] to perceive haptic braille. V-Braille is a simple mechanism for conveying braille using a touchscreen and vibration on a mainstream phone. The screen is divided into six parts to mimic the six dots in a single braille cell. When the part of the screen touched represents a raised dot, the phone vibrates. Although the efficiency of an active approach is less than that of a passive approach, it is easier to learn and is more controllable. Thus, the active interaction method is more in line with Nielsens' controllability principle [13].

C. Tactile Texture Encoding and Display

Tactile displays are now becoming available in a form that can be easily used in a user interface. Brewster et al. described a new form of tactile output, called tactons [14]. The construction of tactons includes the vibration frequency, amplitude, and duration of a tactile pulse, rhythm, and location. Chu et al. investigated the user perception of various tactile stimuli patterns over a frictional surface on Tpad [15]. Their study designed 36 different tactile texture patterns with different strips on them to evaluate the discrimination and distinguish the time. The results of this study can be used as a reference for the design of the tactons, and to obtain an eye-free interaction or encoding of tactile language.

III. TACTILE NUMBER READING TECHNIQUES

The main objective of this study is to design two active texture tactile interaction methods to enable eye-free number reading on a variable-friction surface for smartphones equipped with a TPad device. These two methods are implemented using different finger motions (left/right or up to down) as interactive gestures. For contrast, we compared these two methods with another method that converts a variable-friction perception into a typical vibrotactile perception.

A. Number Encoding and Combination

Referencing the denominations of currency in circulation, we choose four numbers as the numeric units: 0, 1, 2, and 5, which can be combined with other numbers with the least numeric units.

Each numeric unit is encoded as a sequence of periodic tactile feedback textures with a different width of the discrete alternating stripes. A 1 is encoded using stripes of w1 = 0.2 mm and w2 = 0.2 mm. A 2 is encoded using stripes of w1 = 1.5 mm and w2 = 1.5 mm stripes. A number 5 is encoded using stripes of w1 = 3.2 mm and w2 = 3.2 mm, whereas zero is encoded using a full white pattern. Furthermore, zero is also presented at the end of an interaction. Here, we use W1 to present a white stripe (least friction feedback) and W2 to present a black stripe (most friction feedback). Figure 1 shows the numeric units for 0, 1, 2, and 5 tactile textures.

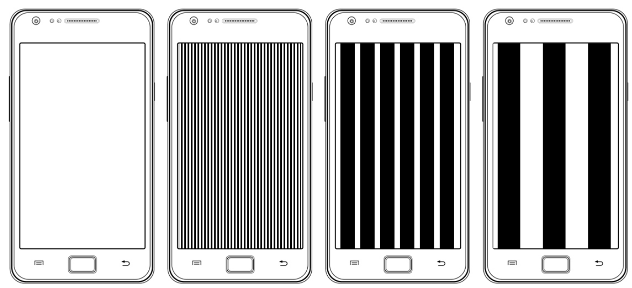

Fig. 1. Numeric unit encoded, from left to right: 0, 1, 2, and 5

Other numbers are combined with the numeric units. For example, a number 6 can consist of a 1 and 5, and a number 9 can be made using a 2, 2, and 5. However, we apply a diverse numeric combination texture pattern and reading mode for each different interaction method.

B. Left/Right Slide Motion Gesture Interaction Method

For the left/right slide motion (LRSM) gesture interaction method, we map each numeric unit with a full screen portrait orientation interval of stripe textures. The reading mode is as follows:

When the user's finger touches the screen and starts to move in a left or right direction, the system provides the tactile texture of the numeric unit on the screen, and then provides the tactile texture of another numeric unit immediately when the user moves their finger in the opposite direction when perceiving the tactile texture. This process continues until the user perceives the tactile texture for zero.

For instance, a 6 is combined with numeric units 1 and 5. First, if the user moves their finger in the left direction on the screen, they can then perceive the tactile texture of the number 1; the user can then move their finger in the right direction, and can feel the feedback signal from the tactile texture of number 5, and finally move their finger left again and until perceiving the texture for the number zero, which indicates that the reading is finished. Thus, the user can accumulate the numeric units together and obtain the final number as 6. Figure 2 shows how the user perceives the number 6 in this reading mode.

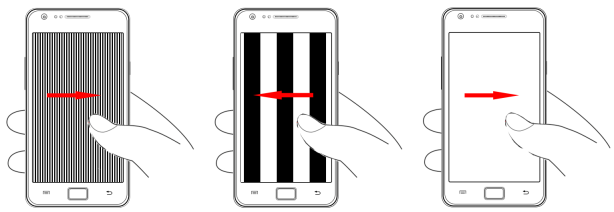

Fig. 2. Reading of tactile number 6

C. *Up to down slide motion gesture interaction method*

Contrary to an LRSM gesture, which separates each numeric unit into an entire texture and a portrait orientation, with this method, the stripes for the tactile texture are in the horizontal orientation. In addition, the entire texture is divided equally into four areas in the vertical direction. All numeric unit stripes are placed with one texture in different areas.

The user's finger touches the top of the screen and moves from the top to the bottom of the screen. Similarly, users add all the numeric units together to obtain the final number. Figure 3 shows the tactile texture indicating a number 6.

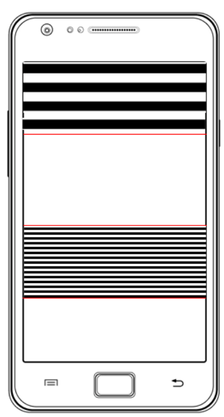

Fig. 3. Tactile texture for number 6 in UToDSM

D. *Vibrotactile Perception Method*

To contrast and estimate the results of the previous methods, we introduce a traditional motor vibration equipped in a smart phone.

In vibrotactile mode, we employ a different duration (pulse length) and time interval of the vibrotactile stimuli to encode the numeric units. We defined one unit length of a pulse as a 10 ms duration. Therefore, number 1 is encoded in a single pulse. Number 2 is encoded in two pulses with an interval of 10 ms between them. Number 5 is encoded in two pulses without an interval. Number 0 is encoded in three pulses. In addition, the other numbers are made using these three numeric units with 20 ms interval between them.

In vibrotactile perception mode, the user holds the smartphone in their hand and perceives the vibrotactile pulse produced by the vibration motor.

IV. EXPERIMENT EVALUATION

We conducted an experiment to evaluate the usefulness of the tactile number reading technique, which focuses on LRSM and UToDSM. In addition, we compared the two methods with a traditional vibrotactile perception method.

We estimated and quantified the interactive efficiency, recognition accuracy, and subjective user satisfaction of these three methods using Nielsen's usefulness evaluation principle [13] and a within-subject experiment.

A. *Apparatus*

The experiment used the client/server (C/S) architecture contained in a TPad phone (Android OS, as the client)[1] and a tablet computer (Android OS, as the server), connected using Bluetooth. The tablet computer is responsible for randomly generating a number to read and sending this information to the TPad phone, and continues calculating and recording the user's recognition accuracy and recognition time for each tactile number.

The TPad phone provides dynamic friction on the touch screen by using an air-squeeze-film technique [16]. The device is used to produce a tactile number texture on the screen according to the number information sent by the server. During the experiment, a screen size of 4.7 inches and a display resolution of 720 pixels × 1280 pixels were used.

B. *Subjects*

A total of 12 volunteer participants (six males and six females, aged 19–22) were recruited from Zhejiang University of Media and Communication. All of them have experience using a smartphone; however, none has previously used a TPad phone. Each participant was paid 50 yuan (RMB) for participating in the study.

C. *Procedure*

Before the experiment, we demonstrated the experiment apparatus, interactive method, and objective to the participants. We then let them try to obtain a preliminary understanding of the tactility by allowing them to experience the tactile friction and vibration. Thereafter, we showed the participants all of the tactile number patterns and requested them to undergo a training procedure to be familiarized with all of the tactile perceptions. After the subjects fully understood the interactive reading methods, we started the formal experiment.

The experiment includes three sessions (LRSM session, UToDSM session, and vibrotactile perception method session). In this experiment, a Latin Square design was employed for counterbalancing purposes. We divided the subjects into three groups, with four participants in each

[1] http://www.thetpadphone.com/

group. Each group carried out the experiments in different order.

We proceeded in two phases for each session: a training phase followed by the experiment phase. In the training phase, the participants could choose the number on the server's screen on their own, and when the number was sent to the client, the participants could see the tactile texture on the client's screen and try to perceive and remember the tactile number pattern. During the experiment phase, the numbers (0–9) were sent by the server to the client in random order. Each number appeared five times randomly. The tactile number pattern had no visual feedback shown on the screen. The participants were instructed to move one finger on the screen to perceive the tactile number pattern. When the server had sent the number information to the client, and the participant touched the client's screen, the server started to time when the participant's finger touched the screen. The timing procedure continued until the finger left the screen and selected the number identified on the server. This process aims to record the recognition time and interactive efficiency. Meanwhile, the server records the selected number for recognition accuracy. Finally, the participants were asked to complete a 7-point Likert scale questionnaire to collect subjective feedback (efficiency, sensitivity, usability, and overall rating) for the three interactive methods.

In the experiment phase, each number appears five times. Thus, in every session, 50 perceived steps were carried out. In total, the experiment contained 12 participants × three sessions × 50 steps = 1800 steps. When one session ended, the participant was required to take a 10 min rest. Each experiment lasted about 1 h for each participant.

Noise-cancelling headphones were used to block disturbing ultrasonic sounds from the TPad. In addition, a tissue was used to keep the participants' fingers dry. The experiment environment was quiet, with no other interference (see Figure 4).

Fig. 4. Experiment environment

V. RESULTS

The main dependent measures are the interactive efficiency, recognition accuracy, and user subjective satisfaction. Interactive efficiency is used to report the recognition time (ms), which is the time the participants take to perceive the tactile number. The recognition accuracy is introduced to measure the accuracy of each method for each tactile number. User subjective satisfaction is used to reflect the user's preference for each method through a Likert scale questionnaire.

A. Interactive Efficiency

Table I and Figure 5 indicate that UToDSM is the most efficient and stable interaction method (821.9 ms, SD = 190.4). Compared with UToDSM, the interaction of the LRSM (2172.7 ms, SD = 1167.36) and vibrotactile (1839ms, SD = 1005.75) methods is less efficient and stable. Furthermore, the recognition time is increased as the number increases. However, the recognition time of the number units (0, 1, 2, and 5) is less than that of the other numbers.

TABLE I. INTERACTIVE EFFICIENCY (RECOGNITION TIME, IN MS)

Number	***LRSM***		***UToDSM***		***Vibrotactile***	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***
0	659	327	562	278	612	404
1	844	411	632	288	774	369
2	1685	598	673	296	1318	380
3	2300	690	876	403	2087	600
4	3177	964	846	393	2772	835
5	846	353	673	370	769	385
6	1903	753	873	387	1376	547
7	2526	752	833	392	2089	758
8	3431	1164	1016	531	2748	948
9	4356	1125	1235	603	3845	1025
Total	2172.7	1167.36	821.9	190.4	1839	1005.75

Table I illustrates the average and standard deviation of the recognition time for each tactile number.

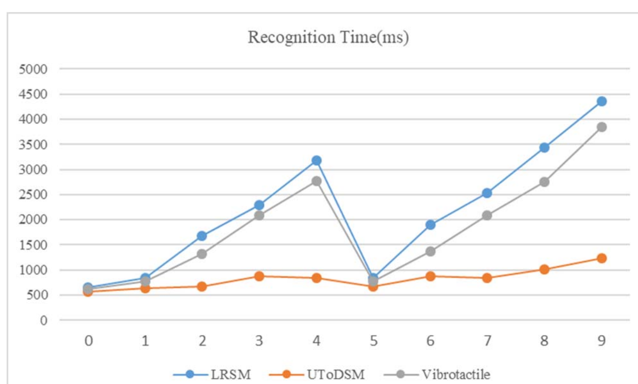

Fig. 5. Recognition time (ms) of each number

TABLE II. ANOVA ANALYSIS OF INTERACTIVE EFFICIENCY

Number	***LRSM vs UToDSM***		***LRSM vs vibrotactile***		***UToDSM vs vibrotactile***	
	F (1,118)	***P-value***	***F (1,118)***	***P-value***	***F (1,118)***	***P-value***
0	2.158	0.1444	1.01	0.3168	0.632	0.4283
1	**8.973**	**<0.005**	1.022	0.3141	4.398	0.0381
2	**98.389**	**<0.0001**	**17.332**	**<0.0001**	**63.948**	**<0.0001**
3	**271.358**	**<0.0001**	6.107	0.0149	**171.694**	**<0.0001**
4	**331.864**	**<0.0001**	**14.455**	**<0.005**	**288.0633**	**<0.0001**
5	6.45	0.0124	7.805	0.0061	0.147	0.7017
6	**112.451**	**<0.0001**	**22.269**	**<0.0001**	**59.003**	**<0.0001**
7	**219.738**	**<0.0001**	6.209	0.0141	**115.402**	**<0.0001**
8	**271.109**	**<0.0001**	**10.937**	**<0.005**	**166.683**	**<0.0001**
9	**462.019**	**<0.0001**	**23.723**	**<0.0001**	**295.315**	**<0.0001**

We found that the recognition times of the numbers 2, 4, 8, and 9 have a large statistical significance with each method. With LRSM, the participants were inclined to slide their finger a longer distance for greater confidence that they perceived the correct number. With the vibrotactile method, more time is needed to present the tactile numbers.

B. Recognition Accuracy

Table III and Figure 6 show that the recognition accuracy of UToDSM is 97.34% (SD = 10.67), that of vibrotactile is 96.93% (SD = 12.64), and that of LRSM is 90.83% (SD = 25.41). Based on an AVOVA analysis, the UToDSM and vibrotactile method have no statistical significance. However, the UToDSM and vibrotactile method show a statistical significance compared with the LRSM. Therefore, the UToDSM and vibrotactile method obtain the highest accuracy in the experiment (see table III and Figure 6).

TABLE III. RECOGNITION ACCURACY

Number	***LRSM***		***UToDSM***		***Vibrotactile***	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***
0	100	0	100	0	100	0
1	94.4	22.9	100	0	97.2	16.4
2	91.7	27.6	100	0	100	0
3	97.2	16.4	97	13.7	100	0
4	88.9	31.4	94.3	20.1	94.4	22.9
5	80.6	39.6	100	0	97.2	16.4
6	83.3	37.3	98.2	14.2	97.2	16.4
7	94.4	22.9	96.3	19.3	88.9	31.4
8	80.6	39.6	93.5	21.3	94.4	22.9
9	97.2	16.4	94.1	18.1	100	0
Total	90.83	25.41	97.34	10.67	96.93	12.64

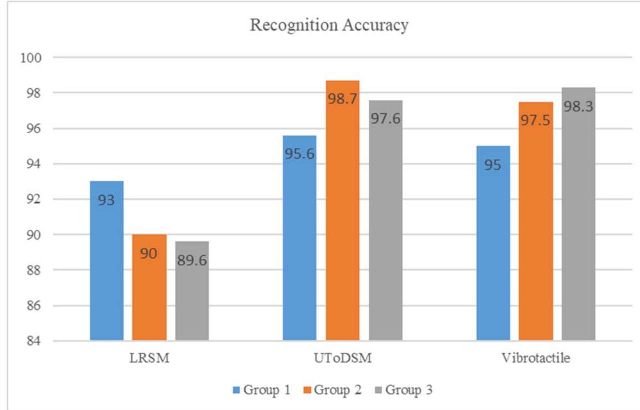

Fig. 6. Recognition accuracy

C. User Subjective Satisfaction with 7-point Likert Scale

Based on the scores of the 7-point Likert scale-based questionnaire (see Figure 7), most of the participants (11 out of 12) expressed a preference for the vibrotactile method (6.45 SD = 0.6), followed by UToDSM (5.025 SD = 0.72), and LRSM (4.2 SD = 1.2). They argued that they found the vibrotactile method to be more familiar and intuitive. They all seemed to think that, although friction-based methods are novel, their feedback is weak and not easy to perceive.

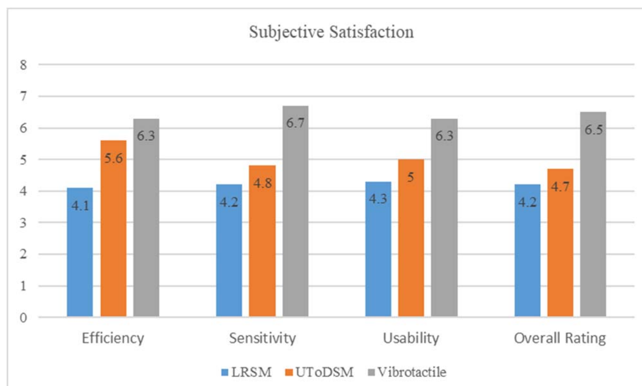

Fig. 7. User subjective satisfaction

VI. DISCUSSION

We found that UToDSM leads to the highest interactive efficiency and stability, followed by the vibrotactile method and LRSM. Furthermore, the participants took less time to recognize the numeric units than the other numbers.

The table III and figure 6 provided in this paper indicate that UToDSM and the vibrotactile method achieved the highest accuracy during the experiment, whereas the LRSM yielded the lowest accuracy.

Through a user subjective satisfaction questionnaire, we found that most of the participants prefer the vibrotactile method over LRSM and UToDSM. One reason for this is that the vibrations of a smartphone are more familiar and intuitive. Another is that the feedback of friction-based methods have a lower quality tactility. However, the participants all agreed that the dynamic friction tactility has brought forth a new idea.

VII. CONCLUSION

We explored the possibility of tactile number reading on a smart phone. We employed two friction-based tactile methods (LRSM and UToDSM) and one vibrotactile method. The first two methods used numbers (0–9) encoded with a tactile texture, and the third used vibration-encoded numbers.

In this paper, we evaluated the interactive efficiency, recognition accuracy, and user subjective satisfaction of the three methods. We found that UToDSM has the highest interactive efficiency and recognition accuracy. Most of the participants argued that, if friction-based tactility can strengthen the feedback, it might be more practical.

In our future work, we would like to improve the dynamic-friction based tactile device to strengthen the tactile feedback. We will also encoded more numbers and find a more suitable encoding method to increase the tactility of the numbers present on a TPad. Furthermore, we will extend the numeric encoding to more characters.

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