UbiBraille: Designing and Evaluating a Vibrotactile Braille-Reading Device

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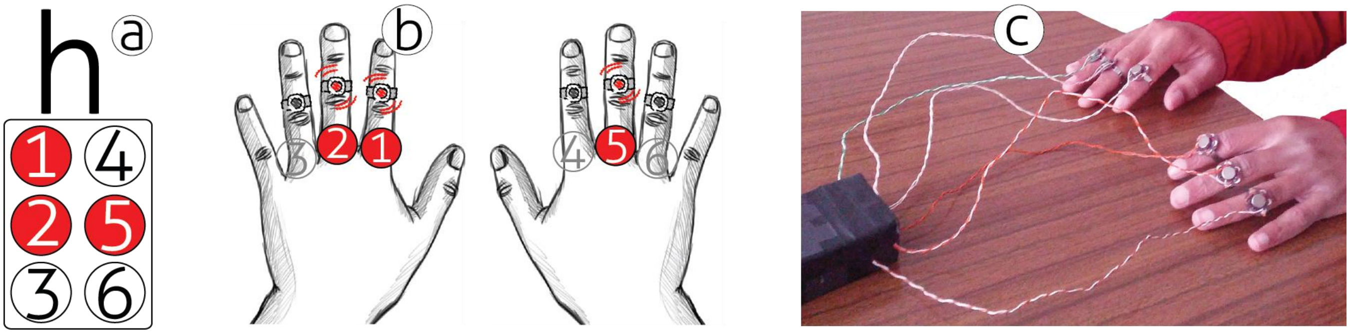

Figure 1. UbiBraille, our Braille-reading vibrotactile prototype, outputs individual characters using the same coding used for writing with a Braille typewriter. (a) The figure illustrates the matricial representation of 'h' using the Braille code: dots 1, 2, and 5. (b) The device communicates the letter by simultaneously actuating on the fingers that are used to write it on a mainstream Braille typewriter. (c) The UbiBraille prototype consists of six rings augmented with vibrotactile capabilities. The rings are worn on the index, middle, and ring fingers of both hands.

ABSTRACT

Blind people typically resort to audio feedback to access information on electronic devices. However, this modality is not always an appropriate form of output. Novel approaches that allow for private and inconspicuous interaction are paramount. In this paper, we present a vibrotactile reading device that leverages the users' Braille knowledge to read textual information. UbiBraille consists of six vibrotactile actuators that are used to code a Braille cell and communicate single characters. The device is able to simultaneously actuate the users' index, middle, and ring fingers of both hands, providing fast and mnemonic output. We conducted two user studies on UbiBraille to assess both character and word reading performance. Character recognition rates ranged from 54% to 100% and were highly character- and user-dependent. Indeed, participants with greater expertise in Braille reading/writing were able to take advantage of this knowledge and achieve higher accuracy rates. Regarding word reading performance, we investigated four different vibrotactile timing conditions. Participants were able to read entire words and obtained recognition rates up to 93% with the most proficient ones being able achieve a rate of 1 character per second.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: Haptic I/O

General Terms

Measurement, Design, Experimentation, Human Factors.

Keywords

Vibrotactile, Finger, Braille, Reading, Wearable, Blind.

1. INTRODUCTION

We are currently living in the information age. Accompanying the popularization of mobile devices, communication services such as SMS, email, twitter, facebook, and so forth, have developed rapidly. More than ever, people are constantly "online", producing and consuming textual information. In order to achieve an inclusive and truthful information society, proving equal access and opportunities to all is of upmost importance.

For blind people, this information is typically provided through auditory feedback. Unfortunately, this communication modality is not always possible or desirable. Noisy environments or privacy concerns prevent the usage of such solution. Refreshable Braille displays are an alternative, but these devices are expensive (up to $5000) and difficult to use by those with low tactile discrimination (e.g. due to diabetes). As a result, blind people may be unable to timely access the desired textual content.

We present a wearable system where vibrotactile feedback allows blind users to inconspicuously and privately access textual information. Our approach draws inspiration from the traditional Braille writing mechanism where finger chords are used to input 6-dot codes (see Figure 1).

Braille was initially devised in 1824 to give access to information to blind people when there was none. In this new information age, it revealed itself as an inspirational source to ease the mobile writing process [3, 8, 20, 18].

In this paper, we go one step further by using the Braille code to make sense of vibrotactile information; that is, vibrotactile stimuli are given simultaneously on the fingers that are used to write a given Braille character. We assess the feasibility of such approach through two user studies with Braille typists. Results for character and word discrimination are reported. Participants recognized characters, on average, with 82% accuracy with as little training as 10 minutes. More importantly, they were able to take advantage of previously acquired Braille knowledge when using UbiBraille. Regarding word discrimination, participants obtained recognition rates up to 93%. A preliminary assessment with two blind people revealed that these results scale to sentence-level decoding. These results pave way for further developments in vibrotactile stimuli empowering the communication abilities of blind people along with providing new opportunities for inconspicuous communication.

2. RELATED WORK

The related work reviewed in this section is two-fold: first, we look into previous research on vibrotactile feedback for mobile technologies; second, we focus on works leveraging the Braille alphabet to convey textual information.

2.1 Vibrotactile Output

Vibrotactile feedback has shown to improve users' performance with touchscreen devices in several tasks, such as target selection [9], text-entry [12], and list item selection [13].

Even with only one actuator, it is possible to convey semantic information via different vibration features such as frequency, rhythm, and strength [4]. Vibration patterns have been used to convey progress information, such as users' scrolling rate and position on the screen [22], or associated to Morse code [24] in order to transmit richer information. One other example is the PocketNavigator [21], which allows users to leave the device in the pocket while being guided through vibrotactile patterns that encode direction and distance.

Yatani and Truong [26] proposed the use of multiple actuators in order to generate different vibration patterns that flow in one direction to help users interact with a mobile device. Others have used similar non-visual approaches to inform users about downloads' progress [11] or enrich remote voice communication [6]. More recently, Israr and Poupyrev [14] suggested the use of an array of actuators on the users' back to provide directional information in gaming situations.

In fact, several authors have proposed the attachment of vibrotactile actuators on users' body to work as mnemonic information [5, 10, 16]. For instance, Brown et al. [5] investigated the use of multiple vibration motors on the users' arm to access calendar information. Kammoun and colleagues [16] proposed the usage of two vibrotactile bracelets in order to aid blind people during orientation and navigation tasks.

Overall, previous research has demonstrated that vibrotactile output can be used to convey semantic information and help users perform a variety of tasks when visual and auditory feedback is not available. Moreover, controlling vibration features such as frequency, intensity, and duration, as well as the number of actuators allows the production of richer feedback. In our research, we explored the usage of such features and strategically placed vibration motors on users' fingers creating a mnemonic association with the Braille-writing system.

2.2 Braille and Mobile Technologies

The Braille system was devised by Louis Braille as a method of writing and reading for blind people. Each character or cell is represented by combinations of dots on a 3 by 2 matrix (Figure 1.a). A traditional Braille keyboard consists in 7 main keys paired with each of the six dots of the Braille code and a space key. To input text, users simultaneously press the intended set of keys entering a character as a chord. Indeed, Braille is a powerful language, making it possible to represent alphabet letters, accentuated letters, punctuation, numbers, mathematical symbols or even musical notes.

In the past few years, Braille-based approaches have been proposed to allow visually-impaired people to input text on the latest mobile touchscreen devices [3, 8, 20, 18]. Both single- [20] and multi-touch [3, 8, 18] approaches have been devised for input, yet feedback is always given through the auditory channel.

Similarly to our work, other authors have also explored wearable devices that emulate the traditional Braille chord-based system [7, 2]. A key difference to our work lays in the fact that they focused on writing tasks. Our research aims to provide an alternative reading method that does not rely on visual or auditory feedback.

Rantala et al. [23] investigated several ways to present the six-point Braille cell on touchscreen mobile devices with tactile output. The authors conclude that offering a rhythm (pattern) of feedback corresponding to each point in the Braille character (separated by periods of silence) is the most efficient and positively received method.

Another example is the V-Braille [15] system. The mobile screen is divided into six regions and when the user touches any location inside a cell that represents a raised dot, the device vibrates.

More recently, Al-Qudah and colleagues [1] also proposed a vibrotactile method to present Braille characters on mobile devices. Each character is represented by two vibration patterns (one per column) that were inspired by Morse code (series of dots and dashes). Results show that character discrimination may reach 90% accuracy, however learning vibrotactile patterns may require long training phases.

Ohtsuka et al. [19] proposed Body-Braille, a system intended to help deaf-blind people communicate. The authors take advantage of the whole human body and attached six vibration motors on the users' body. As with previously presented systems, it lacks of a thorough reading performance evaluation. Indeed, most projects focus on character-level discrimination and fail to show the systems' effectiveness for communicating words.

In this paper, we present a new Braille-based vibrotactile reading concept and prototype. We also contribute two user studies on character- and word-level discrimination performance with blind participants, showing that vibrotactile reading is feasible.

3. VIBROTACTILE BRAILLE READING

The main goal of this work is the development and assessment of a vibrotactile reading system that leverages Braille knowledge. In this section, we present our design concept, as well as the built device in reproducible detail.

3.1 UbiBraille

The design of UbiBraille draws inspiration from the standard writing system of the Perkins Brailler[1]; however, with a small difference. Instead of using chords to input text, users receive vibrotactile feedback from six actuators, simultaneously. Each actuator represents one dot of the Braille cell (or character).

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[1] http://www.perkins.org/store/braillers/

Table 1. Participants' profile. From left to right: age, Self-Rated (SR) Braille writing, SR Braille reading, Braille reading speed (correct words per minute), Braille writing speed (words per minute), Braille writing quality (minimum string distance error rate), and digit span score.

Participant	Age	SR Braille Writing	SR Braille Reading	Braille Reading Speed (cWPM)	Braille Writing Speed (WPM)	Braille Writing Quality (MSD ER)	Digit Span Score
P1	27	5	4	49.41	26.41	1.28%	66
P2	33	4	4	21.32	13.35	0%	72
P3	26	4	3	40	30.61	2.08%	96
P4	21	4	2	72.41	42.84	0%	54
P5	53	5	5	75	40.78	0%	114
P6	60	5	5	45.16	8.06	0%	72
P7	62	4	5	80.77	13.41	0%	90
P8	62	3	3	19.09	15.17	1.04%	42
P9	40	5	5	40	12.35	0%	36
P10	61	5	4	38.53	3.74	3.13%	72
P11	49	4	3	19.18	21.97	2.32%	42

We first prototyped and informally tested a number of possible options before deciding where to attach the vibration motors. Various positions on the wrists and fingers were initially considered. Results showed that the middle of fingers yielded the best results in stimuli discrimination. Still, further research should thoroughly explore this issue.

Our final design consisted of small vibration motors attached to six rings that were worn in the index, middle, and ring fingers of both hands. This design has the clear advantage of providing direct correspondence to the fingers used in the Braille writing system. Thus, we expect this mnemonic feature to aid users in learning and translating vibrotactile information into their textual form.

Reading speed was also taken into account in this design. Unlike previous research, where a character consists of several vibrotactile patterns [1, 15, 23], UbiBraille encodes a character in a single point in time by actuating simultaneously in different fingers. This simultaneous feedback is provided to maximize reading speed and leverage the knowledge and habit of writing with Braille typewriters.

3.2 Hardware

Figure 1.c shows the UbiBraille prototype. Vibrotactile feedback is transmitted via adjustable aluminum rings. Each of the six rings is actuated using a lily pad vibe board[2], which comprises a small vibration motor (diameter=10mm, body length=3.4mm). The vibe boards are attached to the rings by double sided sticky tape.

In order to communicate a Braille character, the required vibration motors are turned on, using a voltage of 3.8Volts, while the remaining actuators maintain turned off. The vibration motors ran at a rated speed of 12000 rpm and amplitude of 0.8G. These motors are connected to an Arduino Mega ADK board, which is placed inside a case.

In preliminary experiments, we noticed that the vibration of each motor was also transmitted to adjacent rings whenever their wires touched. Thus, all wiring was tapped to the board's case in order to prevent this issue. The board is programmed via a USB port and communicates with a computer through a serial port connection.

3.3 Software

The software running on the Arduino board receives messages to be performed from a computer program. To vibrate each motor, the computer software selects which fingers need to be activated and sends this information to the Arduino board (it encodes the information as an array of six values).

Although our software can control the intensity of the vibration by reducing the amount of voltage sent to the motor, a pilot study showed that participants had difficulties perceiving softer vibrations.

3.4 Limitations

UbiBraille is the first prototype of our Braille reading system and therefore comprises limitations. Most importantly, it adds six wired rings to be worn by users. Although this is a proof-of-concept, we envision futuristic versions of the prototype with miniaturized, wireless, and easy to attach actuators.

4. STUDY 1: CHARACTER READING

The purpose of this user study was to validate our design concept of using the Braille writing system as a mnemonic to read vibrotactile information. Particularly, we were interested in answering questions such as: Will participants be able to correctly discriminate simultaneous stimuli on their fingers? Will they be able to take advantage of previous knowledge of Braille writing system and correctly identify the required characters? What will be the most common errors?

4.1 Participants

Eleven blind participants (light perception at most), 8 male and 3 female, took part in the user study. They were recruited from a formation centre for blind and visually impaired people. Their age ranged from 21 to 61, with a mean of 45 (SD=16) years old. All participants knew the Braille alphabet and how to write with a Perkins Braille typewriter. Table 1 depicts the participants' profile regarding age, self-rated Braille reading/writing, Braille reading/writing speed, and digit span score.

4.2 Apparatus

The UbiBraille device, previously described in Section 3, was used in the experiment. The Arduino Mega ADK was connected to a laptop computer via USB connection, whereas the evaluation monitor controlled the experiment through a C# application.

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[2] http://lilypadarduino.org/?p=514

Figure 2. Participant during user study. His hands were resting on the table whilst receiving vibrotactile feedback.

Each stimulus had the duration of two seconds. In an informal pilot user study, this value showed to be sufficient to feel and discriminate different stimuli. The evaluation monitor registered the participants' answers in the evaluation program for later analysis. Moreover, video and sound were recorded throughout the user study.

4.3 Procedure

The user study comprised two phases that were conducted in different days: one to assess the participants' profiles and a second session to investigate character discrimination performance. Both phases were conducted in a formation centre for blind and visually-impaired people.

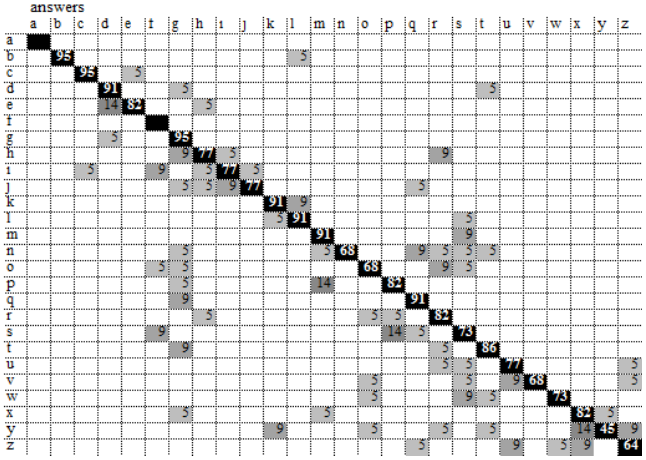
The characterization session took approximately 15 minutes and included: an oral questionnaire about demographic data and Braille proficiency; a Braille reading/writing evaluation; and a working memory assessment.

To assess Braille proficiency, participants were asked to input text with a Perkins Braille typewriter and read a series of words from a paper sheet. For the writing evaluation, participants were asked to write three individual sentences as fast and accurately as possible. The Perkins typewriter was made available by the researchers. Speed and accuracy results are illustrated in Table 1 as words per minute and minimum string distance error rate [17], respectively.

For the reading assessment, participants were asked to read 70 Braille written words and repeat them as fast and accurately as possible. All words had 5 characters and were extracted from a *corpus* that consisted in the most commonly used Portuguese words.

To evaluate attention and memory, the subtest Digit Span of the revised Wechsler Adult Intelligence Scale (WAIS-R) was used [25]. In a first phase, the participant must repeat increasingly long series of digits presented orally, and on a second stage, repeat additional sets of numbers but backwards. The last number of digits of a series properly repeated allows calculation of a grade to the participant's working memory.

On the second day, 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 place their hands on the table in a comfortable position (Figure 2).



answers

	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	■																									
b		95										5														
c			95		5																					
d				91			5													5						
e				14	82			5																		
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p							5						14			82										
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v															5				5		9	68				5
w															5				9	5			73			
x							5						5											82	5	
y											9				5			5		5				14	45	9
z																	5				9		5	9		64

Figure 3. Letter recognition rates (%). 7th line reads as 5% of 'g' has been recognized as a 'd'.

For each evaluation trial, participants heard an auditory signal 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 an answer about the character they felt they had received. All participants performed 2 blocks of 26 letters. The evaluation procedure took on average 30 minutes.

4.4 Design and Analysis

The study used a 26 x 2 within-subjects design with one independent variable: letter. Letters were randomized for each block. Participants completed all trials: 26 *letters* x 2 *blocks* x 11 *participants* = 572 *trials*. Letter Recognition Rate did not present a normal distribution (Shapiro-Wilk, p<.05). Statistical analysis to this and other ordinal values was performed resorting to Friedman test and Wilcoxon Signed rank tests. Post-hoc tests were applied with Bonferroni corrections.

4.5 Results

Braille characters vary in the number of dots used as well as in the combination of those. As such, while an *'a'* is represented as a single dot of the 6-dot cell (⠁), an *'h'* uses 3 dots (⠓). Analogously, UbiBraille communicates characters by vibrating the fingers used to input these Braille codes on traditional Braille typewriters.

Letters NOVYZ harder to recognize. Overall, participants obtained an average accuracy of 82% (SD=17.25%). The confusion matrix in Figure 3 presents character-level recognition accuracy as well as the relationship between asked and recognized characters. We found higher error rates on characters that required several stimuli on both hands. Examples of characters with the highest average error rates are the *'Y'* (54.5%), 'Z' (36.4%), *'N'*, *'O'*, and *'V'* (all with 32%). All of these codes comprise the usage of both hands and a high number of stimuli (four or more). Exception is made for 'O', which is coded with 3 dots (⠕); however, showed a pattern that is prone to be confused.

Half of the errors were due to 1-finger issues. More than half (M=51.6%) of the recognition errors were characterized by having one inaccurately identified single dot (or stimulus). These are the cases where a false positive (e.g., S ⠎ → P ⠏) or false negative (e.g., P ⠏ → M ⠍) occurs. Both error patterns were balanced in the

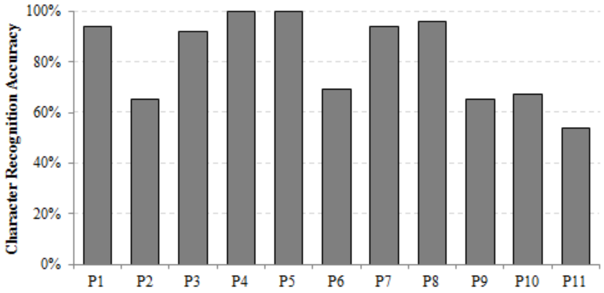

Figure 4. Character recognition accuracy per participant.

number of occurrences (M=46% and M=54%, respectively). Overall, there are two main causes of errors: 1) omitting a stimulus when all fingers in that hand are being actuated (omission) or 2) incorrectly feeling a finger vibrating when nearby fingers are vibrating.

The cases where two fingers were misidentified (M=25.3%) were in their majority (M=84%) due to the combination of a false positive and false negative (e.g., M ⠍ → S ⠎). The remaining cases, where more than two fingers were misrecognized accounted for, on average, 23.1% of errors.

The effect of individual differences. Due to the small size of the sample, results are prone to be affected by individual behaviors (see Figure 4). For instance, two participants correctly identified all characters on both trial blocks (total of 52 trials) while 4 others showed a recognition error rate equal or lower than 8%, meaning that they misinterpreted 4 of the 52 presented characters. On the other hand, 4 participants misidentified between 30% and 35% of the prompted codes, while one participant showed a recognition error rate of 46%.

Although the majority of the participants were able to effectively identify most letters, there is still a large difference between the ones with best performance (error rates as low as 0%) and the ones that were not able to identify more than 30% of the codes (worst case of 46%). We explored how these results relate to the participants' individual attributes: age; Braille proficiency; and attention and memory (i.e. digit span).

Participants can leverage Braille knowledge. Letter recognition error rate was not correlated with participants' *age*. In fact, this absence of correlation had been already revealed when relating a*ge* with Braille writing and reading functional performance (see Table 1). Moreover, no significant correlations were found with the participants' self-ratings for writing and reading Braille abilities.

On the other hand, participants' performance on Braille-based tasks showed to be significantly correlated with recognition rate. Faster Braille readers were more accurate at identifying characters [Spearman correlation, rho=-.571, *p*=.066, N=11]. We found the same effect with Braille writing performance, where faster writers decoded characters more accurately [Spearman correlation, rho=-.627, *p*=.039, N=11). These results suggest that previous knowledge of Braille can be successfully transferred to UbiBraille usage.

Memory and Attention was not relevant to letter recognition. Digit span score, a measure for attention and memory, was not revealed as relevant to the letter identification process. This came as a surprise as, in our understanding, for a novice user this process is demanding both perceptually and cognitively. The time used for the recognition along with the unrestrained time to provide an answer may also explain why this feature was not correlated with recognition accuracy.

Still, at the debriefing phase, some participants considered UbiBraille to be attentionally demanding, at least on a learning stage, and reported to have failed recognitions in moments they felt less concentrated. Nonetheless, they all felt that they could improve performance with an extended period of training.

4.6 Discussion

User study 1 demonstrates that users are generally able to recognize single letters using UbiBraille. We also gained insights about the design of the prototype: 1) characters consisting in more than 3 dots are harder to recognize, making letters "NOVYZ" the most problematic; 2) misrecognized letters are mostly due to a single vibrotactile stimulus misinterpretation.

These findings suggest that vibrotactile stimuli should be character-dependent. A possible alternative would be to adapt vibrotactile intensity of each finger accordingly to character, and therefore ease the recognition process.

Finally, results show that users are able to transfer knowledge between previous writing experience on Braille typewriters and vibrotactile reading using UbiBraille. This means that blind users are able to take advantage of years of experience with previous technologies and resort to mnemonic memory. One particular participant stood out in this matter by being unable to identify which fingers were vibrating if asked so during the training phases, but to accurately identify the character equivalent to the vibration pattern.

5. STUDY 2: WORD READING

Previous research on vibrotactile Braille reading performance is usually restricted to character discrimination. However, the demand of identifying a single character differs from that needed to read an entire word.

In this user study, we assess the participants' performance on word reading. We believe this to be an important step to demonstrate the feasibility of such solution in real-life scenarios. In detail, we aim to find whether participants are able to read complete words using UbiBraille and at what rate.

5.1 Participants

Participants of this user study were recruited from Study 1 (see Section 4) accordingly to availability. The group was composed by a total of seven participants (Table 1: P1-P5, P7-P8).

5.2 Apparatus

The apparatus was identical to Study 1, except for the evaluation application that randomly chose and transmitted (i.e. vibrate the participants' fingers) entire words instead of individual characters.

5.3 Procedure

At the beginning of the user study, participants were told that the overall purpose of the study was to investigate how vibrotactile output can be used to communicate entire words. We then explained the experimental setup and showed how words could be transmitted. Participants were given warm-up trials for ten minutes.

For each evaluation trial, participants heard an auditory signal followed by several vibrotactile stimuli, corresponding to each character of the selected word (Grade I Braille). Characters were separated by a time interval. Four different conditions were tested (see Table 2) in order to assess the most adequate communication rate for UbiBraille's novice users. Notice that both the duration of stimulus and interval between stimuli change. Although we only explore the effect of the total interval between characters (start to start), further research is needed to investigate the effect of each of these vibrotactile features on reading performance and user preference.

Table 2. Conditions for the word reading user study.

Condition	Stimulus duration (ms)	Interval duration (ms)
4000ms	2000	2000
2000ms	1000	1000
1000ms	500	500
500ms	250	250

Participants were presented with one word at a time and were asked to identify ten words per condition. They completed each trial by providing an answer about the word they felt they had received. Each word had five characters and was extracted from a *corpus* that consisted in the most commonly used Portuguese words. No two words were given to the same participant during the study. The evaluation procedure took on average 35 minutes.

5.4 Design and Analysis

The study used a 10 x 4 within-subjects design with one independent variable: duration. Both conditions and words were randomized. Participants completed all conditions: 10 *words* x 4 *durations* x 7 *participants* = 280 *trials*. As with the previous study, not all conditions presented a normal distribution for recognition accuracy; non-parametric alternatives were used.

5.5 Results

In this section, we report results for word identification using UbiBraille prototype.

Two seconds per character for word discrimination is enough. Figure 5 illustrates the word recognition rate per duration level. A Friedman test, revealed significant differences between conditions [$\chi^2(3)=18.344$, $p<.001$]. The longest durations show very similar recognition rates suggesting that time spans higher than 2000ms are not required for word-level decoding. On the other hand, post-hoc tests with Bonferroni corrections, revealed statistically significant differences between 2000ms and 1000ms conditions [Wilcoxon Signed Rank test, Z=-2.041, $p<.05$]. Still, condition 3 (1000ms) presents a high dispersion (SD=34%), suggesting wide variations between individuals. Furthermore, duration 4 (500ms), when compared with duration 3 (1000ms), is certainly more demanding for a novice user [Wilcoxon Signed Rank test, Z=-2.379, $p<.05$], yielding a recognition error rate above 65%.

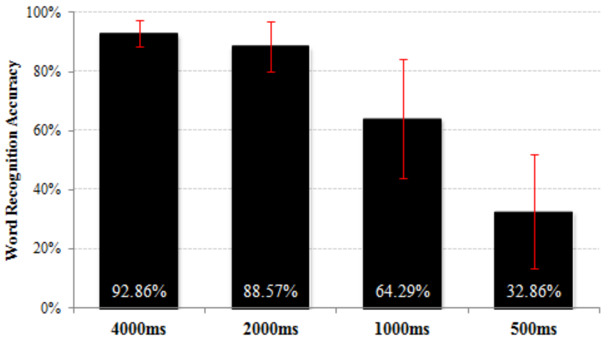

Figure 5. Word recognition accuracy per duration condition. Error bars denote 95% confidence interval.

Less demanding conditions allow for discrimination through context. Word-level discrimination comprises the recognition of individual characters plus the cognitive processes of remembering all previous letters and trying to come up with a word. It would be expected that letter and word recognition rates were somehow correlated. This correlation showed only to be significant for the most demanding condition [Spearman correlation, rho=.808, $p<.05$]. A strong correlation with minor significance was also found for the second most demanding condition (1000ms) [Spearman correlation, rho=.679, $p=.094$].

These results suggest that the negative effect of misrecognizing a letter is higher in the most demanding settings. In the less demanding conditions, participants were able to use context (i.e. previous letters) to decode the remaining characters, reducing the impact of misrecognition. In fact, participants stated that failing to understand a character in the most demanding settings, particularly characters at the beginning of the word, would make word identification very difficult. This raises a greater concern in guaranteeing the correct perception of the first characters.

Participants take advantage of Braille knowledge on word discrimination. Participants' performance on paper sheet reading tasks also showed to be significantly correlated with recognition rate for most of the conditions. Faster Braille readers were more accurate at identifying words, mainly in the second condition (2000ms) [Spearman correlation, rho=.837, $p<.05$, N=7]. We also found strong correlations with the third (1000ms) [Spearman correlation, rho=.523, $p=.229$, N=7] and fourth (500ms) [Spearman correlation, rho=.543, $p=.208$, N=7] conditions; however, non-significant ($p>.5$). The absence of correlation on the least demanding condition (4000ms) and reading proficiency can be explained by the consistent high accuracy results suggesting that higher ability levels were not stressed.

We found similar effects with Braille writing performance, where faster writers identified words more accurately. This result is most noticeable for the most demanding condition (500ms) [Spearman correlation, rho=.805, $p<.05$, N=7], where only the most proficient participants were able to timely discriminate words.

In line with character discrimination results, these findings also support that previous knowledge of Braille can be successfully transferred to UbiBraille usage, mainly in the most demanding conditions. In contrast, attention and memory abilities did not revealed themselves as relevant to the word identification process.

Participants prefer higher character durations. Regarding participants' opinions towards the presented conditions, they were consistent in stating the easiness of the longest condition while also being consistent in stating the difficulty of the shortest interval and duration.

Table 3 presents the central tendency and dispersion for the user's ratings to the easiness of perceiving a word in each setting (using a 5-point Likert scale).

Table 3. Median and Inter-Quartile Range per duration condition.

Condition	Median	IQR
4000ms	5	1
2000ms	5	2
1000ms	3	2
500ms	2	1

A Friedman test revealed the differences between settings to be significantly different [$\chi^2(3)=20.455$, $p<.001$]. Post-hoc tests, with Bonferroni corrections, revealed these differences to be significant between the two shortest settings [Wilcoxon Signed Rank test, Z=-2.428, $p<.05$] and between the two middle conditions [Wilcoxon Signed Rank test, Z=-2.530, $p<.05$]. This goes in line with participants' comments on the debriefing phase, where they stated that the second longest duration was enough for a suitable recognition.

Opinions regarding the two middle settings (i.e. 2000ms and 1000ms) were more controversial; some participants stated that the 1000ms condition was more demanding, while for others it was as demanding as the 2000ms. These differences in opinion are backed up by a larger dispersion from the central rating tendency (see Table 3, 2nd and 3rd lines).

Personalization and context may play an important role. Overall, participants stated to be able to identify words using UbiBraille. Still, they also mentioned that they felt to be improving and with more training they would be able to attain better performances. These comments suggest that there is still room for performance improvements and personalization of reading speed should be adaptable over time.

Moreover, one of the participants brought the context into the discussion and stated that it would always be dependent of that. If alone and fully concentrated on the reading, then a faster setting could, and should, be employed; on the other hand, if in a more demanding situation (e.g., in the street), only the longest settings, where there is time for contextual decoding, would be feasible.

5.6 Discussion

User study 2 showed that blind users are able to read entire words using UbiBraille. Moreover, according to recognition results and participants' opinions, the 2000ms duration (stimulus and interval) seems to be a reasonable one for individual character transmission. Nonetheless, three of the seven participants were able to read words using the 1000ms condition and obtaining accuracy rates between 90-100%. This would result in a reading rate of approximately 12 words per minute resorting exclusively to vibrotactile output.

These findings are in line with the BodyBraille [19] prototype's, which also showed a communication rate of about one character per second for deaf-blind users. However, participants had three opportunities to guess the right word. V-Braille [15], allowed for much slower rates, ranging between 4.2 and 26.6 seconds per character, which could result in approximately 13 minutes to read a 21-character sentence.

A preliminary assessment of UbiBraille's ability to transmit 5-word (average size of 4.48 characters) sentences using the 1000ms condition was conducted with two participants. Interval between words was 1000ms. One of the participants obtained a perfect score by correctly identifying 10 sentences. The second participant achieved an 8/10 score and only misrecognized three words.

These results demonstrate the potential of the prototype to go beyond single word transmission and communicate comprehensive messages. Still, considering the participants' reading speed of 12 words per minute, we do not aim to replace auditory feedback. However, when audio is inadequate (e.g. meeting) or impossible (e.g. deaf-blind) to use, UbiBraille shows to be a viable solution for reading short text messages.

Reading complete sentences through vibrotactile feedback requires a great deal of attention. UbiBraille can be extended with navigation mechanisms, which can ease the cognitive load and provide reading speed control. Indeed, these issues were considered in the design of UbiBraille; since users wear rings to perceive information, it enables them to use the fingertips to perform other actions, for example, on a mobile device screen.

6. CONCLUSION

We have presented UbiBraille, a non-visual, non-auditory output device that actuates on users' fingers through vibrotactile feedback. UbiBraille allows blind users to leverage Braille knowledge by using a similar metaphor to traditional Braille writing systems. Six actuators are placed on the users' index, middle, and ring fingers of both hands, taking advantage of their mnemonic associations with a Braille character. Letters are communicated through simultaneous stimuli on users' fingers.

In this paper, we demonstrated the feasibility of such approach and report character and word discrimination performance. Recognition rates are usually high; however, some characters are more troublesome. For example, while 'A' and 'F' were always correctly recognized (100%), 'Y' obtained an average accuracy of 45%. Indeed, some error patterns emerged from our data. For instance, both number of stimuli and number of actuated hands have a negative effect on recognition rates. We intend to address this issue by dynamically adapting vibrotactile features, such as intensity and duration, and improve character discrimination. Nevertheless, participants obtained on average 92.86% accuracy on word recognition tasks, if stimuli and interval duration were carefully selected. Moreover, results showed that participants were able to take advantage of their Braille expertise and transfer that knowledge in order to correctly recognize words.

Furthermore, preliminary results with two participants provided anecdotal evidence that UbiBraille enables reading complete sentences, which goes beyond other Braille-based reading approaches, and suggests its use for inconspicuous textual communication.

7. FUTURE WORK

While this work focused on knowledgeable Braille typists, we believe that UbiBraille can also be used for novice Braille users. Particularly, we envision it being used in in-class situations as an alternative reinforcement modality to the teacher's speech descriptions while learning Braille. In fact, the device can be deployed in many different domains, such as entertainment, games, communication, learning, and so forth.

Finally, in line with the presented related work, we envision its usage as a device to facilitate and improve communication with deaf-blind people.

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