EdgeVib: Effective Alphanumeric Character Output Using a Wrist-Worn Tactile Display

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ABSTRACT

This paper presents *EdgeVib*, a system of spatiotemporal vibration patterns for delivering alphanumeric characters on wrist-worn vibrotactile displays. We first investigated spatiotemporal pattern delivery through a watch-back tactile display by performing a series of user studies. The results reveal that employing a 2×2 vibrotactile array is more effective than employing a 3×3 one, because the lower-resolution array creates clearer tactile sensations in less time consumption. We then deployed EdgeWrite patterns on a 2×2 vibrotactile array to determine any difficulties of delivering alphanumerical characters, and then modified the unistroke patterns into multistroke EdgeVib ones on the basis of the findings. The results of a 24-participant user study reveal that the recognition rates of the modified multistroke patterns were significantly higher than the original unistroke ones in both alphabet (85.9% vs. 70.7%) and digits (88.6% vs. 78.5%) delivery, and a further study indicated that the techniques can be generalized to deliver two-character compound messages with recognition rates higher than 83.3%. The guidelines derived from our study can be used for designing watch-back tactile displays for alphanumeric character output.

ACM Classification Keywords

H.5.2. Information interfaces and presentation: User Interfaces: Haptic I/O.

Author Keywords

Wrist-Worn Tactile Display; Alphanumerical Character Output; Spatiotemporal Vibrotactile Pattern.

INTRODUCTION

As a variety of wrist-worn devices, *e.g.*, smartwatches, have been introduced to the market, employing a wrist-worn tactile display (WTD) to deliver information through eyes-free interaction has become a viable approach to supplementing the limited visual display area. A single vibrotactor is the most basic type of WTD, enabling producing different durations of vibration as a mean of notification, which can be generalized as *"Morse-like"* messages [22]. However, because these

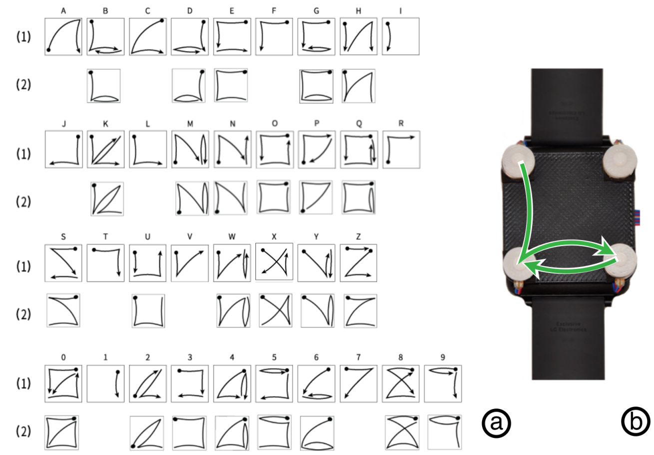


Figure 1. (a) EdgeVib$^{(2)}$ is a set of spatiotemporal vibration patterns for wrist-worn tactile displays that are based on EdgeWrite$^{(1)}$. Alphanumeric characters are presented through multiple directional vibrotactile patterns. (b) A wrist-worn 2×2 tactor array was used in the user studies. The green arrow illustrates the vibrotactile EdgeVib pattern *"b"*.

temporal signals are relatively more difficult to interpret and memorize than spatial ones, the application of a single vibrotactor WTD is limited to providing notifications in a limited numbers of categories.

Recently, researchers have sought more intuitive solutions for rendering more expressive spatiotemporal patterns to achieve effective communication. For this challenge, previous research has either extended the WTD to a 2D vibrotactile array [13], or used *skin drag displays* [11] to produce stronger skin tactile sensations than vibrotactile displays can. Although these approaches can achieve satisfactory accuracy for simple symbols (*e.g.*, 89% on 12 directional patterns [13] and 99% on circles with other parameters [14]), the recognition rates drop significantly when applied to more complex spatiotemporal patterns (*i.e.*, 57% on six Graffiti characters with six directional patterns under vibrotactile conditions, and 76% for the aforementioned 12 patterns under skin-drag conditions [11]). These results lead us to the following question: Shall we keep pursuing higher resolution of tactile displays to deliver more expressive patterns?

The *expressiveness* of a WTD is determined by two factors: 1) the number of tactile signal patterns that a WTD can deliver, and 2) the clarity of tactile signals that humans can perceive and decode. Although a greater number of signals can be delivered using a high-resolution WTD, the delivery also requires more time because of the long activation duration of actuators. Moreover, because of the limited bandwidth of human tactile perception in the dorsal side of the forearm [17], subtler features of tactile signals may be difficult for humans to discriminate. Due to the conflicts of the two factors, continually increasing the resolution of a WTD might not be the ideal solution for this challenge. Hence, in this work we seek an effective way for delivering expressive alphanumerical characters that enables humans to easily perceive, decode, and recognize them.

EdgeVib: Multistroke Alphanumeric Patterns

This paper introduces EdgeVib (Figure 1), a set of multistroke alphanumeric patterns based on EdgeWrite [24]. EdgeWrite is a system of unistroke pattern designs that represents characters through a sequence of corner points on a square, leading to patterns consisting of only straight and diagonal *strokes*. Compared with the Graffiti, EdgeWrite requires a shorter learning period [23]; moreover, its stroke-based representation is more compatible with any array of $N \times N$ vibrotactors, where $N>2$. Each stroke can be rendered by sequentially vibrating the tactors in-between the corresponding corners, thus the patterns can be rendered through the traversal of strokes. Nonetheless, since rendering EdgeWrite characters through this method may result in different signal lengths, ranging from two to six strokes as shown in Figure 1, the perceptional and memory loadings of tactile sensation should thus be considered to prevent degradation of recognition rates due to the limited capacity of human information processing.

On the basis of *chunking* [16], a mechanism that facilitates human memory by binding individual pieces of information together, and the results of a series of exploratory user studies, we subdivided each unistroke EdgeWrite pattern that is longer than four vibrations into multiple 2- or 3-vibration patterns as chunks, and displayed them sequentially to help the users recognizing the alphanumerical patterns. The performances of EdgeVib was evaluated through two user evaluations. The first 24-participant evaluation revealed that EdgeVib demonstrated reliable recognition rates for both alphabets (85.8%) and digits (89%) delivery, which not only show that the subdivision strategy effectively enhances the overall recognition accuracy, but also show that users who have learned EdgeWrite can readily recognize EdgeVib patterns. The second 12-participant evaluation further suggested that EdgeVib can be generalized to deliver 2-character compound messages (*e.g.*, **M2**: *"**2** unread **M**ails"*) to enrich device applications.

The main contributions of this work are two-fold: 1) The development of EdgeVib, a novel system of multi-stroke vibration patterns for delivering alphanumeric patterns. The multistroke design successfully retains both favorable expressiveness and recognition rates simultaneously. 2) The guidelines derived from our studies can be used for designing WTDs for alphanumeric character output.

RELATED WORK

A single vibrator has been used to deliver messages through utilizing different rhythms that carry Morse code [22] or other non-visual information [3]. This method can also enrich the interactivity of wearable devices, such as enabling eyes-free interaction for a wristwatch [18]. To enhance expressiveness, Lee *et al.* [13, 14] have used three vibrotactile units with different parameters to produce 24 distinguishable patterns, and a 4×4 array on the back of a wrist-watch to transfer directions and shapes, such as letter **L**. For non-wearable uses, Yanagida *et al.* [25] delivered alphanumeric patterns with approximately 90% accuracy by applying nine vibrators on a chair. Yatani *et al.* [26, 27] have attached vibration motor arrays to the back of mobile phones for information transfer.

Previous studies have been conducted to determine the suitable spatial configurations of vibrotactile displays worn on the forearm, such as by using a 3×3 array [17] and a 1D 12-tactor array [7]. Different parameters, such as frequency and intensity, have also been examined [4, 9]. Lee *et al.* [13] reveal that the tactor type, sensory saltation, and locus of stimuli can affect the performance of information transferring. Additionally, vibrotactile tasks across various body parts have also been the subjects of numerous experiments. For example, Sofia *et al.* [21] compared the localization accuracy at different locations on forearm, palm and thigh. Chen *et al.* [6] and Matscheko *et al.* [15] have also investigated the human capability to localize vibrotactile stimulation on both dorsal and volar sides around the wrist. OmniVib [1] indicated that tactile displays can benefit from using tactor array of lower resolution to help users recognize the separability of different vibration points. It motivates us to design expressive tactile messages on low-resolution tactile displays.

Researchers have also attempted to create tactile displays other than vibrotactile ones. On the basis of previous studies on delivering tactile messages by stretching and pulling the skin [2, 5], skin drag displays [11] use a wrist-worn draggable tacton to deliver 12 patterns. However, how the pattern set can be extended to a more expressive one, such as alphanumeric characters, remains unclear. Gesture Output [19] sends expressive alphanumeric characters nonvisually to users by dragging their thumb writing to write Graffiti patterns across a mobile touchscreen device. Such an approach has opened the possibility of conveying expressive alphanumeric messages on a small contact area and motivated us to develop EdgeVib for WTDs.

EXPLORATORY USER STUDIES

On the basis of common apparatus and procedures, three user studies were conducted to determine the fundamental principles and guidelines of designing an effective WTD for displaying alphanumerical patterns.

Common Apparatus: We implemented a wrist-worn watch-shaped device with a 3D printed plate of a 40×40 mm^2 area, and choose 10-mm Precision Microdrive 310-113 Eccentric Rotating Mass (ERM) vibration motors to generate tactile stimulus. Following a previous study [12], we further attached a 4-mm-diameter cylindrical plastic tip to each tactor to produce a clearer signal from using a smaller contact area. A damping sponge was placed between each tactor and the plate to isolate the vibration (Figure 2c). Two different resolutions of tactor arrays (*i.e.*, 3×3 and 2×2, which had a tip-to-tip distance of 1.5 cm and 3 cm, respectively), were employed (Figure 2a and 2b). Following the suggestions of

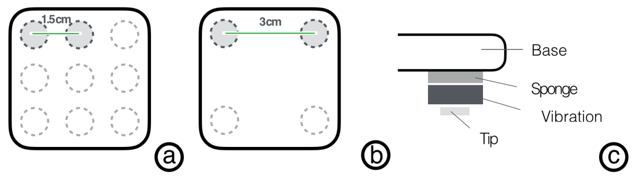


Figure 2. Hardware prototype. (a) 3×3 layout. (b) 2×2 layout. (c) Overview.

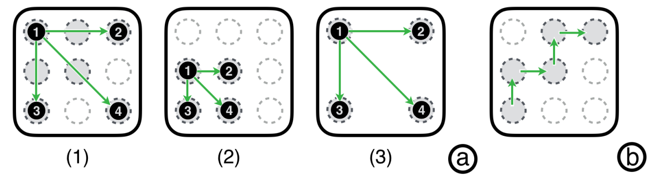


Figure 3. (a) Linear vibration patterns tested in Study 1. (b) Example of a complex pattern that can be generated only by the 3×3 layout.

previous work [11] and the results of our six-user pilot study, we determined that a running vibration period of 500 ms interleaved with gaps of 100 ms would yield the optimal result. An Arduino is used to control a multiplexer, which controled the DC power supply for activating the motors.

Common Procedures: We recruited participants from various departments in our university, with different participants recruited in each study. Only right-handed participants were recruited, and the prototype device was all worn on their left hand. During the study, the participants were asked to wear a headset playing pink noise to block out the sounds caused by the vibrators. In all the studies, the participants were tasked with recognizing a set of vibrotactile patterns. Each study includes a *training session* and a *testing session*, and took less than 60 minutes to complete. In the training session, the participants were asked to perceive a predefined set of tactile patterns delivered by our prototype device. Each pattern appeared for a fixed number of times and the order that the patterns were displayed was counterbalanced. In each trial, participants were then asked for the displayed pattern. After they gave their answer, the screen prompted the actual answer and thus the participants could proceed to the next trial. The participants could ask to repeat the questions as many times as necessary if they were not confident of their answers. In the testing session, the set of tactile patterns and procedure were identical to the training session, except that in each trial, each pattern was displayed only once before the participants were asked for their answers. In this session, a short break was provided after every 20 trials.

Study 1: Optimal Resolution for WTDs

This study aimed to investigate the optimal resolution for vibrotactile displays with a *watch-back configuration*. A total of 12 participants (8 female; age: 20∼25 years) were recruited and divided equally into two groups according to low- and high-resolution displays.

Procedure: For the two resolutions, the participants were asked to perform different tasks. For the 3×3 layout, the tasks were to recognize the following patterns: 1) corner-to-corner linear patterns containing three vibrating points (Figure 3a(1)), and 2) corner-to-corner linear patterns created by four neighboring actuators (Figure 3a(2)). On the 2×2 layout, the task was to recognize the corner-to-corner linear patterns containing two vibrating points (Figure 3a(3)). The training and testing session are described in Common Procedures section. All patterns were vibrated four times in the training phase, and five times in the testing session, and the sequences were displayed under counterbalanced conditions. In total, data were collected for 720 trials (12 patterns×5 rounds×12 participants) for linear pattern recognition tasks.

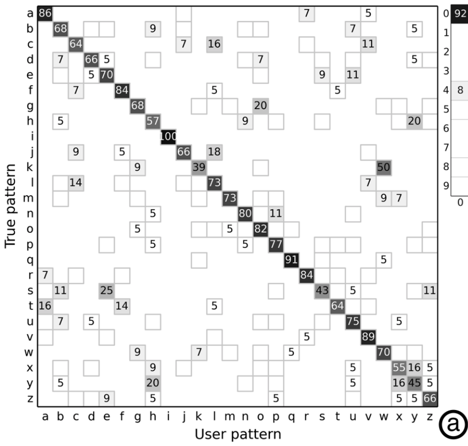
Results: The accuracy of recognizing corner-to-corner lines on the 2×2 layout was 79.3% (SD = 10.1%), whereas the accuracy of the 3×3 layout was 71% (SD = 9.1%). A pairwise t-test revealed that the difference was significant ($t(11) = 3.59$, $p < 0.01$), indicating that the 2×2 layout can deliver clearer linear patterns of the same length. However, the recognition rate for shorter linear patterns on the 3×3 layout (45%, SD = 13%) was significantly lower than that of the other layout.

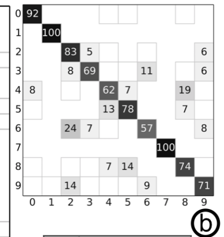
Discussion: On the basis of the results, we suggest that the 2×2 layout is more effective than the 3×3 one because of the following reasons: 1) The recognition rates of the 2×2 layout were higher than those for the 3×3 one, implying that *placing tactors apart from each other by a distance larger than the minimal gap* would be the more effective strategy than *spacing them with shorter distance* for pattern recognizing tasks. 2) Short linear patterns are very difficult to recognize (45%). Besides, combining short linear patterns to form a longer one may lead to relatively complex patterns, such as 3b), which is inefficient to deliver. In consideration of simplicity, we argue that the 3×3 layout possesses a set of effective tactile patterns equivalent to the set for the 2×2 layout, which is reduced to corner-to-corner linear patterns. 3) For the rendering time, the 2×2 layout is more efficient than the 3×3 one. For example, the 2×2 layout can render a linear pattern by using only two vibrations and one gap whereas the 3×3 layout requires three vibrations and two gaps. Overall, the 2×2 layout outperforms the 3×3 layout in terms of both recognition rate and time efficiency. In addition, drawing recognizable Graffiti-based patterns is not a practical approach because those patterns are too fine-grained to be reliably recognized. Thus, we propose to use EdgeWrite symbols as the delivered patterns.

Study 2: Recognizable Length of EdgeWrite Patterns

This study was designed to facilitate determining the recognizable length of EdgeWrite patterns rendered on the 2×2 layout. A total of 24 participants (13 female; age: 21∼29 years) were recruited and evenly assigned into two groups who received trials of digit and alphabetic patterns, respectively. Both groups completed the same study procedure.

Procedure: In addition to the training and testing sessions, a 15-minute learning session was included in this study to familiarize the participants with the EdgeWrite patterns. A tutorial program was created to prompt the participants with one alphanumeric character at a time. The participants were then requested to type in the correct sequence of the prompted character by using EdgeWrite patterns. After this session, a brief test was performed to ensure that each participant could memorize the EdgeWrite patterns correctly. In the training session, all EdgeWrite patterns were displayed twice in a random order. Typically, the training sessions were completed





Vib	Letters
2	i
3	a c f j l r t v
4	b d e h n p s u x y z
5	g k m o w
6	q

c

Figure 4. Results of exploratory user study 2. (a) Alphabet letters. (b) Digits. (c) Vibration counts of the alphabet letters.

within 15 minutes. In the testing session, there were a total of 600 (5 times×10 patterns×12 users) and 1,248 (4 times×26 patterns×12 users) trials for the digit and alphabet patterns, respectively. The test patterns appeared in a counterbalanced order, and the participants took breaks after every 20 trials. The testing session was typically completed in less than 30 minutes, and a post-study interview was conducted for each participant after the entire process was completed.

Results: Figure 4 shows the confusion matrices for recognizing alphabet letters and digits. We analyzed the results by first excluding one subject who was an outlier because of her low overall alphabet recognition rate (32.7%), resulting in overall recognition rates of 11 participants to 70.7% and 78.5% of alphabetical and numeric patterns, respectively. Subsequently, all answers for the letter "**i**" and "**q**" are also excluded from the analysis because of their unique (two and six) vibration counts, which made them easier to distinguish compared with the other patterns. For the remaining eight 3-vibration (76.1%), eleven 4-vibration (63.8%) and five 5-vibration (66.4%) patterns in the test set, a one-way repeated measured ANOVA revealed a significant effect between the vibration count and recognition rate ($F(2, 20) = 8.42$, $p < 0.01$). Pairwise t-tests with Bonferroni's correction further indicated that the recognition rate of 3-vibration patterns was significantly higher than those of both the 4- and 5-vibration patterns (both $p < 0.05$).

Discussion: According to the results of Study 2, one can see that in general both 2- and 3-vibration patterns could be regarded as recognizable and thus more favorable for application in WTDs. However, the results may be valid only for EdgeWrite patterns, because the tested set share uneven numbers of data. Some characters with relatively high vibration counts, such as the letter "**q**" and digit "**0**", also achieved very high recognition rates. This phenomenon was clarified by the post-study interview, because most of the participants reported that sometimes they judged a pattern according to the number of the vibrations instead of the spatial distributions. For example, because only the letter "**q**" has six vibrations among all the alphabetic characters, it was easily distinguished. Such *counting vibrations* behavior also was discussed by Pasquero *et al.* [18].

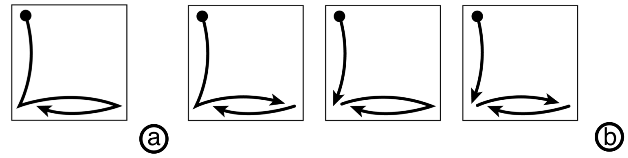


Figure 5. (a) Original EdgeWrite pattern of the character "*b*". (b) Three possible segmentations.

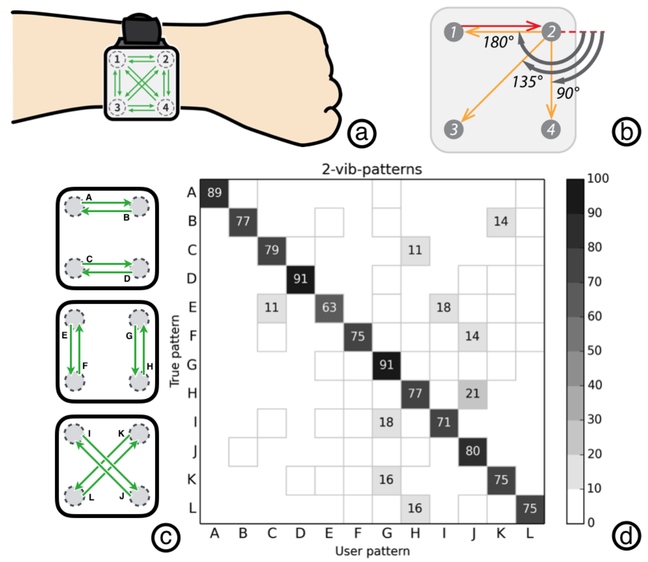


Figure 6. (a) 2-vibration patterns tested in Study 1. (b) Possible angles of a 3-vibration pattern. (c) Proximal lines: A-D; lateral lines: E-H; oblique lines: I-L. (d) Results of exploratory user study 3.

Study 3: Optimal Segmentation of EdgeWrite Patterns

This study was designed to facilitate determining the optimal strategy of segmenting the EdgeWrite patterns. A total of 12 participants (8 female; age: 21∼25 years) were recruited.

For long tactile patterns such as the EdgeWrite characters, there are many possible approaches to segmenting them (Figure 5). Because we had determined that the patterns containing two or three vibrations are easier to recognize (Study 2). Study 3 was aimed at investigating the effectiveness of the 2- and 3-vibration strokes and their influences on the recognition rates. From the results of Study 1, we determined that the mean recognition rate of 2-vibration patterns was 79.3% (Figure 6d). Therefore, the following experiment was conducted to investigate the accuracy of 3-vibration patterns, which are actually two lines combined together by a turning point. The three possible turning points were 90°, 135°, and 180°, as shown in Figure 6b.

Procedure: Similar to Study 1, a training session and a testing session were conducted. During the training session, each of the 36 3-vibration patterns was shown once randomly. In the testing session, all 36 vibration patterns were tested three times in a counterbalanced order. A short break was provided after every 20 trials. Hence, there were a total of 1,620 trials (36 patterns×3 rounds×15 participants) in this experiment.

Results: The mean recognition rate of the 3-vibration patterns in this experiment was 79% (SD=10.6%), which approximated that of the 2-vibration patterns (79.3%) in Study

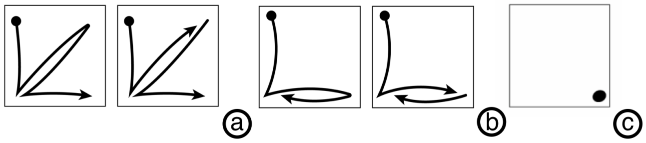


Figure 7. Examples of EdgeVib. (a) The letter "*k*": two 3-vibration patterns; and the letter "*b*": a combination of a 3-vibration and a 2-vibration patterns. (b) The delimiter was a short (200ms) vibration at the bottom-right corner.

1. Although they have similar accuracies, the 3-vibration patterns were more preferable because they were more efficient in terms of rendering time.

Discussion: After further analysis of the 2-vibration pattern results, among all the errors, 59% were determined to be due to the confusion of differentiating between lateral (*i.e.*, lines E-H in Figure 6c) and oblique lines (*i.e.*, lines I-L in Figure 6c), which was significantly higher than that caused by the other error types ($p < 0.01$). This finding that: "*lines in lateral (i.e., across the arm) and oblique (i.e., 45° cross the arm) orientations are easily confused with each other*" is consistent with the findings of previous studies [8, 10], that have indicated that tactile sensations in the lateral orientation are considerably greater than those in the proximal orientation (*i.e.*, along the arm; lines A-D in Figure 6c). Proximal lines are easier to perceive because no lateral movement is involved. However, to differentiate lateral and oblique patterns, the users must carefully sense whether there is a proximal component in the pattern, which makes recognition harder.

DESIGNING EDGEVIB PATTERNS

On the basis of the previous findings, we derived a novel set of multistroke tactile patterns based on EdgeWrite. The design principles are as follows.

1. Apply as many 3-vibration strokes as possible. Because delivering 3-vibration strokes is more time-efficient, we first divided the strokes into multiple 3-vibration patterns, such as letter "**k**" (Figure 7a). Each stroke started at the last vibration point of the preceding stroke.

2. If a pattern cannot be totally subdivided into 3-vibration strokes, include 2-vibration strokes based on the expected combinatorial accuracy. Based on the individual accuracies obtained from Studies 1 and 3, we multiplied every possible combination to obtain the expected combinatorial accuracies. For example, the letter "**b**" could be divided into a 2-3 or 3-2 stroke combination. Accordingly, we multiplied the accuracy of the first stroke by the accuracy of the second stroke to obtain the expected combinatorial accuracy of each combination, and then selected the combination with the higher expected accuracy (*i.e.*, the 3-2 stroke shown in Figure 7b).

3. A delimiter is required in multistroke design. Participants in a three-person pilot study reported that issuing a signal to clearly indicate the end of a pattern is imperative. Accordingly, we used a 200-ms vibration on the bottom-right corner as a pattern delimiter (Figure 7c). Because 200 ms is shorter than the typical vibrations [20] and the bottom-right corner is not the beginning of any EdgeWrite patterns, this delimiter can be easily recognized.

PERFORMANCE EVALUATION

In this section, two possible usages of EdgeVib were evaluated: 1) single character output, and 2) compound messages.

Evaluation 1: Studying EdgeVib Characters

To compare the accuracies of the original EdgeWrite patterns, single characters were tested. Alphabet-only messages (*e.g.*, "T" for tweet, "R" for raining, "U" for Uber-coming) are effective methods of delivering symbols that are too complex to deliver in their full forms, because of the directness of semantic mapping.

Participants: 24 participants (12 female, age: 21∼25 years) were recruited and divided into two groups. Each group was tasked with receiving different patterns: one group received digits, and the other group received alphabets letters.

Procedure: The procedure was similar to that used in Study 2, which included an EdgeWrite learning session, training session, and testing session. It is worth noting that, in the EdgeWrite learning session, what participants practiced and learned were the original unistroke EdgeWrite patterns. The only difference between this Evaluation 1 and User Study 1 was that the participants were told to expect that the patterns will be divided into *multiple strokes*, with the order of vibrations remaining unchanged. The whole process required less than 60 minutes to complete, the same as Study 1, and an interview was conducted after the process.

Results: Figure 8 shows the confusion matrices for recognizing alphabet letters and digits. The mean recognition rates were 88.6% (SD = 10.4%) for digits and 85.9% (SD = 6.3%) for alphabet letters. A student's t-test revealed that the multistroke EdgeVib achieved significantly higher recognition rates than the original unistroke EdgeWrite did for both alphabet letters (85.9% vs. 70.7%, $p = 0.005 < 0.01$) and digits (88.6% vs. 78.5%, $p = 0.038 < 0.05$). Most of the participants reported that they recognized the patterns from the combination of strokes; some of them further reported that, despite their failure to identify certain strokes because of a lack of attention or an unclear sensation, they could still recognize the patterns based on the remaining strokes that they successfully perceived. These results support our assumption that dividing unistroke patterns that containing vibrations longer than the effective length into multistroke ones can enhance the overall accuracy.

Evaluation 2: Studying Compound Messages

To extend the range of expressiveness, employing compound messages, *i.e.*, combination of a letter and a digit, is a simple and effective approach. Compound messages can be useful for delivering semantic information involving quantities. For example, "**m5**" could indicate "*five messages*". The letter and digit were distinguished by a delimiter.

Because all possible compound messages form such a large test space that they cannot be exhaustively tested, we formulated a reasonably sized test space by generating two different groups of testing messages: 1) the four alphabetic letters of the highest accuracies (**a**, **d**, **i** and **n**) combined with the digits

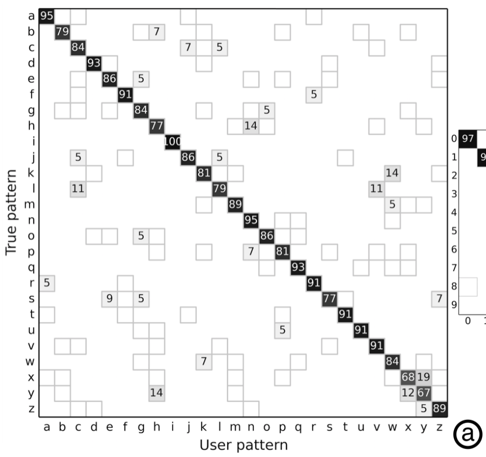


Figure 8. Results of Evaluation 1. (a) Alphabet letters. (b) Digits.

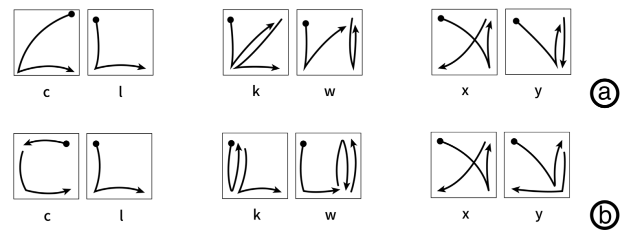


Figure 9. (a) EdgeVib character pairs that are prone to being misrecognized. (b) Alternative EdgeVib patterns that eliminate the ambiguity caused by lateral and oblique lines.

of **1**-**9**, and 2) the four alphabetic letters of the lowest accuracies (**c**, **p**, **x** and **y**) combined with the same nine digits. The results obtained from these two groups provided a reasonable estimate of the upper and lower bounds of the recognition accuracies for most compound messages.

Participants: 12 participants (six female, age: 22∼25 years) were recruited and evenly assigned to two groups who received trials of the four highest-accuracy alphabet letters and the four lowest-accuracy alphabet letters, respectively.

Procedure: The procedure was similar to that for Evaluation 1, with the only difference being that only the preselected set of test characters were shown to the participants in the training session. In total, 1,080 trials were conducted for each group (4 letters×9 digits×5 rounds×6 participants).

Results: The four highest-accuracy letters (Group 1) achieved a mean average accuracy of 89% (SD = 9.7%), whereas the four lowest-accuracy letters (Group 2) achieved 83.3% (SD=11%). The between-groups difference was statistically significant. The results indicated that choosing any four alphabet letters in combination with the digits 1-9 to compose compound messages should result in an accuracy level from 83.3% to 89%, which further confirms the feasibility of delivering compound messages.

LIMITATIONS AND FUTURE WORK

Hardware Prototype: The inclusion of conventional ERM actuators in our prototype device not only ensures the replicability, but also made the device readily mobile. However, a drawback of ERM actuators is that they have a long response time (30∼60 ms) and limited expressiveness (*i.e.*, binary state), which impeded us to further investigate the limit of human perception. Future work should consider using more responsive actuators that have shorter response time to explore and exploit the unused design space.

Confusion between Lateral and Oblique Orientations: Differentiating line segments of lateral and oblique orientations presented in the patterns of both EdgeWrite and EdgeVib is difficult. Figure 9a illustrates several pairs of EdgeVib characters that are easily confused with each other because of this problem. For example, the letters "**x**" and "**y**" merely differ in their last line segments, which are of oblique and lateral orientation, respectively. A possible solution to this problem is to alter the orientations of ambiguous line segments to create more differentiable patterns. Take the letter "**c**" as an example, a designer can either apply an alternative writing sequence proposed in the original EdgeWrite design [24], or escaping the design of the original EdgeWrite patterns. Figure 9b shows several potentially more effective alternative EdgeVib patterns corresponding to those shown in Figure 9a. Although such modifications may increase the total signal delivery time, they may be beneficial for reducing the misrecognition rates with the other pattern. Future work should also consider other pattern designs to more effectively resolve the confusion between lateral and oblique directions.

Real-World Scenario and Multi-Tasking: Our studies were conducted in a controlled laboratory environment where users remained in a sitting posture and were presented with only the single task of recognizing tactile patterns. Thus, potentially lower accuracies may exist in more complex real-world situations, such as recognizing patterns while moving and multitasking. We expect future work testing the performance of EdgeVib in a real-world settings to understand the applicability of this techniques in our daily life.

CONCLUSION

This paper presents an effective solution for displaying alphanumeric characters, *EdgeVib*, which is a system of multitorke vibration patterns based on EdgeWrite for application on WTDs. EdgeVib can be rendered on a relatively low-resolution WTD, comprising only four actuators. The results of our exploratory and evaluation studies reveal that the multistroke design of alphanumeric patterns supported by EdgeVib can be easy for WTD users to learn and recognize, and the guidelines obtained from the studies were also proven to be useful for alleviating the perceptional and memory loadings of the users. The results may be useful for future researchers in designing more expressive WTDs.

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