A Comparative Evaluation of Mechanical Vibration and Ultrasonic Vibration on Smartphones in Tactile Code Perception

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ABSTRACT To improve touchscreen accessibility, it has been proved efficient to integrate tactile feedback into touchscreen devices. Two typical techniques can be used to offer tactile feedback on smartphones, namely, *mechanical vibration* (MV) and *ultrasonic vibration* (UV). However, (a) whether MV and UV are equally perceived and evaluated on usability is unknown, and if not, (b) which technique/feedback provides better usability and satisfaction. In this study, a comparative user study was conducted to evaluate user performance on tactile codes perception generated by MV and UV techniques. 10 tactile codes were designed using the two techniques, and 16 sighted and 5 visually impaired people were invited to take part in a tactile code perception experiment. Tactile codes perception accuracy, response time, and satisfaction on the MV and UV were recorded during the experiment. The experimental results show that the user perception performance of MV was significantly better than UV for both sighted and visually impaired participants. Participants obtained an accuracy approximately 3% higher, with the response time at least 3 s faster, and user satisfaction significantly higher (6.1 vs. 4.6 on a 7-point Likert rating scale) when using MV. Both sighted and visually impaired participants assessed MV with a higher preference over UV. Our results suggest that MV fits better to applications that require precise tactile code perception, for which UV may not be as suitable due to its lower recognition efficiency.

INDEX TERMS Vibrotactile, ultrasonic vibration, tactile interfaces, touchscreen interaction, empirical studies.

I. INTRODUCTION

Touchscreens offer intuitive and direct input for mobile inter-actions. However, most information is presented to the user through the visual channel and the user is required to focus on the screen and use finger touch on graphical icons to perform a task. When the visual channel is occupied by other tasks, sparing extra visual attention to touchscreen interactions is an inconvenience.

To improve the usability of touchscreens and reduce the cognitive load on the visual channel, manufacturers have invested substantial efforts in acquiring new technologies to produce various types of tactile smartphone feedback. For

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example, most smartphones offer *mechanical vibration* (MV) motors that provide vibrational tactile feedback. Vibration on/off patterns can be used to reproduce surface textures [1], [2] and convey various information in different usage con-texts, such as improving typing performance on a virtual keyboard [3], counting the number of vibrations to access application functions fast and invisibly [4], and adopting vibration feedback to present Braille codes on a mobile device for visually impaired users [5], [6]. However, vibration sim-ulates the entire palm by vibrating the entire device, which may not be appropriate in some circumstances, such as when the touchscreen is used by only one finger [7].

Another emerging technique is *ultrasonic vibration* (UV), which utilizes friction modulation methods based on the squeeze film air effect to provide a dynamic friction control

on a touchscreen. Devices that employ this technique are already available, such as Fujitsu haptic tablet [8] and the open-source TPad project [9]. Intuitively, these techniques provide distinct tactile sensations through which the feedback is produced only on the touching fingertip rather than the entire device. Hence, UV can provide specialized and less disturbing tactile feedback on the touchscreen. For example, it can simulate the bumpy surface of crocodile skin or the strings of a zither while the user's finger slide on the touchscreen [10], [11]. Furthermore, tactile textures can be rendered with various densities [12], [13], and the touching of textures can be simulated to provide physical surface sensations on a touchscreen [14]. However, in UV, feedback is only generated when a finger motion is detected on the touchscreen.

Clearly, the MV and UV increase touchscreen interaction channels [15], [16], but they are different and each has advantages and disadvantages, which are important design elements that deserve more formal and rigorous studies in academia and industry. However, the literature on human-computer interaction (HCI) provides limited information on the effects and characteristics of MV versus UV in tactile perception, giving rise to the following research questions for investigation:

- Are MV and UV feedback types the same or different in users' tactile perception?
- What is the tactile perception difference or similarity between the two feedback types regarding performance?
- Is one type of tactile feedback more effective than the other in providing users with a greater sense of control and satisfaction?

Generally, quantifying the difference between MV and UV can provide useful guidelines for tactile interface design. To the best of the author's knowledge, limited effort has been done in the HCI research community to address these pressing questions. Studies on the interface design of tactile code perception such as Braille reading exist, which were designed with MV [6], [17], or UV [5]. However, these studies barely focused on the performance differences between the two types of feedback.

We set out to conduct the first comparative investigations between MV and UV in tactile code perception. An ISO 9441-11 usability study was conducted and a statistical analytical approach was adopted to evaluate tactile perception performance. Tactile code perception is designed with directional gestures and dynamic tactile feedback using vibration and friction, respectively.

II. RELATED WORK
A. CHARACTERISTICS OF TACTILE FEEDBACK
Mechanical vibration (MV) actuator technology mainly includes eccentric rotating mass (ERM) motors and linear resonant actuators (LRA). The ERM motors are the most popular technologies in mobile devices, offering strong amplitude vibration that could vibrate the entire device.

TABLE 1. Characteristics of the two types of tactile feedback.

Feedback	Advantage	Disadvantage
MV	- Strong feedback - Passive and active touch	- Noisy - Vibrates the entire device - Relatively slow response
UV	- Feedback only on fingertips - Offers density of textures - Quick response	- Only active touch feedback

Their weaknesses lie in the relatively long actuating time (50 – 100 ms [18]) to generate vibration and the loud working noise threatening individual privacy. As for the LRA technique, its advantages are shorter actuating time (typically 40 – 60 ms [18]) and lower working noise than ERM. However, LRA is slightly more localized in that the vibrations are only perceptible nearby the actuator, thus they can hardly offer a complete tactile feedback solution for touchscreen devices. For example, iPhone, besides an LRA adopted on Home Button for simulating physical push-button feedback, still integrated an ERM motor inside the device for cases like notifications.

Ultrasonic vibration (UV) actuator technology uses dynamic friction control to implement a tactile textured surface on the touchscreen. Piezoelectric actuators are employed to generate ultrasonic frequencies of vibrations on touch surfaces so that a reduction in friction between the sliding finger and surface can be created via the effect of squeeze film [19]. The advantage of ultrasonic actuation techniques is that they could provide sophisticated feedback to the fingertip rather than the entire hand as provided by mechanical actuators. Besides, the piezoelectric actuators take the shortest actuating time (approximately 1 ms [18]) to reach their work frequency. Therefore, UV is the most promising technique to be integrated into touchscreen devices. The TPad phone is one of the most successful UV integrated products in the smartphone market. Another technology less common on the smartphone market is electrostatic vibration (EV), which uses electrostatic force to increase the friction between finger and surface by electroadhesion [20]. However, it requires a high voltage (around 120 V) that can hardly be implemented in a smartphone device.

The characteristics of MV and UV tactile feedback for smartphones are summarized in Table 1.

B. TACTILE PATTERNS AND PERCEPTION
One of the fundamental factors in tactile interaction design is the appropriate tactile patterns (or tacton) that can be discriminated by users and used to convey different information.

On smartphones, the tactile patterns are typically designed by varying the stimulus duration, that is, the on/off feedback switching paradigm (or adjusting the sizes of low- and high-friction zones in UV frictional surfaces) to convey information. Tactile patterns can be further manipulated by multiple

dimensions, including intensity, frequency, duration of a tactile pulse, rhythm, and spatial location.

For example, Saket *et al.* [21] proposed combining different MV durations (duration of vibration for 600 ms or 200 ms) to code tactile patterns and reported a high accuracy (95.8%) recognition of four patterns with each stimulus duration of 4,500 ms. Furthermore, Rekik *et al.* [12] reported a 75% accuracy in different sizes of low- and high-friction zones in pattern identification, with a mean of 7.48 s of identification time on a UV frictional surface.

Defining an appropriate duration of tactile pulse to distinguish the number of stimuli is another way to design tactile patterns. For example, Philippi *et al.* [22] examined the interstimulus interval (ISI) in temporal numerosity judgment. They studied different ISIs (20 ms to 320 ms) and suggested that larger ISIs (160 and 320 ms) tend to obtain a good perception accuracy. Furthermore, Liao *et al.* [4] reported that a minimum of 25 ms of vibrations and 170 ms interval with a 3-beats-per-chunk design could achieve a good perception accuracy and is efficient for implementing counting techniques on smartphones. Their results have been adopted in designing counting interfaces in mode selection and PIN entry applications [4], [23].

By quickly altering the states of stimuli, that is, on/off or low/high friction while users move their fingers across the active surface, we can simulate roughness or bump sensations [12], [13], [24], which is also a way of designing tactile codes. In this method, the stimuli strength can be typically valued using the magnitude estimation method in which users provide an empirical value of the stimuli [25], and then a clustering algorithm, such as hierarchical clustering [26], is used to group stimuli to convey different code information.

Another aspect is leveraging surface haptics for simulating graphic patterns such as lines, geometric shapes, and contour-based images on a vibrating touchscreen [27]–[29]. Experimental results showed that visually impaired people could recognize simple graphic patterns simulated on a vibrating touchscreen with more than 74% accuracy. These basic tactile patterns can be encoded into interfaces accessible to visually impaired users, to indicate streets on virtual maps, or to convey information about graphs [30].

The high-level tactile pattern design scheme combines tactile patterns with touch gestures, such as using directional gestures (e.g., left/right/up/down sliding) to perceive tactile patterns in Braille or Morse codes for visually impaired people [5]. Several works have been conducted and successfully implemented Braille code reading on a mobile device, such as sliding gestures combined with vibration rhythms [6], [17].

Although tactile patterns can be designed in many ways, the fundamental technique in design is to define a group of tactile patterns that are distinguishable from each other and help users easily identify patterns with high accuracy and efficiency. In addition, combining gestures with dynamic tactile patterns can offer plenty of tactile design schemes, which is an effective way to increase the dimensions of code design.

Although tactile patterns and perception paradigms adopt either MV or UV, tactile pattern designs can be easily transferred between the two, that is, the vibration on/off altering paradigm can be transferred to the low/high friction altering representation and vice versa. However, the differences between MV and UV regarding tactile code perception are unclear, so we conducted user studies to clarify their differences.

III. EXPERIMENT DESIGN

According to ISO 9441-11, usability can be measured by effectiveness, efficiency, and satisfaction.

- *Effectiveness* is the completeness and accuracy by which users achieve certain goals. Completeness is measured as the ability to perform a task, while accuracy is the number of errors made during the experiment tasks.
- *Efficiency* is the relationship between effectiveness and the resources expended to achieve the goals. Generally, it is measured as the duration of time spent by participants in completing certain goals.
- *Satisfaction* is the user's comfort with and positive attitude toward the use of the system. A post-experiment questionnaire of the Likert rating scale is typically used to measure user attitudes.

In this study, ISO 9441-11 was adopted to quantify the usability factors of MV and UV. Effectiveness was measured in two aspects: completeness, which is 100% when the user could perform the perception task, and 0% when the user could not complete the task or give up. Accuracy was the number of errors, that is, the wrong perception results reported by users. Efficiency was measured as the time that users took to perform the perception task. Satisfaction was evaluated through a questionnaire after the experiment. Therefore, the experiment was designed to compare the usability of both types of tactile feedback using these metrics.

A. PARTICIPANTS

A total of sixteen sighted college students (6 females) took part in the experiment; the mean (SD) age was 20.6(1.1) years. All participants were right-handed. All had over 5 years of experience in using touchscreen smartphones. Each participant was paid 50 Chinese yuan upon completion of their trials. The experiment duration for each participant was approximately one hour. In addition, five visually impaired people (mean age: 34.6, SD = 6.9) were invited from the local community who received our experiment invitation letter in WeChat groups. They were organized to join the same experiment as sighted people did, to check whether the results from the latter can be generalized to visually impaired users.

B. APPARATUS

A TPad phone [9], which was introduced by an open-source project,[1] was adopted for the experiment. This device provides dynamic frictions in different locations on the

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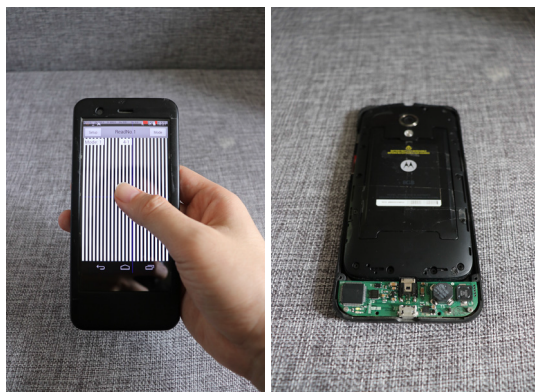
[1]http://tpadtablet.org

FIGURE 1. The TPad phone is presented by tpadtablet.org. The circuit plugged into the phone USB interface is the UV control circuit.

touchscreen by using UV, an air-squeeze-film damping technique [31]. The device provides APIs for customizing surface frictions dynamically while users move their fingers on the screen at run time. The TPad phone was assembled based on an Android smartphone, which has a 4.7-inch touchscreen and a display resolution of 720×1280 pixels. The device has a traditional vibration actuator inside to offer vibrotactile feedback. The dimensions of the whole device are 16.5 cm in length, 7.0 cm in width, and 1.0 cm in height. The device weighs approximately 160g (see Figure 1). The TPad phone is an ideal platform that offers both MV and UV feedback on a single device, facilitating the comparative experiment. The default working parameter of the TPad in the experiment was a piezoelectric operation frequency of 40 kHz to produce the strongest feedback. And mechanical vibration was set to the strongest level using Android API.

C. STIMULI

Two tactile textures distinguished by densities, namely, *dense* and *sparse* patterns (see Figure 2, white zones in the gratings representing vibration on, and black zones off), were adopted to design tactile codes. We chose only two patterns because a binary decision requires a lower cognitive burden and thus may provide a higher identification rate. In our pilot study, we found that participants could identify two patterns with approximately 100% in less than 1 s. However, when the number of patterns increased to 3 or more, participants took more than 2 s to identify the patterns with an accuracy rate lower than 95%. Indeed, using two patterns to design tactile codes has been proved effective in applications such as Braille and Morse tactile-code designs [6], [21], [32].

The parameters for dense patterns were 0.5/0.5 mm (widths of vibration-/spacing-zones), and for sparse patterns were 1.5/1.5 mm. The MV and UV vibrations were produced only when the finger is moving across the white zones, as shown in Figure 2. We chose these two parameters to generate distinctive sensations for users. Indeed, a larger disparity in widths could provide a more distinctive sensation, as found in our previous study [13]. However, for the sparse pattern, when the widths of vibration-/spacing-zones increase, users must move
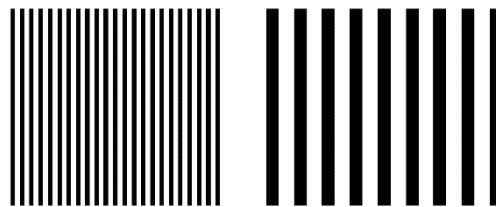

FIGURE 2. Dense and sparse tactile patterns with parameters of 0.5/0.5 mm and 1.5/1.5 mm of widths of vibration-/spacing-zones.

fingers at a relatively long distance to perceive the pattern and thus lower perception efficiency. Therefore, we must choose a relatively short vibration-/spacing-zones for the sparse pattern while ensuring its discriminability from the dense pattern. In our pilot study, users could discriminate the two patterns, designed as 0.5/0.5 vs. 1.5/1.5 mm, with approximately 100% accuracy. In comparison, combinations with the smaller disparity in widths, such as 0.5/0.5 vs. 1.0/1.0 mm, showed lower accuracy of discrimination. Hence, we adopted these parameters to design tactile codes.

D. DESIGN

The basic interaction scheme in tactile codes perception is using directional sliding gestures combined with dynamic tactile patterns presentation, and the tactile codes are conveyed by the number of gestures and different patterns presented. This scheme is simple, effective, easy to learn, and widely used in designing perceiving tactile graphics [11], reading tactile numbers [33], [34], and Braille [5], [6]. Therefore, we chose this fundamental interaction scheme to examine the perception of tactile codes. The interaction procedure is described as follows:

1. Touch and slide left/right using one finger to sense the first tactile pattern presented on the device and count the sliding gesture as the number 1 action.
2. Then, move the finger in the opposite direction to sense if a tactile pattern is presented on the device while sliding. If a texture is presented, count the sliding gesture as the number 2 action.
3. The left/right sliding should be continued until no tactile pattern is presented on the device. When sliding in the direction without a tactile pattern presented, the perception of a tactile code is completed. The number of sliding gestures performed with tactile texture presented is the tactile code to perceive. For example, in Figure 3, the user moves a finger from right to left in the third gesture, but the device produces no feedback; thus, the user recognizes that the current code perception is completed, and the code to be perceived should be 2.
4. During the perception, the finger's sliding speed was not constrained. Participants were asked to choose their normal speed comfortably adopted in their everyday touchscreen usage.

Based on the preceding interaction paradigm, and by combining the left/right sliding gestures with the two dynamic patterns (*dense* as D and *sparse* as S), several tactile codes
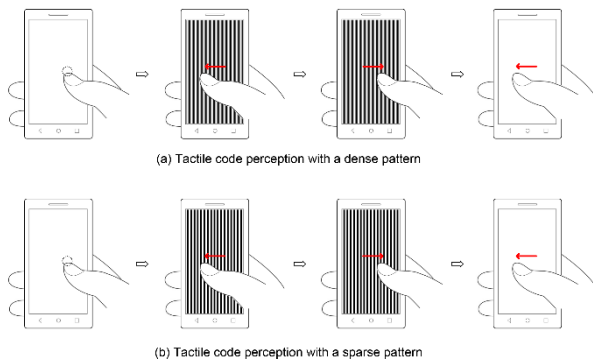
FIGURE 3. Examples of tactile code perception procedure with two types of patterns in the perception of code 2. A tactile code perception finishes when no feedback is given while the user keeps sliding the finger.

could be implemented. In this study, to simplify the perception, 10 tactile codes were examined: D1, D2, D3, D4, D5, S1, S2, S3, S4, and S5. A minimum of two left and right sliding gestures were required to perceive D1 or S1, and a maximum of six left and right sliding gestures are required to perceive D5 or S5.

E. PROCEDURE

The experiment was conducted in a usability laboratory. The experiment procedure followed the typical tactile interface evaluation scheme [35], which consists of four steps for each participant: 1) preparation, 2) self-training, 3) the main testing, and 4) subjective rating.

During the preparation step, the experimenter collected the demographic information of the participants and explained the purpose, procedure, and tasks to be conducted. The participants could learn how to use the application and familiarize themselves with the interaction and ask any questions at this point before moving on to the next step. When the participants fully understood and were familiar with the interaction paradigm, they proceeded to the self-training step. The preparation step lasted for approximately 10 min.

In the self-training step, a tutorial on frictional surface usage was conducted because most of the participants were using UV frictional surfaces for the first time. The tutorial used the built-in "texture sensing" application on the TPad phone to explain feedback and frictional sensation to the participants.

An application was developed to show the participants the dense and sparse patterns and let them identify the difference and memorize the two patterns which were used to convey different code information.

The experimenter demonstrated how to perceive tactile codes. The participants followed the demonstration and were asked to report the codes they obtained to the experimenter to see whether they obtained the code correctly. The participants were asked to perceive 10 codes using both MV and UV feedback during the self-training step to familiarize themselves with the design of tactile code perception.

The 10 test trials of the 10 tactile codes were presented in random order to the participants, who could have their perception results printed to check whether they answered correctly. The participants were free to take the training multiple times until they had gained the confidence to move on to the main test. This step lasted approximately 10 minutes.

During the main test, the experimenter first loaded the tactile code perception application on the TPad. Then, participants were asked to perceive the tactile code only once on the TPad using sliding gestures and report the code they perceived back to the experimenter. The participants were required to wear a soundproof headset to prevent the interference of vibration sound and environmental noise from affecting the tactile perception. Each participant went through the 2 code types of 5 random tactile codes in 5 repetitions using MV and UV. The order of these conditions was counterbalanced in a Latin Square pattern. This step lasted approximately 20 minutes.

The total number of experimental trials was 2100 (2 types of tactile techniques $\times$ 2 code types $\times$ 5 codes $\times$ 5 repetitions $\times$ 21 participants).

Finally, the subjective rating step was performed immediately after the main testing. Each participant needed to complete a questionnaire in which they were asked to rate the two types of tactile feedback in tactile code perception according to their ease of use (Q1), subjective efficiency (Q2), and preference (Q3) in performing the task. Their opinions on the advantages and disadvantages of each feedback were also collected.

F. MEASURES

The experiment was a within-subject repeated measures design. The independent and dependent variables are as follows:

Independent variables: the 2 tactile techniques (MV and UV) each had 10 tactile codes (the dense tactile codes: D1, D2, D3, D4, and D5; and the sparse tactile codes: S1, S2, S3, S4, and S5).

Dependent variables: the task completeness, error rates, perception time, and user satisfaction.

Task completeness was defined as the participants' ability to perform the perception tasks. The completeness was 100% when the user could perform the perception task and 0% when the user could not complete the task or gave up.

The number of errors was the number of mistakenly perceived tactile codes reported by the participants. The error rate was defined as the ratio of the number of errors to the number of trials;

Perception time was defined as the time from the start to the end that a finger moves on the touchscreen to perceive a single tactile code.

The post questionnaire consisted of three statements of assessments in a 7-point Likert scale score, where 1 indicates strongly disagree and 7 indicates strongly agree.

- Q1: The feedback is easy for me to perceive the tactile codes.

TABLE 2. Characteristics of the two types of tactile feedback.

	Completeness (%)	*p*	Errors (%)	*p*
MV	100.0 (0.0)		3.33 (1.91)	
UV	100.0 (0.0)	-	6.85 (3.07)	< 0.01

- Q2: The feedback is efficient for me to perceive the tactile codes.
- Q3: I would like to use this feedback to perceive tactile codes.

IV. RESULTS

To determine whether differences exist between the perception of the two tactile techniques, paired-samples *t*-tests were used in the data analysis. For subjective preference analysis, Wilcoxon signed-rank test was used. To analyze the differences between sighted and visually impaired participants, independent *t*-tests were used. All tests were run at a significance level of $\alpha = 0.05$.

A. EFFECTIVENESS

Effectiveness was measured through two indicators: the completeness of tasks and the number of errors.

Participants could complete the tasks 100% successfully using both MV and UV feedback in all task trails (Table 2), thus no statistical analysis was performed. And therefore, we can conclude that no difference exists between the completeness of the two types of tactile feedback for users in perceiving tactile codes.

For error rates, MV resulted in significantly fewer error rates than UV for both sighted and visually impaired participants. Regarding sighted participants, they achieved approximately 3.13% (SD = 1.09) error rate for MV and 6.13% (SD = 1.44) for UV. The paired-samples *t*-test analysis showed a significant difference between MV and UV, $p < 0.01$. The mean error rates for MV and UV are as shown in Figure 4. And the overall error rates of MV and UV are shown in Table 2.
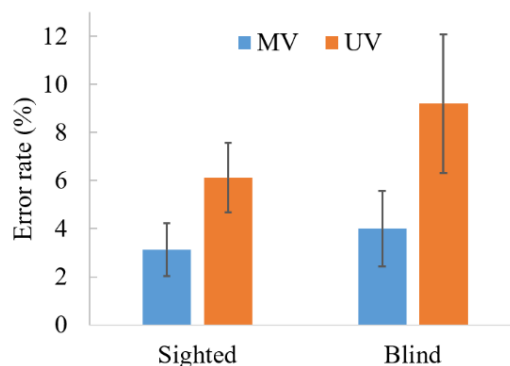
Correspondingly, for visually impaired participants, the error rate was 4% (SD = 1.58) for MV and 9.2% (SD = 2.88) for UV. The paired-samples *t*-test analysis showed a significant difference between MV and UV ($p < 0.02$).

Finally, we compared error rates between sighted participants with their visually impaired counterparts. The independent *t*-tests showed that there was no significant difference between the two groups of participants, with $p = 0.49$ for MV and $p = 0.12$ for UV.

B. EFFICIENCY

Efficiency was measured by the time participants took to complete the tasks.

MV resulted in a significantly shorter time than UV for both sighted participants and their visually impaired counter-

FIGURE 4. Mean error rate for sighted and visually impaired participants on MV and UV code perception. Error bars represent standard deviation.

parts. The participants' mean total recognition time for MV and UV are shown in Figure 5.

For sighted participants, they obtained approximately 9.64 s (SD = 1.76) perception time to complete the tasks for MV and 12.45 (SD = 2.11) for UV. The paired-samples *t*-test analysis showed a significant difference between MV and UV ($p < 0.01$).

Similarly, for visually impaired participants, the perception times were 11.16 s (SD = 2.76) for MV and 13.42 s (SD = 3.63) for the UV technique. The paired-samples *t*-test analysis showed a significant difference between MV and UV ($p = 0.02$).

Finally, we compared the time taken by sighted and visually impaired participants to complete the tasks. The independent *t*-tests showed that there was no significant difference between the two groups of participants, with $p = 0.13$ for MV and $p = 0.39$ for UV.

C. SATISFACTION

In general, MV feedback was rated higher in all statements than UV feedback as shown in Figure 6. For sighted participants, the Wilcoxon signed-rank test showed that the difference between the two types of feedback was significant for every question: for Q1, $z = 3.27$, $p < 0.01$; Q2, $z = 3.56$, $p < 0.01$; and for Q3, $z = 3.33$, $p < 0.01$.

Similarly, visually impaired participants had significant preference for MV over UV as well. The Wilcoxon signed-rank test showed that, for Q1, $z = -2.0$, $p = 0.046$; Q2, $z = -2.24$, $p = 0.025$; and for Q3, $z = -2.04$, $p = 0.041$.

Participants were also asked in the questionnaire about the advantages and disadvantages of each tactile feedback. For MV feedback, 62.5% of the sighted participants said it was faster and more comfortable because it was more noticeable and did not need much concentration to perceive the tactile patterns. The disadvantage pointed out most frequently (50%) about UV is that it generally requires a more cognitive load because the feedback is subtle. This condition generally results in a long time for participants to recognize UV codes although they have the same ability to obtain MV codes. Most of the participants (75%) were more interested in UV because it could provide unique sensations that they
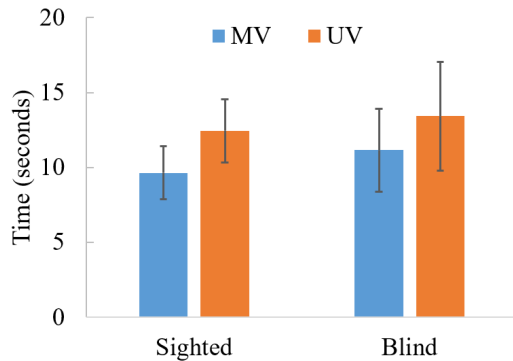
FIGURE 5. Total times for sighted and visually impaired participants on MV and UV code perception. Error bars represent standard deviation.
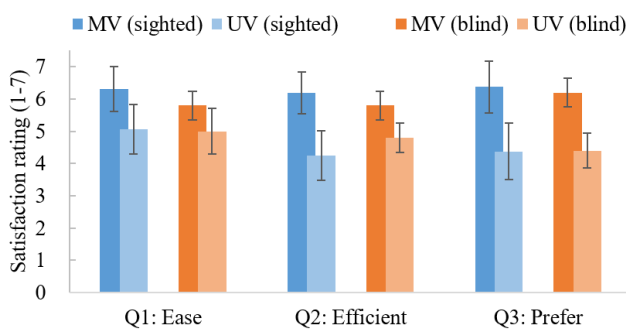

FIGURE 6. Subjective satisfaction for sighted and visually impaired participants on MV and UV code perception. The error bars represent the standard deviation.

have never experienced on a touchscreen. The advantage of UV as pointed out by the participants was that the feedback was distinctive and could quickly respond to each specific fingertip movement. Visually impaired participants generally commented on MV and UV techniques with similar experience to sighted participants. However, they perceived MV and UV with less difference in the level of ease in tactile codes.

The applications of tactile codes using MV and UV were discussed with participants after the questionnaire. Since the MV codes were more distinguishable and precise in recognition, participants were supposed to use them to represent tactile characters such as Morse or Braille codes in eyes-free scenarios. Whereas, UV codes were believed efficient to enhance interaction experience in touching interfaces, such as providing gestures with tactile textures while dragging a graphic widget. These can be potential directions for adopting MV and UV in practical applications.

V. DISCUSSION

In general, our analysis shows significant differences between the two types of techniques in effectiveness, efficiency, and satisfaction while participants perceive tactile codes. However, no significant differences were found in participants' ability to perceive tactile codes since participants could complete all the perception tasks using both MV and UV techniques.

It is the above comparative observation that differentiates our study from prior work. As described in Section II, both MV and UV techniques have been commonly adopted to design tactile interfaces such as Braille reading [5], [6], tactile line [27], or tactile graphics [36], without providing a comparison between the two techniques or testing whether their conclusions obtained on one technique could be generalized to the other. However, MV and UV may have a significant difference in tactile perception, thus suitable for different experimental conditions or purposes, which indicates a necessity for a basic overview for the comparative study of MV and UV tactile feedback. Hence, the disparity of quantitative results from our study could provide a beneficial guideline for making choices between MV and UV techniques in designing tactile perception applications.

Our experiment led to unexpected results: the MV technique, despite its longer actuating time compared with UV, turned out to have a shorter time and lower error rate for participants to perceive the tactile codes. This outcome might be due to the fact that tactile feedback latency is not the significant factor affecting codes perception. Such a finding is largely in line with the study [37] which also showed that the tactile feedback with a latency of less than 118 ms did not affect interaction performance on a touchscreen. This deduction has also been supported by subjective feedback from our participants, all of whom said that they did not notice the tactile feedback latency between MV and UV while perceiving the codes.

We also find subjective feedback inspirational in terms of user experience: all of the participants preferred the MV technique due to its easiness of perceiving tactile codes. According to participants' reports, MV was accessed as more noticeable and discriminable in perception tasks, while UV feedback, which only acted on the fingertip, required more attention and concentration on the finger, thus more likely to be neglected. Such results can be partially supported by the existing study [38] which also showed that the vibration amplitude is one of the major factors affecting tactile codes perception. As we all know, MV generates a higher vibration amplitude than UV does. Besides, another possible reason that may account for participants' preference for MV lies in that MV is more widely used in smartphones, which participants may feel more familiar with. In contrast, UV, as a new technique, has not been widespread on the smartphone market yet. Therefore, during the introduction phase before the actual experiment, it took a relatively long time for the experimenter to explain the UV technique, what the vibration would feel like, and how it would differ from MV. Understandably people tend to feel more comfortable doing what they have already been familiar with and good at.

By comparing the results between sighted and visually impaired participants, we found that they showed similar performance in perceiving tactile codes on the touchscreen device. Moreover, they also prefer MV over UV in the post questionnaire. This result is partially in line with existing studies [36] which showed that visually impaired since

birth (BSB) and visually impaired folded sighted people had a similar perception accuracy in perceiving tactile information on a vibrating touchscreen. Although in our study not all visually impaired participants were BSB (i.e., 60% BSB), they all had used a smartphone skillfully for over 10 years, therefore having no major obstacles using touchscreens. In this sense, involving sighted participants in tactile perception experiments is an effective practice, given their generally similar performance to visually impaired participants, as shown in the Results section.

Based on the observations above, we could reasonably draw the conclusion that the current MV technique is more suitable for designing effective tactile codes due to its higher user performance of perception. However, UV can hardly achieve comparable performance in tactile code perception. This conclusion induces us to recommend MV for tactile code designs when applications require users to perceive tactile codes with accuracy, such as applications conveying visually impaired-reading tactile letters and eyes-free messages.

This study has some limitations that also suggest many future directions. First, we only examined the perception performance on the TPad phone; however, for other MV and UV devices available on the market (such as Fujitsu tablet [8], TeslaTouch [20], GelTouch [39]), we did not investigate user experiences in tactile perception. Therefore, our future studies will investigate and compare perception factors on more types of tactile devices. Second, we have explored the perceived performance of a typical tactile code design paradigm with 10 codes. Other complex letter-coding schemes using MV or UV, such as Braille [5] or Morse [40], may rely on perception mechanisms different from our study. Further investigation into their characteristics may be beneficial to tactile application designs. Third, we studied the disparity between MV and UV in perception performance, leaving unexamined the possibility of combining both techniques for joint tactile feedback. Future studies will explore such joint feedback, aiming at designing new tactile codes and comparing their efficiency with results in our current study.

VI. CONCLUSION

This study presented an experiment to evaluate (a) whether MV and UV feedback can provide the same performance on user perceptions and, if not, (b) which tactile feedback is more effective in providing users with greater efficiency and satisfaction. The experimental results indicate that MV is better than UV in terms of effectiveness, efficiency, and satisfaction, although no significant difference was observed in users' ability to perceive the tactile codes. Furthermore, users preferred MV in perceiving tactile codes because vibration is more noticeable than UV. Whereas, UV offers a high-density texture that may be beneficial for graphic UIs to improve the usability of touchscreen interaction. The results would be useful for tactile interface researchers and designers because they can provide design implications in adopting appropriate types of feedback to improve their designs.

REFERENCES

[1] D. Pyo, T.-H. Yang, S. Ryu, and D.-S. Kwon, "Novel linear impact-resonant actuator for mobile applications," *Sens. Actuators A, Phys.*, vol. 233, pp. 460–471, Sep. 2015.

[2] A. I. Weber, H. P. Saal, J. D. Lieber, J.-W. Cheng, L. R. Manfredi, J. F. Dammann, and S. J. Bensmaia, "Spatial and temporal codes mediate the tactile perception of natural textures," *Proc. Nat. Acad. Sci. USA*, vol. 110, no. 42, pp. 17107–17112, Oct. 2013.

[3] E. Hoggan, S. A. Brewster, and J. Johnston, "Investigating the effectiveness of tactile feedback for mobile touchscreens," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, Florence, Italy, 2008, pp. 1573–1582.

[4] Y.-C. Liao, Y.-C. Chen, L. Chan, and B.-Y. Chen, "Dwell+: Multi-level mode selection using vibrotactile cues," in *Proc. 30th Annu. ACM Symp. User Interface Softw. Technol.*, Quebec City, QC, Canada, Oct. 2017, pp. 5–16.

[5] J. Rantala, R. Raisamo, J. Lylykangas, V. Surakka, J. Raisamo, K. Salminen, T. Pakkanen, and A. Hippula, "Methods for presenting Braille characters on a mobile device with a touchscreen and tactile feedback," *IEEE Trans. Haptics*, vol. 2, no. 1, pp. 28–39, Jan./Mar. 2009.

[6] Z. Al-Qudah, I. A. Doush, F. Alkhateeb, E. Al Maghayreh, and O. Al-Khaleel, "Utilizing mobile devices' tactile feedback for presenting Braille characters: An optimized approach for fast reading and long battery life," *Interacting Comput.*, vol. 26, no. 1, pp. 63–74, Jan. 2014.

[7] S. Khurelbaatar, Y. Nakai, R. Okazaki, V. Yem, and H. Kajimoto, "Tactile presentation to the back of a smartphone with simultaneous screen operation," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, San Jose, CA, USA, May 2016, pp. 3717–3721.

[8] Fujitsu. (Apr. 11, 2022). *Fujitsu Haptic Tablet*. [Online]. Available: https://www.fujitsu.com/global/about/resources/news/press-releases/2014/0224-01.html

[9] J. Mullenbach, C. Shultz, A. M. Piper, M. Peshkin, and J. E. Colgate, "Surface haptic interactions with a TPad tablet," in *Proc. Adjunct Publication 26th Annu. ACM Symp. User Interface Softw. Technol.*, 2013, pp. 7–8.

[10] M. Biet, G. Casiez, F. Giraud, and B. Lemaire-Semail, "Discrimination of virtual square gratings by dynamic touch on friction based tactile displays," in *Proc. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, Mar. 2008, pp. 41–48.

[11] J. Mullenbach, C. Shultz, J. E. Colgate, and A. M. Piper, "Exploring affective communication through variable-friction surface haptics," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, New York, NY, USA, Apr. 2014, pp. 3963–3972.

[12] Y. Rekik, E. Vezzoli, L. Grisoni, and F. Giraud, "Localized haptic texture: A rendering technique based on taxels for high density tactile feedback," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Denver, CO, USA, May 2017, pp. 5006–5015.

[13] S. Chu, F. Zhang, N. Ji, F. Zhang, and R. Pan, "Experimental evaluation of tactile patterns over frictional surface on mobile phones," in *Proc. 5th Int. Symp. Chin. CHI*, New York, NY, USA, 2017, pp. 47–52.

[14] S.-C. Kim, A. Israr, and I. Poupyrev, "Tactile rendering of 3D features on touch surfaces," in *Proc. 26th Annu. ACM Symp. User Interface Softw. Technol.*, St Andrew, U.K., Oct. 2013, pp. 531–538.

[15] W.-E. Ju, Y.-J. Moon, C.-H. Park, and S. T. Choi, "A flexible tactile-feedback touch screen using transparent ferroelectric polymer film vibrators," *Smart Mater. Struct.*, vol. 23, no. 7, Jul. 2014, Art. no. 074004.

[16] S. Ryu, D. Pyo, S.-C. Lim, and D.-S. Kwon, "Mechanical vibration influences the perception of electrovibration," *Sci. Rep.*, vol. 8, no. 1, p. 4555, Mar. 2018.

[17] Z. Al-Qudah, I. A. Doush, F. Alkhateeb, E. A. Maghayreh, and O. Al-Khaleel, "Reading Braille on mobile phones: A fast method with low battery power consumption," in *Proc. Int. Conf. User Sci. Eng. (i-USEr)*, Nov. 2011, pp. 118–123.

[18] B. Schweber. (Apr. 11, 2022). *Haptics Components, Pt 1: LRA, ERM, and Piezo Actuators*. [Online]. Available: https://www.powerelectronictips.com/haptics-components-pt-1-lra-erm-and-piezo-actuators/

[19] G. Casiez, N. Roussel, R. Vanbelleghem, and F. Giraud, "Surfpad: Riding towards targets on a squeeze film effect," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, Vancouver, BC, Canada, May 2011, pp. 2491–2500.

[20] O. Bau, I. Poupyrev, A. Israr, and C. Harrison, "TeslaTouch: Electrovibration for touch surfaces," in *Proc. 23rd Annu. ACM Symp. User Interface Softw. Technol.*, Oct. 2010, pp. 283–292.

[21] B. Saket, C. Prasojo, Y. Huang, and S. Zhao, "Designing an effective vibration-based notification interface for mobile phones," in *Proc. Conf. Comput. Supported Cooperat. Work*, New York, NY, USA, 2013, pp. 149–150.

[22] T. G. Philippi, J. B. F. van Erp, and P. J. Werkhoven, "Multisensory temporal numerosity judgment," *Brain Res.*, vol. 1242, pp. 116–125, Nov. 2008.

[23] A. Bianchi, I. Oakley, and D.-S. Kwon, "Open sesame: Design guidelines for invisible passwords," *Computer*, vol. 45, no. 4, pp. 58–65, Apr. 2012.

[24] L. Potier, T. Pietrzak, G. Casiez, and N. Roussel, "Designing tactile patterns with programmable friction," in *Proc. IHM*, Fribourg, Switzerland, 2016, pp. 1–7.

[25] S. J. Lederman, "Tactile roughness of grooved surfaces: The touching process and effects of macro- and microsurface structure," *Attention, Perception Psychophys.*, vol. 16, no. 2, pp. 385–395, Mar. 1974.

[26] A. Žiberna, N. Kejžar, and P. Golob, "Comparison of different approaches to hierarchical clustering of ordinal data," *Metodološki Zvezki*, vol. 1, no. 1, pp. 57–73, Jan. 2004.

[27] J. L. Tennison, P. M. Uesbeck, N. A. Giudice, A. Stefik, D. W. Smith, and J. L. Gorlewicz, "Establishing vibration-based tactile line profiles for use in multimodal graphics," *ACM Trans. Appl. Perception*, vol. 17, no. 2, pp. 1–14, Apr. 2020.

[28] M. E. Lahib, J. Tekli, and Y. B. Issa, "Evaluating Fitts' law on vibrating touch-screen to improve visual data accessibility for visually impaired users," *Int. J. Hum.-Comput. Stud.*, vol. 112, pp. 16–27, Apr. 2018.

[29] S. Wu, X. Sun, Q. Wang, and J. Chen, "Tactile modeling and rendering image-textures based on electrovibration," *Vis. Comput.*, vol. 33, no. 5, pp. 637–646, May 2017.

[30] C. Basdogan, F. Giraud, V. Levesque, and S. Choi, "A review of surface haptics: Enabling tactile effects on touch surfaces," *IEEE Trans. Haptics*, vol. 13, no. 3, pp. 450–470, Jul. 2020.

[31] M. Biet, F. Giraud, and B. Lemaire-Semail, "Squeeze film effect for the design of an ultrasonic tactile plate," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 54, no. 12, pp. 2678–2688, Dec. 2007.

[32] S. Chu, "Understanding the perception of vibrations and designing tactile reading on smartphones," *J. Comput.-Aided Des. Comput. Graph.*, vol. 31, no. 6, pp. 1046–1052, 2019.

[33] T. Pakkanen, R. Raisamo, K. Salminen, and V. Surakka, "Haptic numbers: Three haptic representation models for numbers on a touch screen phone," in *Proc. Int. Conf. Multimodal Interfaces Workshop Mach. Learn. Multimodal Interact.*, Beijing, China, 2010, pp. 1–4.

[34] A. Bianchi, I. Oakley, and D. S. Kwon, "Counting clicks and beeps: Exploring numerosity based haptic and audio PIN entry," *Interacting Comput.*, vol. 24, no. 5, pp. 409–422, Sep. 2012.

[35] I. Sinclair, J. Carter, S. Kassner, J. van Erp, G. Weber, L. Elliott, and I. Andrew, "Towards a standard on evaluation of tactile/haptic interactions," in *Proc. Int. Conf. Hum. Haptic Sens. Touch Enabled Comput. Appl.* Leiden, The Netherlands: Springer, 2012, pp. 528–539.

[36] J. Tekli, Y. B. Issa, and R. Chbeir, "Evaluating touch-screen vibration modality for visually impaired users to access simple shapes and graphics," *Int. J. Hum.-Comput. Stud.*, vol. 110, pp. 115–133, Feb. 2018.

[37] T. Kaaresoja, E. Anttila, and E. Hoggan, "The effect of tactile feedback latency in touchscreen interaction," in *Proc. IEEE World Haptics Conf.*, Jun. 2011, pp. 65–70.

[38] M. Azadi and L. A. Jones, "Evaluating vibrotactile dimensions for the design of tactons," *IEEE Trans. Haptics*, vol. 7, no. 1, pp. 14–23, Jan. 2014.

[39] V. Miruchna, R. Walter, D. Lindlbauer, M. Lehmann, R. von Klitzing, and J. Müller, "GelTouch: Localized tactile feedback through thin, programmable gel," in *Proc. 28th Annu. ACM Symp. User Interface Softw. Technol.*, Charlotte, NC, USA, Nov. 2015, pp. 3–10.

[40] H. Z. Tan, N. I. Durlach, W. M. Rabinowitz, C. M. Reed, and J. R. Santos, "Reception of Morse code through motional, vibrotactile, and auditory stimulation," *Attention, Perception, Psychophys.*, vol. 59, no. 7, pp. 1004–1017, Jan. 1997.

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