Establishing Vibration-Based Tactile Line Profiles for Use in Multimodal Graphics

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7

Vibration plays a significant role in the way users interact with touchscreens. For many users, vibration affords tactile alerts and other enhancements. For eyes-free users and users with visual impairments, vibration can also serve a more primary role in the user interface, such as indicating streets on maps, conveying information about graphs, or even specifying basic graphics. However, vibration is rarely used in current user interfaces beyond basic cuing. Furthermore, designers and developers who do actually use vibration more extensively are often unable to determine the exact properties of the vibration signals they are implementing, due to out-of-the-box software and hardware limitations. We make two contributions in this work. First, we investigate the contextual properties of touchscreen vibrations and how vibrations can be used to effectively convey traditional, embossed elements, such as dashes and dots. To do so, we developed an open source, Android-based library to generate vibrations that are perceptually salient and intuitive, improving upon existing vibration libraries. Second, we conducted a user study with 26 blind or visually impaired users to evaluate and categorize the effects with respect to traditional tactile line profiles. We have established a range of vibration effects that can be reliably generated by our haptic library and are perceptible and distinguishable by users.

CCS Concepts: • **Human-centered computing** → **Human computer interaction (HCI)**; **User studies**; **Touch screens**; **Haptic devices**; *Usability testing*; *Accessibility technologies*; *Accessibility systems and tools*; • **Social and professional topics** → People with disabilities;

Additional Key Words and Phrases: Haptics, touchscreen, perception, HCI

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1 INTRODUCTION

For individuals with visual impairments (VI), lack of access to graphical material is one of the most pressing challenges inhibiting independence and productivity [31, 42], as more than 70% of individuals do not hold full employment [5], nearly 30% of individuals do not independently travel [6], and only about 11% of individuals have graduated with a bachelor's degree in the United States [7]. As content continues to rapidly move to digital formats, the graphical access gap is growing. Although digital text-based information can be made accessible via print-to-braille or text-to-speech software, there has yet to be an analog that provides access to spatial concepts and information conveyed digitally in graphics. Several technologies are being investigated as potential solutions employing vibrotactile mechanisms used in commercial devices. For instance, dynamic touch-based interfaces that rely on force feedback, refreshable pin arrays [8, 51], microfluidics [43], moldable alloys, and surface haptic principles have all been put forth as potential solutions (see [33]). Unfortunately, these solutions have yet to become widely available. Further, many have long development timelines, extensive overhead, and limited unit manufacturing, leading to high costs to produce and hence to own by the end user. Most of these devices also require purpose-built hardware platforms, further increasing costs and limiting the likelihood of broad adoption. Auditory solutions are also available, including sonification techniques that exploit auditory parameters such as pitch, loudness, and tempo to convert visual information into acoustic formats [29, 59, 60].

These approaches, however, still lack "touch" feedback, which is often critical in conveying spatial information. Touch shares many similarities with vision, having shared parallel processing channels in the brain [28, 37, 41, 55]. Both sensory aspects extract physical and spatial features from the environment to create comprehensive and coherent representations in memory.

The most commonly used techniques for accessing digital graphics are language-based approaches. These include techniques like captioning and alt tags. However, these descriptions often cannot capture the rich, spatial content being displayed in a graphic, and conveying any spatial content with text description is subject to errors, inaccuracies, and vagueness. In specialized settings such as education, it is common practice to take images of graphics and have an embossed hardcopy tactile graphic created so that individuals can extract information via touch. Although embossed or raised graphics are often the preferred standard for nonvisual interpretation, these approaches require trained personnel to author and specialized resources to produce, often incurring a delay between when a student is given material and when they can inspect it.

Simply providing access to new technology is not enough to adopt it, and it is important to also consider external factors that will drive (or deter) the use of such technologies. This often means solutions that are readily available, multipurpose, portable, and inexpensive. With these criteria in mind, several researchers have noted the potential of vibrotactile touchscreens as a platform to provide graphical information access nonvisually. Touchscreens have become one of the most pervasive information access technologies to date. A 2019 Pew Research Poll reports that 81% now own a smartphone and more than half of people own a tablet in the United States [3].

Although touchscreens are largely visual input/output devices, recent advances in hardware and software are making them more accessible. For instance, built in text-to-speech engines and accessibility options within the native operating system provide access to text-based information and control of on-screen content, respectively. The inclusion of vibration motors within touchscreen hardware also provides a "touch" feedback experience that was not possible previously. Hardware and software advancements coupled with broad adoption poise touchscreens to become a multisensory platform that may help bridge the graphical access gap for individuals with VI.

In this work, we contribute to this growing body of knowledge and investigate how vibration profiles rendered on touchscreens perceptually map to traditional tactile line profiles. Prior research has focused on conveying fundamental graphical elements using vibrations and sounds; however, work has yet to study or understand how the vibration profiles themselves may translate to constructs that are more meaningful than simply indicating whether a user is "on" or "off" of a graphical element. This research contributes to both our understanding of the perception of vibrations in continuous haptic exploration, as well as our understanding of how to optimize the rendering of meaningful multisensory elements on touchscreen platforms.

We detail research efforts in both of these areas in Section 2.2. We then present the design of an open source vibration library to easily generate vibration profiles on touchscreens, followed by a user study with 26 individuals with VI exploring how vibration profiles translate to traditional tactile line profiles. We conclude with a discussion of design guidelines and suggestions toward future investigations for rendering touchscreen-based multimodal graphics.

2 VIBRATION PERCEPTION AND VIBROTACTILE TOUCHSCREEN RESEARCH

There is a growing body of evidence demonstrating the efficacy of using touchscreen-based devices with vibration and auditory feedback as a primary interaction style for conveying graphical information. Here, we detail the underpinnings of the state of the art in vibration perception and vibrotactile touchscreen research in the context of nonvisual graphical access.

2.1 Vibration Perception

Vibration perception differs in several ways compared to the stimuli received from physical tactile graphics. There is significant literature on tactile thresholds for physical stimuli [10, 25], the effect of aging on tactile ability [48], and the tactile "science" supporting braille reading and pattern recognition [56]. Although this information informs understanding in the physical space, vibrations provide different stimuli and target different receptors than traditional tactile perception. Vibrotactile perception is guided by the rapidly adapting (RA) and Pacinian corpuscle (PC) channels of touch. The RA channel is responsible for sensations in the 3- to 100-Hz range, often associated with perceiving flutter [12, 24, 26]. The PC channel is the primary perception channel for vibration and is associated with a frequency range of 10 to 500 Hz. Generally, vibrations less than 3 Hz are perceived as a slow, undulating motion. Vibrations between 10 and 70 Hz tend to be perceived as flutter, and vibrations between 10 and 300 Hz tend to be perceived as a smooth/constant vibration [4]. The frequencies of vibrations strongly dictate the absolute thresholds of vibrotactile stimuli. Smallest detectable displacements can be less than 0.1 μm, but this threshold is affected by several factors, including contact area and age, among others [4]. The perceived intensity of vibration is exponential, governed by Steven's power law, and is a function of both amplitude and frequency [9, 44]. By varying the amplitude over time, the perception of rhythm is created—which is how vibrations can have various patterns [49, 57]. This notion of rhythm is often highly discriminable, making vibrations a viable candidate for representing distinct features, symbols, or objects.

An excellent review of vibrotactile displays and the perception of vibrations can be found in Choi and Kuchenbecker [4]. Vibrations make notable enhancements to the touchscreen user experience, turning a largely visual device into one accommodating of another mode of interaction: touch. Vibratory feedback is commonly used in two ways on touchscreen-based platforms: (1) to create a physical representation of what is being interacted with, and (2) to provide an affirmative response to a user's kinesthetic motion when interacting with the surface of the screen [4, 32]. This means that typing can be made easier, alerts can be made without sight or sound, and actions such as dragging, dropping, or selecting items on-screen can be enhanced with vibratory feedback [22]. Hoggan et al. [18–20] have also done extensive work exploring tactile feedback, particularly from mobile platforms, and have demonstrated important findings illustrating how structured tactile messages (Tactons) can be used to communicate information using different vibration features. Other research has demonstrated that vibrotactile feedback enables users to complete scrolling and inputting tasks faster on a mobile device compared to interfaces that lack such feedback [39, 61], and can improve textual reading in braille (e.g., [1, 23, 30, 40]). Although these are just a few examples of what vibrations enable, they illustrate the depth and limits of information that can be conveyed via vibratory feedback.

2.2 Vibrotactile Touchscreen Research

Recent research has extended the use case for vibrations as a means for interpreting graphical information displayed on touchscreens. Vibrotactile feedback can increase the accessibility of touchscreens by supporting navigation, education, and everyday tasks for VI users [11, 13, 14, 27]. Notably, this includes conveying maps [38], following and perceiving lines and graphs [11, 36, 54], and representing graphical shapes [13, 53]. Recent studies have also demonstrated that the multimodal touchscreen display is not just feasible but can enable information extraction comparable to hardcopy embossed graphics for a variety of graphical concepts [11, 17, 58].

Additional investigations have demonstrated that nonvisual panning and zooming of large format vibrotactile maps that extend beyond the device's display are possible [34, 35], opening up pathways for more complex information to be layered or scaffold. Our group has also explored the effect of screen size (mobile vs. tablet) on a pattern matching task and have found that even smaller screen sizes can support simple vibrotactile graphics despite their low resolution [52].

Numerous reviews detailing the opportunities and limitations of the touchscreen approach to graphical access are available for further details [15, 16, 27, 33]. In short, much of this research suggests promising pathways forward for vibrotactile touchscreens while also acknowledging that further investigations are needed to truly realize the affordances and limitations of this paradigm. In this work, we seek to contribute to these ongoing investigations by understanding how traditional vibration profiles map over to traditional tactile line profiles toward informing which vibration profiles are most conducive for use in multimodal graphic rendering, as well as toward a better understanding of how to appropriately add vibration feedback to graphical elements for continuous exploration and interpretation.

3 VIBRATION SIGNAL GENERATION ON TOUCHSCREENS

To investigate which vibration signals best map to tactile line profiles, we first had to be able to reliably generate regular vibration patterns on touchscreens with known characteristics. For many Android devices, only a few, high-level functions are available to developers to operate the vibration motor. These functions turn the motor on and off, either in isolation or in a pattern, but they only offer abstract and limited control of parameters commonly characteristic of vibration signals, including amplitude and frequency. Android has recently started to offer developers greater control over the motor amplitude, but this functionality is restricted to newer devices and only works with compatible motors [2]. Libraries of various premade vibratory effects have been created, often based on Immersion's Universal Haptic Layer (UHL) [21]. There are two major drawbacks of using these auxiliary libraries: (1) the libraries are often proprietary and obfuscate the parameters under which their vibration patterns are generated, leaving designers with only limited abstracted parameters to create signals, and (2) the libraries may have costs associated with using them. Further, existing vibration libraries were not inherently designed for the use case of continuous haptic exploration of graphics. As a result, they often contain vibration profiles that are only meant for cuing or emphasis, having patterns that are metaphorically named "alert" or "weapon" (e.g., [21]) with little information on the actual vibration characteristics provided [35, 36, 53].

In previous work related to touchscreen-based graphics, many researchers have resorted to using these libraries, as they were sufficient for conveying feasibility. However, as the prospect for vibrotactile graphics continues to grow and as we continued to understand the depth of what is possible using this mode of nonvisual feedback, our team desired a library that was more transparent in creating vibration profiles that were explicitly designed for continuous exploration. Additionally, when trying to replicate features of tactile objects, such as the line profiles in this work, knowing the vibration signal's inherent parameters (e.g., frequency and amplitude) are useful in the design of the signals themselves. Thus, our team desired a library that created vibrations with readily available parameters that could be easily understood as they relate to vibrotactile perception.

3.1 Open Source Vibration Library

To support an expanding branch of research using vibrations as a primary interaction style and for continuous haptic explorations of on-screen content, we developed an open source, Android-based vibration library in both Quorum and Java (Quorum: [46]; Quorum Documentation: [47]; Java: [45]). This library is available under the BSD clause IV software license and is free for commercial or noncommercial use as long as the software is acknowledged. The intent of this library is to bridge the gap between arbitrary, prerendered vibration effects and perceptually salient and distinguishable vibration patterns. This library was designed with researchers and developers in mind, who require finer control over vibrotactile sensation and repetition. This is particularly relevant to experimental and investigative research concerning touch as a primary method of interaction on a touchscreen and the display of visual graphics in nonvisual scenarios, such as for users with VI.

With this library, designers are given more control over the parameters used to create vibration. It allows users to create vibration patterns for specific goals, such as to achieve particular frequencies (within hardware limitations) or to modify vibration intensities. The library provides users with the ability to develop complex patterns with changing intensities, as well as ready-made, empirically tested vibration patterns for a quick start.

The library takes full advantage of the Android Vibration API. The Android API allows for the creation of vibration signals by specifying pairs of pause and activation times (in milliseconds). This information is stored in an array that is then passed to the API. A pattern such as "10, 15" would thus instruct the vibration motor to wait 10 ms and then vibrate for 15 ms. An example of a longer pattern would be "0, 100, 500, 100," which creates a pattern that starts vibrating for 100 ms (skipping the initial pause), pauses for 500 ms, then vibrates for 100 ms. This system allows for control of the frequency of the vibration and the length of the signal, as both motor on and motor off times are variable. Control of repetition is built into the API and allows for no repetition of a signal or repetition from a specified index of the signal array.

The provided functionality in the Android API allows for fine-grained control of the vibration pattern; however, it makes it difficult to achieve easy-to-use distinguishable patterns without considerable experimentation with pattern formulation. This is due to the lack of fine control over vibrations in the Android API and lack of understanding of how each tablet motor reacts to API calls. For example, it is difficult to create lower-intensity patterns without considerable trial and error or scientific validation, such as through the use of a Laser Doppler Vibrometer (LDV) from which amplitude and frequency measurements could be garnered. This is due to discrepancies in the minimum thresholds of operating voltages across tablet vibration motors.

To mitigate motor operation limitations at low intensities, we added an abstraction layer on top of the Android API to introduce more intuitive ways to control the vibration. There were three goals of this abstraction layer: first, to provide prerendered patterns for the simplest use cases; second, to provide a way to control the vibration frequency in Hertz and to specify a vibration length (in milliseconds); and third, to allow for easy specification of intensities over time intervals, and to provide a method to chain together these intervals in a modular way that yields a continuous pattern when played sequentially.

We succeeded in creating basic patterns that map to dotted, dashed, and solid tactile profiles, as demonstrated in the user study discussed in Section 4. These patterns now come standard with the freely available library for other researchers working in this area to use in experimental studies. We also succeeded in giving greater frequency control with special consideration to the frequency at which the tablet actuator can maintain. This affords developers easy access to vibrations at desired frequencies. Intensity control, however, remains an area of future improvement due to hardware limitations and the fact that vibration intensity is a function of both amplitude and frequency. The initial release of the library contains a complete API, although the core algorithm may change to allow for better control over intensity in future iterations.

4 EXPERIMENT

To better understand what vibration signals best translate to tactile line stimuli (e.g., dotted, dashed, and solid) in the context of nonvisual graphic exploration, we conducted a two-part user study. In the first part, we had users categorize various vibration profiles as they relate (or not) to traditional tactile line profiles. In the second part, we had users discriminate between the frequencies most commonly selected in the first part to ensure that the signals chosen are easily distinguishable. We used vibration signals generated from our custom, open source Android library to create the vibrations in the experimental sessions. The study conducted was guided by the following research questions

4.1 Research Questions

(1) *Vibration Categorization*: Within the operating range of the tablet motor, how do VI users classify vibration frequency patterns with respect to elements used in traditional, hardcopy tactile lines?
(2) *Vibration Discrimination*: Is there a distinction between categorized frequencies, and can these frequencies be differentiated by users?

The first question investigates how users map vibrations to traditional, hardcopy embossed tactile graphic components (e.g., solid, dashed, or dotted lines). These data provide insight on what vibration profiles may be most appropriate to use when representing lines in graphics. The second question ensures that the selected vibration profiles are distinctly different from one another on the touchscreen, which is important if multiple vibrations are incorporated in the same graphic.

The following studies were approved by the university's Institutional Review Board, and participants were provided informed consent and compensated for their time.

4.1.1 Demographics. Twenty-six individuals with blindness or visual impairment (BVI) were recruited from conferences for the visually impaired and summer programs for young individuals (12 from the American Council of the Blind (ACB) National Convention, 7 from the National Federation of the Blind (NFB) Illinois Chapter Convention, and 7 from the Midwestern summer camp). Participants were 16 to 70 years old (ACB: $M = 56.42$ years, $SD = 10.99$; NFB: $M = 37.43$ years, $SD = 19.57$; Summer camp: $M = 17.43$ years, $SD = 1.72$).

To incentivize conference participation, a $25 American Express gift card was offered as compensation. Summer camp participants received no incentive, as participation was provided as an optional daily activity at the camp. The summer camp participants were pilot participants and provided feedback on the initial study methods. These 7 participants were not included in data analysis. Of the 19 remaining participants, 2 were removed from analysis due to missing greater than 50% of their data from a software malfunction. The remaining participants consisted of 13 female and 4 male individuals ($M = 47.53$ years, $SD = 16.96$). Table 1 presents participant demographics.

At the start of the study, participants were given a demographics survey to complete. We asked them to report their VI and when they were diagnosed. The most commonly reported diagnosis was retinopathy of prematurity ($N = 7$) followed by retinitis pigmentosa ($N = 4$). Eight individuals reported being diagnosed at birth or before 1 year. Two participants reported having additional VI (nystagmus; microphthalmia, coloboma, and detached retina), 3 reported hearing impairments (not described), 1 reported having a motor impairment (hand sensitivity loss), and 1 reported a "mild" cognitive disability.

4.1.2 Tasks. Individuals were given two tasks to complete on the touchscreen: (1) Vibration Categorization (VC) and (2) Vibration Discrimination (VD). The device used was a 10.0-inch Samsung Galaxy Tab S tablet with a coin motor that is believed to be a linear resonant actuator (LRA). The vibration effects developed consisted of vibrations at frequencies of 2.5, 5, 10, 25, 50, 100, 250, and 500 Hz. These frequencies were chosen to coincide with previous work done on subjective classification of vibrations [50], wherein vibrations up to 3 Hz were considered to feel slow, 10 to 70 Hz were considered fluttering, and 100 to 300 Hz were considered constant and

Table 1. Participant Summary

#	Age	Sex	Diagnosis	Age at Diagnosis (years)
1	33	F	RP	3
2	38	F	ROP	<1
3	60	F	RP	7
4	65	F	ROP	<1
5	61	F	ROP	<1
6	61	M	Glaucoma	2
7	48	F	ROP	<1
8	61	M	RP	58
9	57	M	ROP	<1
10	63	F	ROP	<1
11	70	F	LCA	33
12	45	M	JR	3
13	55	F	Nystagmus	10
14	20	F	RP	4
15	23	F	Brain tumor	18
16	28	F	ROP	<1
17	21	F	Retinoblastoma	<1

RP, retinitis pigmentosa; ROP, retinopathy of prematurity; LCA, Leber congenital amaurosis; JR, juvenile retinoschisis.

smooth. These frequencies were also chosen due to the periods being whole milliseconds and therefore simple to generate in Android.

In the VC task, individuals were asked to trace a straight, vibrating line lengthwise across the touchscreen at a quick and even pace, in less than 2 seconds. This line was 8 mm thick (to account for some error in tracing [36]); 22.8 cm long; and vibrated at 2.5, 5, 10, 25, 50, 100, 250, or 500 Hz. Participants were asked to trace the line only once and to categorize the vibration effect as being solid, dotted, dashed, or not a vibration that they would interpret as a line.

In the VD task, individuals were asked to determine whether two vibration effects were the same or different. The task required users to trace a line outfitted with different effects. Participants were first given a target pattern to remember. The participant would then receive five alternative effects in a random order that varied in similarity to the target (as described in Section 4.1.2). After each effect, the participant was reminded of the target pattern and allowed to feel it again. After each target–alternative effect pair, the participant was asked if the two vibration effects were the same or different. All lines were presented one at a time and could be traced only once. Due to time constraints, we were not able to test every signal from every other signal. Instead, we adopted the median signal of 10 Hz and tested the two signals that were lower and higher in frequency from it. In this part of the study, individuals compared the 10 Hz effect to 2.5-, 5-, 10-, 25-, and 50-Hz effects in a software-determined, randomly chosen order. Vibration frequencies centered around 10 Hz were chosen due to their significant signal stability and continuous repeatability, further discussed in Section 6.

4.1.3 Procedure. Individual sessions took approximately 1 hour to complete. Each session included the demographics questionnaire, a training period, and the two vibration tasks. After completing the demographics form, individuals were given the tablet. No visual information was presented on the darkened screen throughout the session. Participants were not blindfolded, as we have noted in our previous work that this can make people uncomfortable. To ensure consistency between all participants, participants with glasses or other sight aids were asked to remove them for the duration of the study. Participants were provided a brief training period for both the VC and VD tasks. The training period had no fixed time for completion and concluded when the participant felt comfortable with the task.

All participants were given a printout of three tactile line types: dotted, dashed, and solid. This was done to assist participants in establishing differences among the categories. This printout could be referenced at any time during the experiment.

Pilot study. A pilot of the experiment was first completed with seven participants to determine the feasibility of the study procedure. The pilot established the time frame in which the VC and VD tasks could be completed. It also established necessary language regarding the study directions, as well as some suggestions to modify the tablet to make both tasks easier to complete for the participant. After receiving feedback, directions for both tasks were refined. Buttons and menus were covered to avoid accidental presses and a raised plastic sticker was placed on the tablet next to the starting point on the left side of the line to allow users to quickly find the start of the line for each trial. Having the sticker on the left side provided a familiar start to the trial, as reading in Western cultures tends to take place from left to right.

Vibration Categorization. During the VC task, individuals were instructed to use their dominant finger to trace a line on the touchscreen from left to right at a quick and even pace, in under 2 seconds. There were eight effects to trace and 10 replications of each effect for a total of either 80 (ACB participants) or 70 (NFB participants) lines to trace. NFB participants received only 70 lines due to the removal of the problematic 500-Hz effect after the ACB participants pointed out that they could not feel a sensation for this effect. This is elaborated further in Section 6. After tracing each line, participants responded if the effect felt solid, dotted, dashed, or to not be a line. An example of each category was given in a traditional, embossed format as reference.

Vibration Discrimination. During the VD 10-Hz comparison task, individuals were similarly instructed to use their dominant finger at a quick, even pace to trace a set of lines. The lines came in pairs. The first line presented to the participants to trace was always the target, 10-Hz effect. Participants were asked to remember this effect before being given the second line. The second line was either 2.5, 5, 10, 25, or 50 Hz at random. After comparing the 10-Hz effect to each of the five options, the task was repeated five times (for ACB participants) or three times (for NFB participants; due to time constraints).

Upon study completion, participants were thanked for their time and compensated with a gift card.

5 RESULTS

In this user study, 17 participants were asked to trace a line of a given vibration profile and categorize it according to common tactile line profiles (solid line, dashed, dotted, or no line). Users were also asked to distinguish targeted vibration profiles from one another to ensure that signals chosen were differentiable from one another.

In the VC task, users classified low-frequency vibration effects (2.5 to 10 Hz) as dotted or dashed lines 44.19% and 38.03% of the time. Mid-range frequencies (25 to 50 Hz) were classified as solid, continuous lines 41.58% of the time. For high frequencies (100 to 500 Hz), users responded in a couple of ways, either feeling no feedback when tracing or not interpreting the feedback as a representation of a line (61.75%) (Figure 1).

In the VD task, participant success was scored in two ways. First, we examined the participants' success at correctly identifying the 10-Hz vibration within the trial, which was on average 78.87%. After, we examined the success rate to not only be able to identify the 10-Hz vibration but also to dismiss all other similar but incorrect effects. The success rate fell to 45.00%, with the frequency most commonly confused with 10 Hz being 5 Hz (Figure 2). Out of all comparisons ($N = 109$), participants most commonly selected the 10-Hz vibration effect ($N = 53$), followed by 5-Hz ($N = 32$), then the 25-Hz ($N = 18$), 2.5-Hz ($N = 4$), and 50-Hz ($N = 2$) effects.

During the study, participants struggled with feeling higher frequency vibrations due to faintness of sensation and perceived inconsistency of the pattern. This occurred in patterns that were 100 Hz and above. Frequencies

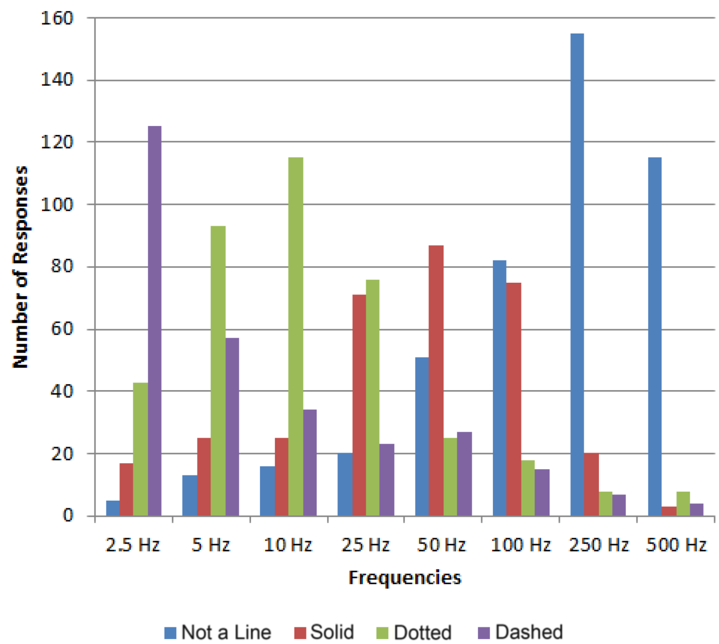

Fig. 1. Line quality interpretation frequencies to each vibration profile (2.5, 5, 10, 25, 50, 100, 250, and 500 Hz).

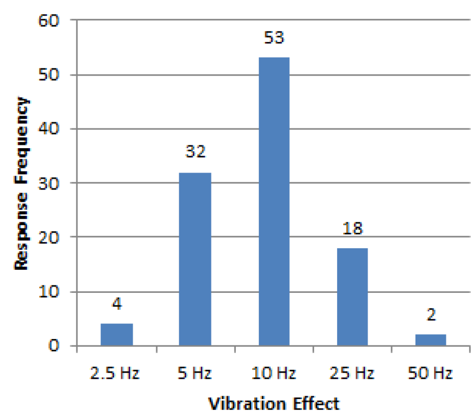

Fig. 2. Participant responses when attempting to identify the 10-Hz vibration from among five options. Participants most commonly selected the 5-Hz effect in addition to the 10-Hz effect when attempting to identify the target 10-Hz effect.

above 100 Hz, especially the 500-Hz frequency, felt choppy and at times had extended periods of no feedback. This may be attributed to the limitations of the coin vibration motor in the tablet as the actuator struggles to turn on and off fast enough to create the signal. To investigate the high-frequency patterns generated with the library and to confirm the low-frequency patterns, we measured the vibration profiles created on-screen with an LDV.

5.1 LDV Validation

An LDV (Polytec PDV 100) and a Keysight InfiniiVision MSO-X 3034T mixed-signal oscilloscope provided velocity and amplitude data of the vibration patterns generated by a Samsung Galaxy Tab S touchscreen.

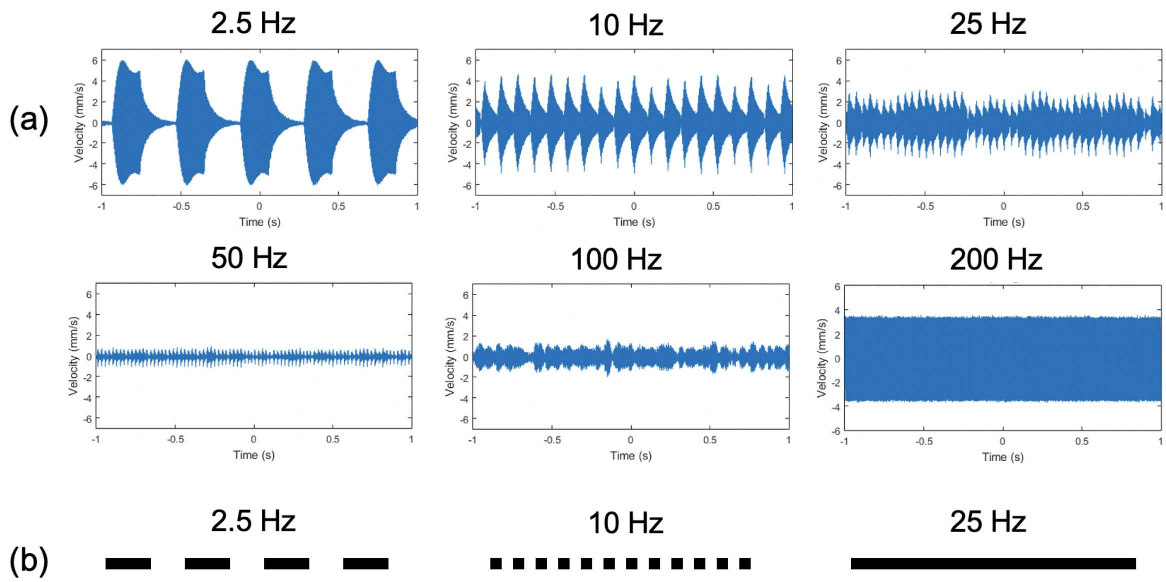

Fig. 3. (a) Velocity measurements of 2.5, 10, 25, 50, 100, and 200 Hz vibration effects at the location of the vibration motor on a Samsung Galaxy Tab S tablet. (b) Mapping 2.5 Hz, 10 Hz, and 50 Hz vibration signals to hardcopy, tactile line profiles when the finger moves at a slow, even pace across the signals.

A stage to take measurements was set up wherein the tablet was placed on a flat surface below the LDV. The distance between the LDV lens and the top of the tablet was 510 mm. This distance was chosen by calculating the ideal standoff distance between the two devices for optimal measurement by the LDV.

Measurements were taken at nine discrete, equidistant points on the tablet arranged in a grid pattern on the active area of the screen. Each of the nine points was affixed with reflective tape, which allowed the LDV to measure the velocity of the tablet at these points. A 2-second measurement duration was specified and velocity data was saved by the oscilloscope. This data was then imported into MathWorks MATLAB 2015a for inspection and waveform recreation.

5.1.1 Validation of Frequency Patterns. A sampling of the velocity data acquired from a single point on the tablet is shown in Figure 3. The quantitative results align quite well with the qualitative user study results. We see that the low-frequency signals (50 Hz and less) are quite clean and consistent, but signals in the high-frequency range (especially above 100 Hz) are quite sporadic.

We believe this is a hardware limitation of the motor. As we cannot control the vibration motor directly, we can only modify the time the motor is on and off to generate a vibration at a particular frequency. Alternating the motor between on and off states too quickly leads to signal degradation. In attempting to generate frequencies in the 100- to 500-Hz range, we discovered the default operating frequency of the vibration motor, which is around 200 Hz.

Using the LDV for validation, we established a range of effects that could be generated by the library and felt by participants with little issue. These effects include 2.5 to 100 Hz, and 200 Hz (see Figure 3). It is important to note that as the frequency increases, the waveform loses amplitude and regularity, appearing slightly choppy or very faint. However, within the range specified, users should still be able to feel these sensations and developers are encouraged to use these for the effects they produce.

6 DISCUSSION

With these user studies, our goal was to establish vibration patterns that could be mapped to hardcopy, tactile line profiles and to determine at what frequencies these patterns could be reliably discriminated. In the VC task, participants categorized the vibration effects with relative consistency. Very low vibrations (2.5 Hz) were frequently interpreted as dashed (65.79% of responses), mid-low-range vibrations (5 to 10 Hz) as dotted (55.03%), mid-range (25 to 50 Hz) as solid lines (41.58%), and above 100 Hz as not a representation of a line (61.75%) (see Figure 3). These findings support previous research in vibrations with dashed lines likely being best represented by low frequencies and dotted and solid lines being represented with frequencies higher in comparison. The challenge in this work, however, is that we are working with a relatively small frequency range overall due to hardware limitations. As such, it is noteworthy that individuals could still discriminate and categorize vibrations with respect to tactile counterparts.

There were two points of contention in participants' categorization of the vibration frequencies: at 25 Hz and again at 100 Hz. At 25 Hz, the most common categorizations of the sensation were dotted and solid, at nearly identical rates, 40.00% and 37.37% of responses, respectively. This 25-Hz signal is demonstrably on the cusp of the two categories and therefore should not be paired with sensations that are more stably categorized as one sensation or the other if the task necessitates differentiating between two sensations. At 100 Hz, the most common categorizations were solid and not representative of a line, again at similar rates, 39.47% and 43.16%, respectively. This is likely due to the saturation of the vibration motor when giving it quick on-off commands. For this frequency, a command for a period of 10 ms was sent to the motor, which is too quick to generate a high amplitude signal, resulting in a very faint vibration (see Figure 3).

In the VD task, we determined the most discriminable effects within the targeted frequency range. Users could best discriminate 2.5 and 50 Hz from 10 Hz (see Figure 2). These findings in conjunction with the first user study findings lead us to recommend the following vibration profiles for ease of generation and discrimination when designing media that best maps to traditional, tactile line profiles (see Figure 1):

(1) 2.5 Hz for mapping to slow, dashed sensations;
(2) 10 Hz for mapping to quick, dotted sensations;
(3) 50 Hz for mapping to constant, solid sensations.

The recommended vibration profiles measured from the LDV along with their tactile counterparts are shown in Figure 3. Generating vibrations at precise and regular frequencies was dependent on how quickly the Android system could turn the motor on and off. While the default frequency of the tablet vibrator was around 200 Hz, other frequencies were created by turning the motor off and on at varying intervals. The 200-Hz signal was not included in the user study testing, as we did not determine the operating frequency of the motor until performing the LDV studies after the fact. Thus, we do not have qualitative data to support its categorization. Based on its LDV profile, however, it suggests this signal would be a stronger, constant vibration (similar to that of the 50-Hz signal) and could potentially serve as a candidate profile for a solid line as well. We note, however, that strong signals are often not preferred due to overstimulation and sensory fatigue.

Of note, above 200 Hz, the vibration motor becomes too saturated with on-off commands to give a regular signal. In this range, the signal is inconsistent at best and absent at worst. The maximum frequency that we would recommend using is 200 Hz (the default motor frequency), after taking into consideration the tablet motor's limitations and the way in which vibrations are generated in the library. However, we again note that starting at about 100 Hz, the signal suffers from low amplitude and, due to the faintness of the sensation, can be hard to perceive. A pattern between 100- and 200-Hz vibration may not be sufficient for many tasks, unless users have good perceptive ability in their fingertips and can concentrate on the sensation.

This is also the reasoning behind removing the 500-Hz effect from subsequent study trials. The 500-Hz signal was found to be almost always flat, categorized by long periods (>2 seconds) of no activity interspersed with low spikes in velocity. As participants rarely experienced any feedback from this effect, the decision was made to remove it from the trials.

Taken together, the user studies coupled with the LDV studies demonstrate that even with a small operating frequency range, there are three distinct vibration profiles that map over to traditional, tactile line profiles, are discriminable, and can be consistently generated with our vibration library.

7 CONCLUSION

This work expands upon a growing body of evidence that vibrotactile touchscreens have the potential to serve as a means for rendering graphics nonvisually for individuals with BVI by providing guidance on which vibrations are most appropriate to use for line representation. The work also builds on the perception of vibrations more broadly by mapping vibrations perceived on a touchscreen in a continuous exploration task to traditional tactile line profiles. Recommended vibration signals are provided for designers to consider using in subsequent research where varying line profiles or line profiles that are often represented with specific formats can be explored in the context of various maps and diagrams. A secondary contribution of this work is an open source library in which designers can generate vibrations on Android devices using innate parameters (e.g., frequency) and with continuous exploration in mind. This library continues to evolve, and new capabilities, such as intensity control, are forthcoming. Taken together, this research provides both guidance and new tools for designers and developers rendering multimodal, touchscreen-based graphics.

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