HoliBraille: Multipoint Vibrotactile Feedback on Mobile Devices

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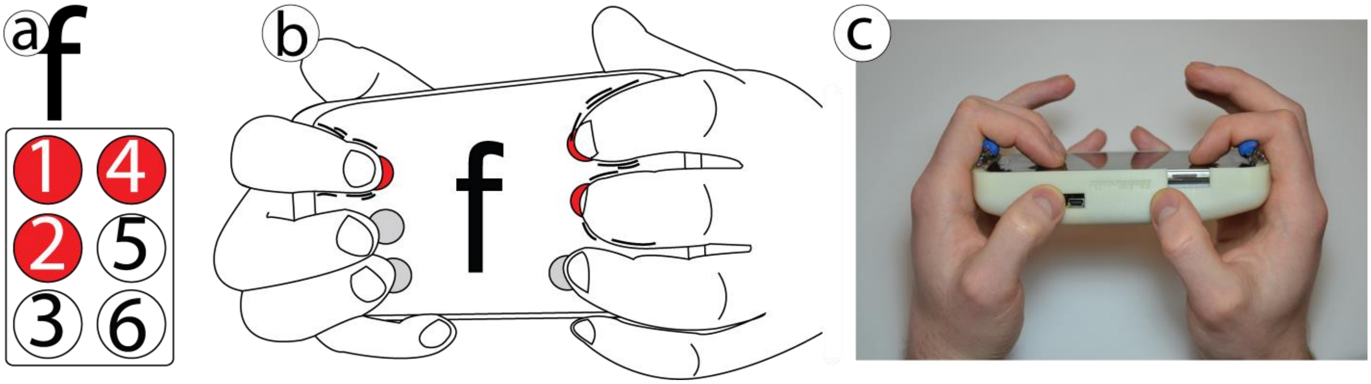


Figure 1. HoliBraille, a multipoint vibrotactile output system for touchscreen mobile devices. (a) Representation of 'f' using the Braille code: dots 1, 2, and 4. (b) The system outputs character 'f' through direct and localized feedback on the user's fingers. (c) The system consists of six vibrotactile motors attached to springs and a 3D-printed case. The springs mould to users' hands and dampen vibrations through the device allowing better stimuli discrimination

ABSTRACT

We propose HoliBraille, a system that enables Braille input and output on current mobile devices. We use vibrotactile motors combined with dampening materials in order to actuate directly on users' fingers. The prototype can be attached to current capacitive touchscreen devices enabling multipoint and localized feedback. HoliBraille can be leveraged in several applications including educational tools for learning Braille, as a communication device for deaf-blind people, and as a tactile feedback system for multitouch Braille input. We conducted a user study with 12 blind participants on Braille character discrimination. Results show that HoliBraille is effective in providing localized feedback; however, character discrimination performance is strongly related with number of simultaneous stimuli. We finish by discussing the obtained results and propose future research avenues to improve multipoint vibrotactile perception.

Categories and Subject Descriptors

H.5.2 **[User Interfaces]**: Input devices and strategies; Haptic I/O, Prototyping.

General Terms

Measurement, Design, Experimentation, Human Factors.

Keywords

Braille; Blind; Input; Output; Multitouch; Vibrotactile.

1. INTRODUCTION

Touchscreen devices are widely used and seem to be the trend for future generations of smartphones. Although touch interfaces are inherently visually demanding, previous research has leveraged touchscreens to provide new input methods for blind users [7]. Particularly, multitouch Braille-based text-entry techniques enable non-visual input using chording actions. However, there is not a non-visual multipoint output method that enables a dialog between the device and the user. Both auditory feedback and single vibrations can inform that a touch occurred; yet, feedback is non-local and usually undirected, failing to provide chording information. Thus, an output channel that actuates directly on users' fingers, supporting localized multipoint feedback is needed.

One common approach is the use of vibrotactile feedback. For example, there have been efforts in using the mobile devices' built-in motor to provide vibrotactile patterns that represent the six-point Braille cell [3, 6]. However, these approaches require users to explore each dot of the Braille cell on the screen in order to decode the information. This method is inherently slow (4-27s) and does not work as real-time chording feedback. Wearables have also been used to convey Braille information directly on peoples' body using an array of actuators [5]. Still, they require users to constantly wear these devices. Alternatively, users can put them on, prior to use, reducing the potential for spontaneous interaction. To our knowledge, there are no reports of a mobile solution capable providing multipoint Braille output on current touchscreen devices.

We introduce HoliBraille (Figure 1), a system capable of localized vibrotactile feedback that can be combined with the input capabilities of mobile devices. We used a custom-made case and off-the-shelf vibrotactile actuators combined with dampening materials. The solution can be attached to mainstream touchscreen devices enabling direct feedback on users' fingers. In this paper, we contribute the following: 1) some application scenarios that can benefit from HoliBraille; 2) the design and technical description of the proposed device; and 3) an evaluation of HoliBraille on a foundational task for future Braille-related applications, i.e. character discrimination.

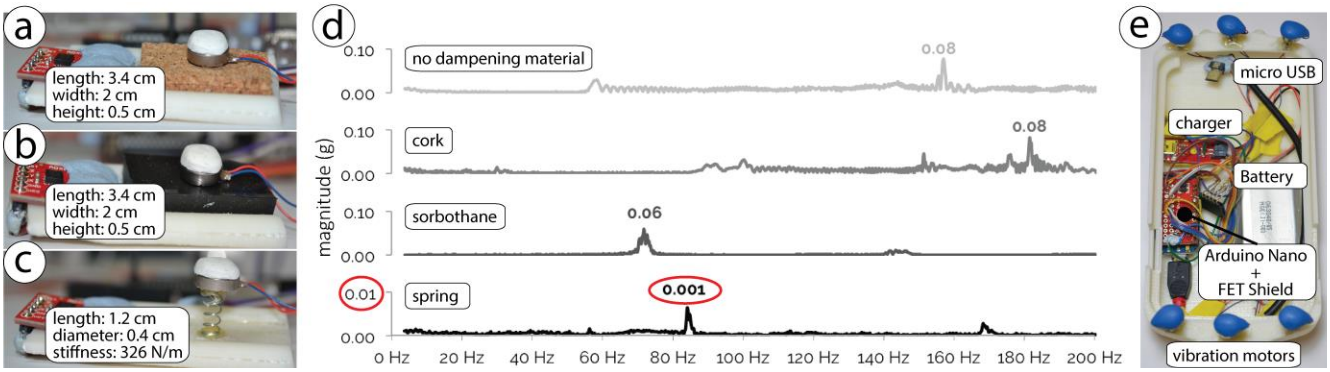


Figure 2. Dampening materials: (a) cork, (b) sorbothane, (c) spring. (d) Spectrum plot with peak magnitude labeled. Y-axis scale is 10 times lower for spring plot and its peak magnitude is significantly lower than other materials. (e) HoliBraille's components.

2. HOLIBRAILLE SCENARIOS

Before describing HoliBraille, we present four scenarios that highlight the unique benefits of the system.

Deaf-Blind communication. Finger Braille is one of the communication techniques used by deaf-blind people. It requires a dedicated non-disabled person, skilled in Finger Braille, in order to code information on the fingers of the receiver as s/he is typing on a Braille typewriter. Such service is expensive and not available on-demand. We envision an all-in-one communication device for this user group by combining HoliBraille and a mainstream smartphone.

Braille literacy. Without reading and writing skills, blind people can face serious challenges to achieve autonomy, financial independency, and contribute to society. HoliBraille can be used in novel methods of teaching Braille. For instance, mobile applications can leverage direct and localized feedback on users' fingers to illustrate the Braille code. Furthermore, tactile feedback can improve users engagement and learning experience. Indeed, further research should investigate whether this multimodal approach increases memorability and learning effectiveness.

Braille typing. Augmenting multitouch Braille-based input techniques with tactile cues is possibly one of the most natural applications. These keyboards are generally error-prone when compared to their physical counterparts [7] due to the inexistence of physical keys. Conveying tactile information directly on users' fingers and being able to "feel" each key could be a great improvement to a non-visual typing experience.

Private interaction. Smartphones contain sensitive and personal data (e.g. emails, bank details). Nonetheless, they are used in public spaces where users face the threat of shoulder surfing. This is especially relevant for blind people, since they may not be aware of such a threat. HoliBraille can be used as a private reading device. Also, novel authentication techniques can be devised to leverage haptic feedback. Specifically, the system could ask the user to input the first, fifth, and sixth characters of her password, solely using tactile feedback, thus preventing others from snooping.

3. THE DESIGN OF HOLIBRAILLE

A preliminary design of HoliBraille was presented in [4]. In this section, we present a refined version of the device in reproducible detail. Moreover, we contribute with a preliminary user study of stimuli discrimination and a technical assessment on vibration propagation between actuators.

Design. The design of HoliBraille is strongly related with the Braille input method. Chord actions are used to code Braille characters (3x2 matrix, Figure 1-a) and input text on touchscreen devices. The input mechanism relies on BrailleTouch's [7] usage setup (Figure 1-b), having the screen facing away from the user. The major contribution of HoliBraille design consists of its output mechanism. It includes six vibration motors on the top and bottom of the device. Each actuator represents one dot of the Braille cell. Prior work [8] has explored the use of multiple motors attached to a mobile device in order to produce multipoint vibrations on specific locations. This approach has a well-known side effect: vibrations go through the device. As a result, pinpointing the source of feedback is challenging. Moreover, it makes it virtually impossible to provide multiple sources of vibration, simultaneously. This is especially relevant when motors are close to each other, such as on a mobile device. In addition to technical challenges, psychophysics research also indicates that multipoint tactile discrimination can be problematic [1]. We address these issues by independently dampening each motor and thus aiming to increase stimuli discrimination.

Localized multipoint feedback. We considered a number of different dampening materials such as cork, sorbothane, and springs; these act as isolation systems that cause energy dissipation from a vibration source. These materials were chosen based on cost, availability, and appropriateness to mobile settings. Nonetheless, further research should investigate the use of other materials or even active dampening systems to provide high quality localized feedback.

Acceleration readings were collected at a 500 Hz sampling rate in order to measure the amount of vibration that went through the device with each material. We recorded 6 seconds of acceleration data and transformed it into the frequency domain through a Fast-Fourier Transform (Figure 2-d). Overall, the peak magnitude with the spring was consistently lower than with other materials, illustrating its effectiveness on dissipating vibration. While sorbothane was only able to reduce acceleration frequency, spring also reduced peak acceleration magnitude in 80-fold (from 0.08g to 0.001g).

In order to understand the effect of spring dampening on human perception, we conducted a preliminary study with 8 sighted participants (ages between 24-30, 2 female) and asked them to identify the fingers they felt vibrating. Stimuli were given on one hand at the time (on one or more fingers). We compared our prototype (Figure 1) with and without dampening. Results show that springs have a positive effect on finger discrimination. We obtained an average accuracy of 90% (SD=9%) and 73%

(SD=18%) for spring and no-spring conditions, respectively [minor effect, Z=1.951, p=.051]. Moreover, it is noteworthy that all participants were able to correctly identify single finger vibrations in the spring condition, suggesting that little noise is transmitted between fingers. However, with no dampening, accuracy decreased to 82% (SD=16%) just to identify a single source of vibration [$t_{(8)}$=2.862, p<.05].

Based on these findings, our final design consisted of six small vibration motors strategically secured to (regular pen) springs (length=1.2cm, diameter=.4cm, stiffness=326N/m) and a 3D printed case. In addition to vibration dampening, springs present an ergonomic benefit as they mould to different hand shapes and allow users to rest their hands in a confortable position. Moreover, they guarantee direct contact between fingers and actuators.

Hardware. Figure 2-e shows the HoliBraille prototype. We attached six vibration motors (Sparkfun ROB-08449) to the top and bottom of a custom-made case[1]. These motors are connected to a mini FET shield (Sparkfun DEV-09627) and Arduino Nano. The Arduino board communicates with a mobile device through the USB serial port connection. Vibration motors are powered by an external lithium battery, which is connected to a charger. Each motor is controlled by a Pulse-Width Modulated signal sent from the board, using a voltage of 2.7Volts and amplitude of 0.8G.

Software. The software running on the Arduino board receives actions (on/off) to be performed from an Android mobile device. To vibrate each motor, the application selects which fingers need to be activated and sends this information to the Arduino board; that is, each motor is controlled individually by the application.

Limitations. HoliBraille consists of a Braille input/output system that augments mainstream touchscreen devices with multitouch vibrotactile feedback. Moreover, the proposed solution is inexpensive and easy to build. However, it comprises limitations. Foremost, the tactile actuators are statically arranged to fit the Braille input method. Although we envision new hardware configurations, they are invariably linked to how the user holds the device and interacts with the screen. Additionally, our dampening material is slightly bulky, primarily due to the spring's height. Integrating a mechanism for retracting the springs when not in operation would result in a more robust and portable version of the prototype. Furthermore, springs may become deformed and degrade in dampening performance over time.

4. EVALUATION

Our goal was to validate our design and assess stimuli discrimination accuracy for Braille characters. Results inform future applications using this technology.

Participants. 12 blind participants (light perception at most), 9 male, took part in the user study. They were recruited from a training centre for visually impaired people. Their ages ranged from 23 to 63 years old, with a mean of 47 (SD=16). All participants knew the Braille alphabet and how to write with a Perkins Braille typewriter.

Apparatus. The HoliBraille device was used in the experiment. It was connected to a Samsung S4, running Android 4.3. The mobile device was connected to a laptop computer via Wi-Fi, whereas the evaluation monitor controlled the experiment through a remote application and logged the participants' answers. Each stimulus had the duration of two seconds. Previous work showed that this value is optimal for novice users, even though it can be reduced to 500ms after some practice [5]. Notice that fingers are actuated simultaneously, reducing the time needed to convey a character.

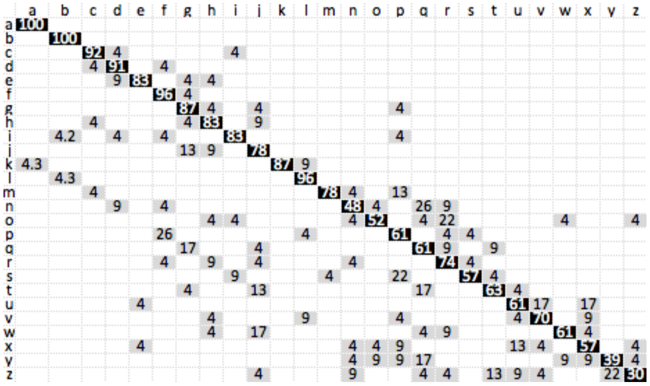
Procedure. At the beginning of the evaluation phase, participants were told that the overall purpose of the study was to investigate how vibrotactile output can be used to communicate Braille characters. We then explained the experimental setup and showed how the prototype worked. Participants were given warm-up trials for ten minutes. They sat on a chair and were asked to hold the device with the screen facing away and their fingers on the vibrotactile motors (Figure 1-c). For each evaluation trial, participants heard an auditory tone followed by a vibrotactile stimulus, randomly chosen by the evaluation application. Participants were presented with one of the 26 alphabet letters. They completed the trial by providing a verbal answer about the character they felt they had received. All participants performed 2 blocks of 26 letters. The procedure took on average 30 minutes.

Experimental Design. The independent variable that we controlled in this experiment was *letter*. Letters were randomized for each block. Participants completed all trials: 26 *letters* x 2 *blocks* x 12 *participants* = 624 trials.

5. RESULTS

Fewer dots mean higher accuracy. Figure 3 illustrates letter recognition rates with a confusion matrix. While letters 'A' ⠁ (100%), 'B' ⠃ (100%), 'F' ⠋ (96%), and 'L' ⠇ (96%) were the easiest to perceive (M=98%), 'N' ⠝ (48%), 'Y' ⠽ (39%), and 'Z' ⠵ (30%) achieved the lowest mean accuracy. Notice that '*ABFL*' require fewer stimuli than '*NYZ*', which comprise the usage of both hands and four or more fingers. Indeed, a logistic regression was performed to ascertain the effect of number of dots on likelihood of error. The model was statistically significant ($\chi^2_{(1)}$=34.442, p<.001) from the null model (no predictors) and showed a good fit to our data (Hosmer and Lemeshow Test, $\chi^2_{(3)}$=3.115, p=.374). As a result, each additional dot increased the likelihood and probability of error by a factor of 2.091 and 68%, respectively (95% CI [1.678, 2.606]). Overall, participants were able to discriminate between all Braille letters with a mean accuracy of 73% (SD=15%).

Generally misrecognizing one finger. Regarding common misperceptions, 61% of errors were due to a single finger error. This difference occurred either because participants did not feel a stimulus (e.g. omission, P ⠏ → F ⠋) or incorrectly felt a finger vibrating (e.g. insertion, S ⠎ → T ⠞). Both error types occurred with similar frequency (47% and 52%, respectively). Errors in which two fingers were misidentified accounted for 22% and



	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
a	100																									
b		100																								
c			92	4					4																	
d			4	91		4																				
e				9	83		4	4																		
f						96	4																			
g							87	4		4						4										
h			4				4	83		9																
i		4.2		4		4			83							4										
j							13	9		78																
k	4.3										87	9														
l		4.3										96														
m			4										78	4		13										
n				9		4								48	4		26	9								
o								4	4					4	52		4	22					4			4
p						26						4				61		4	4							
q							17			4							61	9		9						
r						4		9		4				4				74	4							
s									9				4			22			57	4						
t							4			13							17			63	4					
u					4																61	17		17		
v								4				9				4					4	70		9		
w								4		17							4	9					61	4		
x					4									4	4	9					13	4		57		4
y														4	9	9	17						9	9	39	4
z										4				9			4	4		13	9	4			22	30

Figure 3. Letter recognition rates (%). For instance, 4th line reads as 4% of 'd' was recognized as 'c'.

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[1] https://www.dropbox.com/s/1rp9kz2gkkn9n7q/case.SLDPRT

were, in their majority (83%), due to a combination of an omission and insertion (e.g. Y ⠽ → Q ⠟). The remaining cases, where three, four, and five fingers were misrecognized, accounted for, on average, 10%, 4%, and 2%, respectively.

Finger-dependent errors. Data showed that the most error-prone fingers were the left middle finger and right index finger. Both fingers are equally used and accounted for 35% of errors. Moreover, the left middle finger was prone to insertion errors (85%); that is, participants usually felt that finger vibrating when an adjacent finger was actuated. On the other hand, errors occurring on both ring fingers were mostly due to omissions: 85% and 92% for right and left hand, respectively. These findings suggest that vibrotactile feedback should be carefully designed in order to mitigate different types of errors, either omissions or insertions, accordingly to the fingers that are being actuated.

6. DISCUSSION AND LESSONS LEARNED

Putting results into perspective. Reading Braille is both difficult and slow for novice users. Reading individual characters on embossed paper with fingertips can take more than two minutes with 19% accuracy rates [2]. Direct and localized multipoint feedback techniques have great potential in easing this task. HoliBraille is a novel all-in-one (I/O) Braille multipoint solution for current mobile devices. Although participants were Braille typists, the reading method was completely novel. The system enabled users to identify vibrotactile Braille characters (A-Z) with less than four stimuli at 89% (average 73%) in spite of a short amount of practice; that is, less than ten minutes. In comparison to other mobile Braille feedback solutions [3], HoliBraille is two to 13 times faster due to its multipoint feedback design and presents similar error patterns of wearable vibrotactile rings [5]. Nonetheless, we believe there is room for improvement through extended periods of training and new vibrotactile feedback designs (experienced Braille readers can read about 7 characters a second from meaningful text samples).

Stimuli perception. Most errors with HoliBraille were due to one misrecognized stimulus. While some fingers were prone to insertion errors, others were commonly overlooked. Overall, 89% of ring finger errors were due to omissions, i.e. not feeling that finger vibrating. Although perceptual abilities can vary between fingers, we believe these results are also related with number of stimuli. Notice that these fingers are used in characters with three or more dots (e.g. P ⠏, Q ⠟, Y ⠽), thus they were more susceptible to omission errors. Although our prototype design, using springs, showed to be effective in reducing vibration propagation, characters consisting of four or more simultaneous stimuli were harder to recognize (55% accuracy). Accordingly to psychophysics research this result can be related to human's low tactile acuity. Indeed, we found a strong negative correlation between accuracy and number of stimuli [Pearson's $r_{(26)}=-.695$, $p<.001$], which was confirmed by debriefing comments. However, this effect can be counteracted by providing context (e.g. full words rather than individual characters), leading to significant improvements [5].

Vibrotactile Braille legibility. Findings suggest that it is crucial that the design of Braille vibrotactile feedback aims to maximize tactile perception. This paper contributes with a novel device design and empirical knowledge on multipoint discrimination. Future research should investigate the relationship between the design space of vibrotactile feedback (e.g. duration, amplitude, position, rhythm, frequency, type of motor, etc.) and multipoint discrimination. These findings would go beyond HoliBraille and inform the design of haptic feedback for multitouch interaction. For instance, different timings, vibration amplitudes, or patterns could be used depending on the fingers being actuated.

7. CONCLUSION AND FUTURE WORK

We presented HoliBraille, a novel multipoint vibrotactile device that can be attached to current mobile devices. The design of HoliBraille comprises the use of six vibrotactile motors combined with a dampening system in order to deliver direct and localized feedback on users' fingers. Results show that users can identify Braille letters at 73% average accuracy. Moreover, performance is strongly related with number of stimuli. For example, while A ⠁ and B ⠃ were always correctly recognized (100% accuracy), Z ⠵ achieved an average accuracy of 30%. Future research should aim to understand the effects of different vibrotactile features on multipoint discrimination.

8. ACKNOWLEDGMENTS

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