Memorable Vibration Pattern Design based on Writing Pattern

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Abstract. In this paper, we presented memorable vibration patterns representing digit 0 to 9, which were designed based on writing patterns. Based on the collection of 50 participants' handwriting pattern of 10 digits we gathered, we designed two different types of vibration patterns to generate the digits: vibrotactile flows and discrete vibrotactile simulations. In the user study, we evaluated identifiability and learnability of the patterns we generated. First, participants successfully identified 69.4% of vibrotactile flow patterns and 77.5% with discrete vibrotactile simulations in their first session of 30 trials without training. The average recognition rate in their last session 30 trials increased to 83.6% for vibrotactile flows and 91.1% for discrete vibrotactile simulations after two sessions (60 trials), shows the ease of learning the vibration pattern. We also observed a lasting learning effect of both types of vibrotactile patterns in a delayed recall test was conducted 72-96 hours after the first user study – 90.0% success rate for vibrotactile flows and 91.4% for discrete vibrations.

Keywords: Memorable Vibration Pattern, Digits, Writing Pattern.

1 Introduction

Handwriting letters have been a most popular means to convey information to others in our life. In every moment, we write something--taking a memo, often with drawing something to memorize some information we need. Recent advances in technology make us doing such in a small form-factor mobile device, which impacted how we write and see, but the essentials of handwriting remained the same.

In mobile devices, there is another way to deliver information which has been underestimated—haptic functions. Due to many reasons, the information capability of mobile devices has been limited to convey a few different temporal patterns only in most devices, regardless of its size and price. One of the reasons would be the difficulty and inefficiency of learning tactile patterns, compared to those of audiovisual stimuli. In other words, most of the users do not have motivations to utilize tactile information delivery features. To overcome this, many researchers studied how to effectively convey information using tactile patterns, including our efforts in the current work.

In this work, we suggested a method to design vibrotactile patterns which inspired from handwriting patterns of 10 digits (0 to 9). The vibrotactile patterns can be expressed using vibrotactile flows, continuously moving sensation of vibrotactile stimulation, and discrete vibrotactile stimulation, sequential vibrotactile stimulation with break in between each stimulation. We expected that using well-known spatiotemporal patterns can minimize the users' cognitive load to learning. The following of the paper consists of the literature survey, our approach, user studies, and discussions.

1.1 Related Work

The use of spatiotemporal patterns to convey information has been an essential research topic. Novich *et al*. [1] found that spatiotemporal patterns perform better than spatial and intensity encoded patterns in encoding information to the skin. Luzhnica *et al.* [2] proposed methods to optimize overlapped spatiotemporal patterns for alphabet and words rendering using a glove wearable. Seo and Choi [3] developed a rendering algorithm to create vibrotactile flow which is able to produce diverse perceptual effects. They extended the 1D vibrotactile flows to 2D vibrotactile by rendering vibrotactile flows along the edges of a mobile device using 4 actuators places at its corner [4]. Gong *et al.* [5] developed a handheld haptic device which able to create 3D vibrotactile flows.

While the exploration of spatiotemporal patterns continues, research on haptic communication using tactile devices have garnered attention. Devices and vibration patterns for communication in various forms have been proposed [6]. However, conveying information in a systematic manner to shorten learning time remain crucial to encourage users to use tactile information for communication.

Namely, Morse code is one of the methods that can convey information using vibration with simple vibration patterns. Vibrotactile Morse codes usually use short vibrations to represent dots and longer vibrations to represent dashes in Morse code [7,8,9]. Plaisier *et al*. [9] conducted a study and found that users can learn 15 to 24 vibration patterns in 30 minutes. Braille is also another common method to convey information via touch. Braille can be generated using a refreshable braille display, and many different approaches to display Braille on a smartphone or a wearable device have been proposed [10,11,12]. However, researchers found that it could be hard to learn Braille at a later age [13].

Liu *et al.* [14] proposed Vibrotactile Alphabets, which alphabets are generated by manipulating the duration and frequency of vibrations. Users recognized over 90% of words and symbols correctly after six to eight hours of training. Liao *et al.* [16] created a set of vibration patterns for alphabets and digits inspired by EdgeWrite [15] patterns. The vibration patterns are generated on a wrist-worn tactile display with 2x2 tactor array. Users recognized 88.6% and 85.9% of numeric and alphabetical patterns respectively after a 15-minute learning session to learn the sequence of proposed vibration patterns and a training session in which the vibration patterns were displayed twice in random order. Cauchard *et al*. [17] proposed ActiVibe, which generate 1 to 10 on a smartwatch for communicating progress. They mentioned that 2 minutes of training is sufficient to understand and identify the set of vibrations.

A variety of vibration patterns that convert phonemes to words and express them in vibration on the forearm or arm were proposed in different works. Zhao *et al*. [18] proposed a phonemic approach in which each phoneme is paired with a unique vibrotactile pattern based on articulation placement. The users were able to read 10 words with 60% accuracy, which gradually increased to 83% accuracy after three recognition-recall blocks with 30 trials in each block. De Vargas *et al*. [19] converted phenomes into vibrations based on frequency with two vibrotactile actuators attached to the forearm. Users were able to identify 65% of words correctly after 4.2 hours of training.

1.2 Approach

First, we collected handwriting patterns of the 10 digit, 0 to 9 from 50 participants. Then we grouped the writing patterns based on the shape, starting point, direction, and sequence of strokes. As hardware, we made a mobile device mockup with six vibrotactile actuators. The six actuators were located on the left and right edges of the prototype (see Fig. 2a in Sec 2.3.). On this hardware setup, we designed two sets of vibration patterns to express the digits using vibrotactile flows and discrete vibrotactile simulations. Both types of patterns reflected how we write digits, which described in the Sec. 2.2. With this setup, we conducted a user study to observe the effectiveness of the patterns in information transfer, and their short- and long-term learnability.

The main contributions of this work are:

- We collected handwriting patterns of 0 to 9 from 50 participants and found generalized ways to write each number by following the majority did.
- We designed two types of spatiotemporal vibration patterns for the numbers, using vibrotactile flows and discrete vibrotactile simulations. The patterns were presented on a mobile device mockup with six actuators.
- We conducted two user studies; the first one with 13 participants and showed a rapid learning curve in the early-stage deployment of the patterns, and the second one of delayed recall test showed the patterns' long-term effects.

2 Vibration Pattern Design

2.1 Participants

We gathered handwriting patterns from 50 participants (26 female, age: 20− 35 years, mean: 26.54, SD: 3.6) to design the vibration pattern for each digit. We recruited participants with different nationalities (27 Malaysian, 6 Korean, 5 Pakistanis, 4 Burmese, 4 Indian, 2 Russian, 1 Cambodian, 1 Uzbekistani). The participants are asked to record a video of themselves writing the digit 0 to 9 using a pen on a paper.

2.2 Writing Patterns Categorization

We grouped the collected writing patterns based on the shape, starting point, direction, and sequence of strokes. Figure 1 illustrates the collected writing patterns, with dots representing starting points, arrows indicating endpoints, and the number below each writing pattern representing the occurrence frequency of the writing pattern among the 50 participants.

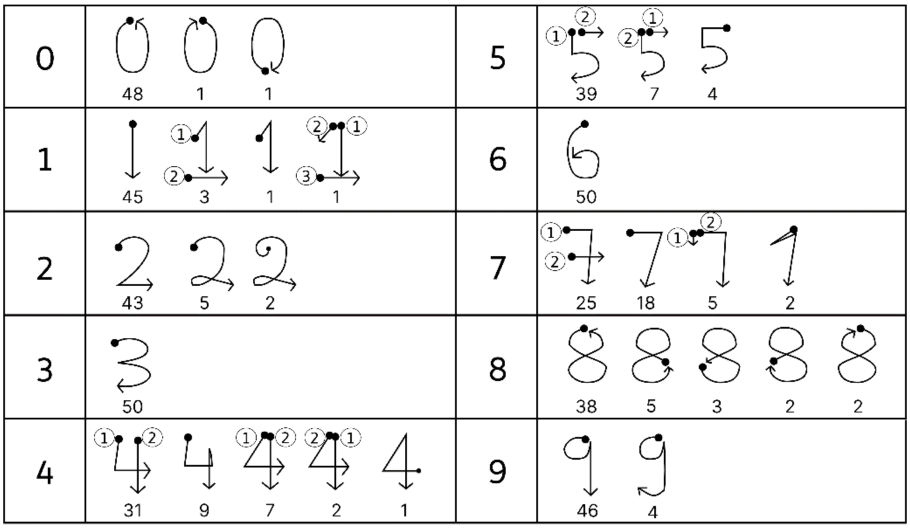

Fig. 1. Writing patterns collected from 50 participants. The dot indicates the start point and the arrow indicates the end point. The digit below each pattern is the frequency of occurrence.

2.3 Vibration Patterns Design

After grouping the writing patterns, we designed vibration patterns with six vibrotactile actuators arranged on the left and right, as shown in Figure 2(a). We designed the vibration patterns to be generated using two different types of vibrotactile sensations, vibrotactile flows and discrete vibrotactile simulations. Figure 2(b) show the vibration pattern generated using vibrotactile flows and discrete vibrotactile simulations.

The following are factors we considered when designing the vibration patterns.

- **Occurrence Frequency of Writing Pattern.** In the collected writing patterns, most of the digits have a single writing pattern that occurred at more than 60% (Except digit 7). Hence, we designed the vibration patterns based on the writing pattern with the highest frequency of occurrence. However, we opted for the second-highest frequency pattern for digit 7 due to its simplicity.
- **Sharp Turning Point and New Starting Point.** Here, we define the point where a circular stroke ends and the immediately following next stroke starts as a sharp turning point. If a stroke initiates from a point different from where the preceding stroke

ends, we identify this as a new starting point. Inspired by our observation that people often pause for a short moment at a sharp turning point and pause for a longer period when starting a new stroke when writing a digit, we added pause at the sharp turning points and the new starting points as one of the characteristics for certain digits (2, 3, 4, 5, 9) to facilitate recognition. We use two different pausing durations, 150ms at a sharp turning point and 250ms at a new starting point in both types of vibrotactile sensations. For discrete vibrotactile simulations generated vibration patterns, we repeated the vibration at sharp turning points after the pause to create a more natural feeling, providing a sense of the ending of a circular stroke and the starting of a next stroke.

- **Different Starting Points among Digits.** To minimize confusion between digits with higher similarity, we designed the digits to have distinct starting points. For example, to reduce confusion between 0 and 6, the starting point of 0 is placed on the top left, while digit 6 starts from the top right. Another example is the digit 2, which has starting point at the middle left, setting it apart from other digits.

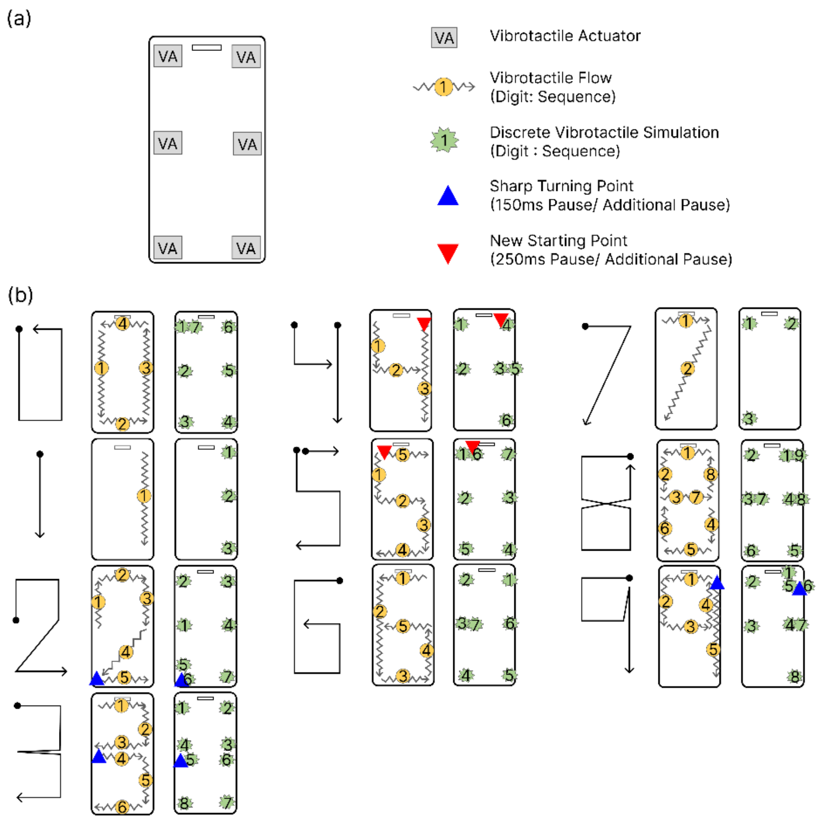

Fig. 2. (a) Arrangement of six vibrotactile actuators. (b) Vibration pattern generated using vibrotactile flows and discrete vibrotactile simulations.

3 User Study

3.1 Participants

We recruited 13 participants (7 female, age: 21− 35 years, mean: 26.46, SD: 3.71) to participate in the user study from the university community. Our participants consist of individuals from various nationalities, including 6 Korean, 2 Indian, and one each from Malaysia, Indonesia, Mongolia, Pakistan, and Tanzania. Among them, 2 participants are post-doctoral researchers at the university, 7 participants are graduate students, and 4 participants are undergraduate students. All participants reported themselves with no known sensory disorders or disabilities. The majority were right-handed, except for one participant who was ambidextrous. Each participant had at least 10 years of experience using a mobile phone and spend a minimum of 2 hours using their mobile phone daily. All participants were paid KRW 10,000 per hour (about USD 7.50) after the experiment and an extra KRW 10,000 was paid to the two participants with the highest score

3.2 Apparatus and Environment

We built a prototype (Figure 3a) with a size of 138 mm * 65 mm *12m, which was selected based on the size of the iPhone SE. We used six linear resonant actuators (JAHWA JHV-10R1) in our prototype. The actuators were operated at 120Hz. An application running on an Android phone (Huawei Nova 2i) was developed to record participants' answers. Participants were asked to grab the prototype with their left hand and the Android phone was placed on a table in front of their right hand. There was no visual cue to participants while the experiment was conducted. During the study, the participants were asked to wear a soundproof earmuff to block out the noise caused by the vibrators.

(a) (b)

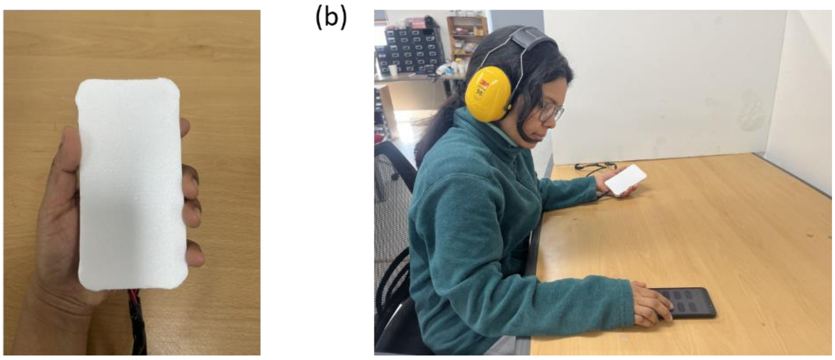

Fig. 3. (a) Prototype for user study. (b) Experiment setup. A participant wearing a soundproof earmuff holding the prototype in her left hand and selecting his answer on the mobile phone with his right hand.

3.3 Vibration Pattern Generation

To prevent participants from guessing the answer based on the total duration of the vibration, we controlled the total generation duration for each digit to be between 2900ms ~ 4000ms.

The vibrotactile flows are generated by simultaneously driving two actuators (VA1 and VA2) with different amplitudes profile [13]. VA1 vibrates with decreasing amplitude across time while VA2 vibrates with increase amplitude across time as shown in Figure 4(a). When there is a sharp turning point or new starting point, a short pause is provided between two flows. Figure 4(b) shows generation of two flows with and without a pause.

For discrete vibrotactile simulations, we calculated the duration for each discrete vibrotactile simulation that fits the total duration to be between the total generation duration we controlled. Each discrete vibrotactile simulation is generated with a 70% duty cycle and additional pause time is added after the off time at the sharp turning points and new starting points. Figure 4(c) shows examples of generating digit 2 and digit 4 with discrete vibrotactile simulations.

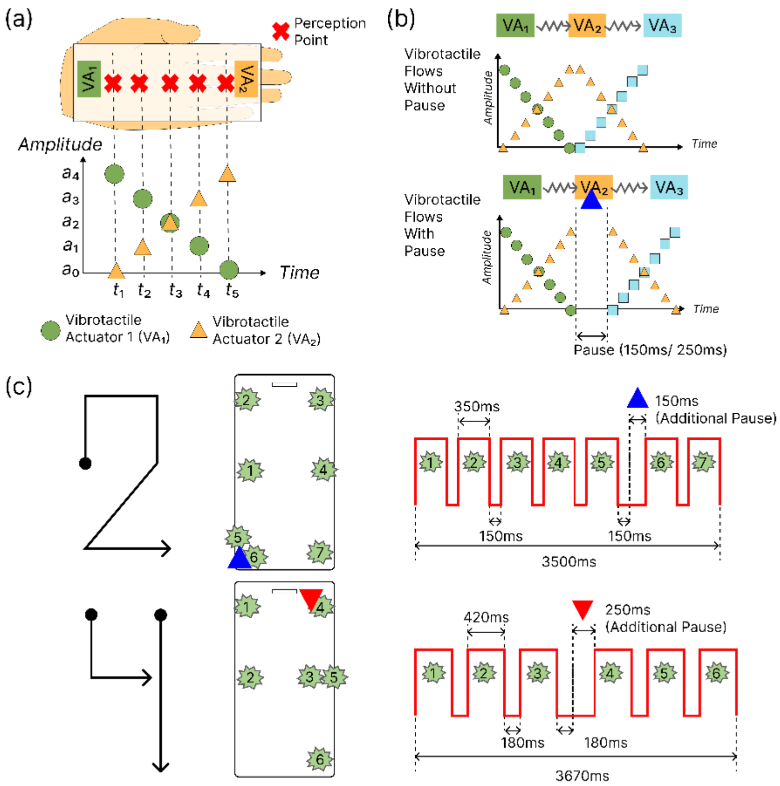

Fig. 4. (a) Generation of vibrotactile flow using phantom sensation. (b) *Top*: Two vibrotactile flows without pause in between. *Bottom*: Two vibrotactile flows with pause in between. (c)Generation of digit 2 and digit 4 with discrete vibrotactile simulations

3.4 Procedure

The user study consists of three sessions for each participant: a practice session for vibration flows generated pattern, a practice session for discrete vibrotactile simulations generated pattern, and a delayed recall test. Each session lasted for about 45 minutes. 7 participants did the practice session for the vibration flows generated pattern in the first session, while the remaining 6 participants did the practice session for discrete vibrotactile simulations generated pattern. The two practice sessions were conducted on the same day with a minimum 6-hour gap between them. The delayed recall test took place three or four days later, depending on participant availability.

Before each practice session started, we verbally explained the vibration patterns and provided graphical illustrations of the patterns, which shows the sequence of the vibrotactile flows or the discrete vibrotactile simulations. There were three sets of trials in each practice session and each set consisted of 30 trials. On each trial, the participant perceived a randomly selected digit and then answered which digit was perceived by selecting their answer on an Android phone. The digit was generated only once for each trial, with no repetition allowed. We provided the correct-answer feedback to participants immediately after each trial. A 10-second break was provided after every trial and a five-minute break was given every 30 trials.

In the third session, we conducted a delay recall test to observe the ability of participants to recall the vibration patterns over time. The participants were tested with 30 trials for each type of vibrotactile sensation. A 10-second break was provided after every trial and a five-minute break was given after the test for the first vibrotactile sensation type. No revision to vibration patterns was provided before the session started and no correct-answer feedback was provided after participants selected their answers.

After the delayed recall test, we conducted a semi-structured interview with participants. We asked the participants to rate the following statements using a 5-Likert scale. Further questions were asked to collect participants' comments and opinions.

Table 1. 5-Likert scale statements in the interview (1-Strongly Disagreed; 5-Strongly Agreed)

	Statement
S1 (F/D)	The vibration pattern for all digits is easy to memorize. (Vibration Flow/ Discrete Vibrotactile Simulation)
S2 (F/D)	The vibration patterns are similar to writing patterns. (Vibration Flow/ Discrete Vibrotactile Simulation)
S3	The pause at sharp turning points and new starting points helps to read the vibrotactile flows generated digits better.
S4	The pause is too short.
S5	The additional pause at sharp turning points and new starting points helps to read the discrete vibration simulations generated digits better.
S6	The additional pause is too short.
S7	The repeated vibration at a sharp turning point helps to read the discrete vibrotactile simulations generated digits better.
S8	The different starting points among the digits help to read the vibration better.

4 Results

We excluded the result from P3 because of her low overall recognition rate. Her results were 30.3% to 36.9% lower than average for vibrotactile flows generated digits and 15.0% to 34.2% lower than average for discrete vibrotactile simulations generated digits throughout the practice sessions. P3 mentioned that she faced difficulty in identifying the exact location of vibrations, attributing it to challenges in grasping the prototype due to her small hand size.

4.1 Experiment Results

Table 2. Experiment results

	Vibrotactile Flow				Discrete Vibrotactile Stimulation			
	Mean	Median	Std.	IQR	Mean	Median	Std.	IQR
Set 1	69.44%	68.33%	18.90%	40.00%	77.50%	75.00%	11.11%	18.33%
Set 2	83.61%	88.33%	14.94%	31.67%	88.33%	90.00%	9.05%	20.00%
Set 3	83.81%	90.00%	16.78%	29.17%	91.11%	91.67%	6.25%	13.33%
Delayed Recall	90.00%	96.67%	14.56%	15.00%	91.39%	96.67%	14.25%	10.00%

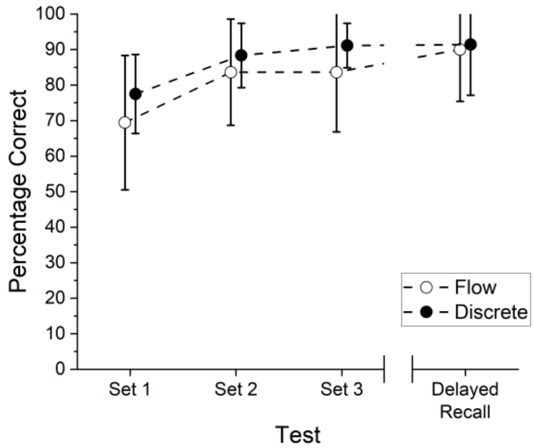

Fig. 5. Mean percentage correct scores. Error bars represent standard deviations.

Table 2 shows the results of our study while Figure 5 shows the trend of mean percentage correct across digits and participants. The mean percentage correct for vibrotactile flows generated digits improved from 69.44% in the first set to 83.61% in the second set and maintained the same in the third set. For the discrete vibrotactile simulations generated digits, the mean percentage correct increased from 77.50% to 88.33% in the second set and gradually increased to 91.11% in the third set. The results of delayed recall test did not drop but improved to 90.00% for vibrotactile flows and 91.39% for discrete vibrotactile simulations.

We performed two-way repeated ANOVA on the percentage correct in each set to analyze the learning rate of the vibration patterns. The learning effect across the three sets of test was significant ($F(2,22) = 25.978$, $p < 0.001$). There is no significant difference between types of vibrotactile sensations ($F(1,22)=3.219$, $p = 0.098$). The interaction term between the two factors was not significant ($F(2,22) = 0.321$, $p = 0.728$).

Figure 6 shows the confusion matrix of results on the delayed recall test. For both vibrotactile flows and discrete vibrotactile simulations, digit 9 has the lowest percentage with 77.8% correct. Vibrotactile flows achieved the highest percentage correct for digit 2 at 97.2%, while discrete vibrotactile simulations performed equally well, with digit 0 and 6 both reaching the same highest accuracy of 97.2%.

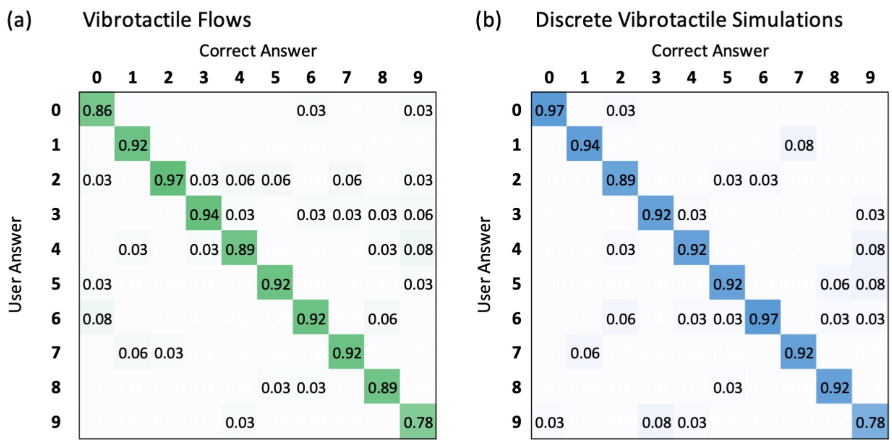

Fig. 6. (a) Confusion matrix for vibrotactile flows generated digits (b) Confusion matrix for discrete vibrotactile simulations generated digits

4.2 Post-Experiment Interview

Figure 7 shows the rating results for statements in Table 1. For the vibrotactile flows generated vibration patterns, all participants agreed to the ease of memorizing (S1(F)) and the similarity of the vibration pattern to writing patterns (S2(F)). While for the discrete vibrotactile simulations generated vibration patterns, two participants remained neutral and one participant disagreed with the ease of memorizing (S1(D)) and the similarity of the vibration pattern to writing patterns (S2(D)).

Among twelve participants, nine found the pause between vibrotactile flows at sharp turning points and new starting (S3) helpful in distinguishing the digits, while three remained neutral. The additional pause between discrete vibrotactile simulations (S5) was generally deemed helpful by the majority of participants in distinguishing digits; however, two participants held a different opinion. Most of the participants (ten out of twelve) disagreed with the statement stating that the pause between vibrotactile flows is too short (S4). Similarly, eleven participants disagreed with the statement regarding the additional pause between discrete vibrotactile simulations being insufficient (S6).

Participants hold different opinions on the helpfulness of the repeated vibration at sharp turning points for discrete vibrotactile simulations (S7) but the majority (nine out of twelve) stand on the positive side. All participants agreed that distinct starting points (S8) helped them to distinguish each digit better.

Besides the factors we considered when designing the vibration patterns, five participants mentioned that the ending points helped them to distinguish digits. While the distinct ending point is being helpful in the recognition of digits, high similarity endings cause confusion. For instance, a few participants also feedbacked that digit 4 and digit 9 are confusing because of their high similarity at the ending, which both have a pause and followed by vibration from top right to bottom right at the ending.

Participants also mentioned that the count of vibrations and duration of each vibration were helpful in reading discrete vibrotactile simulations generated digits. Digit 1 and 7 were created with only three discrete vibrotactile simulations which are less in count and longer in duration for each vibration compared to other digits, setting them apart from other digits. From the confusion matrix for distinct vibrotactile simulations in Figure 6(b), we can observe that participants confused between digit 1 and 7 in some cases but never confused them with other digits.

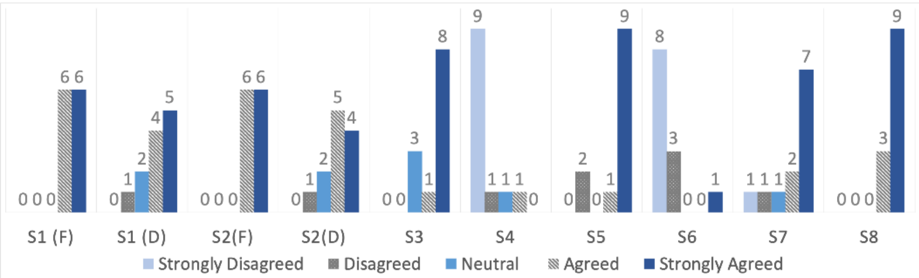

Fig. 7. Rating for statements in Table 1

5 Discussion

5.1 Confusion between Certain Digits

In the post-experiment interview, we received comments on confusion between digit 4 and 9 due to their similarity at the ending (A pause and followed by vibration from the top right to the bottom right). Two participants felt confused when using the vibrotactile flows, another two participants felt confused when using the discrete vibrotactile simulations, and another three felt confused for both. There were also two participants mentioned that they got confused between 2 and 5 for vibrotactile flows due to the similarity in their shape and sequence. Both digits consist of a half-circular shape followed by a pause and a horizontal stroke from left to right.

Although the majority of participants did not think that the pause was too short, but we can observe that participants did not notice the difference in the pausing duration. Digit 4 and 5 have a longer pause for the new starting point (250ms) while digit 2 and 9 have a shorter pausing duration at the sharp turning point (150ms). The pausing duration for sharp turning points and new starting points needs to be optimized to let users differentiate them easily so that users will be less confused.

5.2 Individual Variances in Recognition and Preference

Although in overall, the average recognition rates of discrete vibrotactile simulations generated digits are higher than the vibrotactile flows generated digits, but four participants had a higher top recognition rate for vibrotactile flows generated digits during practice sessions. During the delayed recall test, while other participants had recognition rates with lower than 7% difference between two types of vibrotactile simulations, P1 and P8 had higher recognition rates for discrete vibrotactile simulations generated digits with 26.6% and 20% difference respectively. On the other hand, P13 had a higher recognition rate for vibrotactile flows generated digits with a 30% difference.

In the post-experiment interview, the participants showed difference preferences over the types of vibrotactile simulations. Five participants rated the ease of memorizing vibrotactile patterns generated using vibrotactile flows higher than the discrete vibrotactile simulation, while two participants thought that discrete vibration patterns generated using vibrotactile simulations are slightly easier to memorize. The remaining five participants rated both the same.

5.3 Future Work

Validating Effectiveness of Special Characteristics. In this work, we added a few characteristics, such as sharp turning point and new starting point, in certain digits to enhance recognition. However, as outlined in Section 5.1, that some participants experience confusion when two digits share the similar or analogous special characteristics. This raises the question: did users really recognize the digit, or were they merely guessing based on the special characteristic? The latter scenario could potentially lead to more confusion, especially when more this work is extended to other characters, such as alphabets, where more characters may share the same characteristic. In future experiments, we will test the recognition rate by mixing fake digits with real digits. These fake digits will possess patterns containing the characteristics of the real digit but will differ from the real digits in other aspects. This experiment aims to determine whether users genuinely recognize the digit or merely guess based on specific characteristics.

Application in Real-world Situation. The results of user study showed that the proposed vibration patterns are easy to learn and memorize without requiring high effort from users. However, in real life situation, users usually read more than one digit at once and are surrounded by noise, for example, reading TAG number on a subway. An experiment to evaluate the performance of using the proposed vibrations patterns to read a series of digits in different environment need to be conducted.

Reducing Vibrotactile Actuators Count. In this work, our primary was to assess the learnability and retainability of vibration patterns designed based writing patterns, leading us to refrain from limiting the count of vibrotactile actuators during the vibration pattern design. However, future work could explore the feasibility of creating vibrotactile simulations with the same patterns using only four vibrotactile actuators at the edges, which can be achieved by generating simulations in the middle utilizing Phantom Sensation.

Implementing to Different Types of Devices. We tested the designed vibration patterns using a mobile phone-sized prototype, but the same vibration patterns can be easily implemented to different types of devices, including wrist-worn tactile displays, haptic suits, haptic chairs, and more. Future work could examine the adaptability of the vibration patterns across a spectrum of devices, varying in size and spatial location.

Extending to Alphabets and Other Characters. Currently, we designed the vibration patterns for digits based on writing patterns while the design of vibration patterns for alphabets is not included. However, future research aims to expand this work to include the generation of alphabet characters following writing patterns and potentially explore the feasibility of incorporating certain Asian characters, such as Korean, Japanese, or some Chinese letters. Research towards this direction is ongoing by us.

6 Conclusion

In this study, we proposed two set vibration patterns for digit 0 to 9, which were designed based on writing patterns using different types of vibrotactile simulations. The results confirmed that the proposed vibration patterns are able to convey digits haptically without requiring high effort to memorize and learn the vibration patterns. Writing patterns, as an intuitive and familiar element in our daily life, have a high potential to create intuitive and memorable vibration patterns.

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