Methods for Presenting Braille Characters on a Mobile Device with a Touchscreen and Tactile Feedback

Jussi Rantala, Roope Raisamo, Jani Lylykangas, Veikko Surakka, Jukka Raisamo, Katri Salminen, Toni Pakkanen, and Arto Hippula

Abstract—Three novel interaction methods were designed for reading six-dot Braille characters from the touchscreen of a mobile device. A prototype device with a piezoelectric actuator embedded under the touchscreen was used to create tactile feedback. The three interaction methods, scan, sweep, and rhythm, enabled users to read Braille characters one at a time either by exploring the characters dot by dot or by sensing a rhythmic pattern presented on the screen. The methods were tested with five blind Braille readers as a proof of concept. The results of the first experiment showed that all three methods can be used to convey information as the participants could accurately (91-97 percent) recognize individual characters. In the second experiment, the presentation rate of the most efficient and preferred method, the rhythm, was varied. A mean recognition accuracy of 70 percent was found when the speed of presenting a single character was nearly doubled from the first experiment. The results showed that temporal tactile feedback and Braille coding can be used to transmit single-character information while further studies are still needed to evaluate the presentation of serial information, i.e., multiple Braille characters.

Index Terms—Assistive technologies for persons with disabilities, haptic I/O, input devices and strategies, interaction styles.

1 Introduction

Interacting with mobile devices is challenging for the visually impaired. Getting proper feedback and information on the state of the device is especially problematic as the use of devices is currently based mainly on visual information. Recently, as the computational power of mobile devices has increased, screen readers coupled with speech synthesizers, e.g., [1], [2], have become available for a limited number of devices. However, speech output is not a private medium if used without headphones. In certain situations, such as public spaces, synthesized speech may be inconvenient or even impossible to listen to. The use of synthesized speech also causes disturbance to the environment. Headphones, on the other hand, may prevent one from hearing what is happening around, making it hard to observe the environment.

1.1 Braille Displays

Many blind mobile device users are accustomed to using their tactile sense for reading Braille; for them, it is one of the most common ways of acquiring information. Braille is a reading and writing system which transliterates traditional written letters into tactile characters. In six-dot Braille, each character consists of a rectangular array of two columns and three rows where individual dots are either raised or lowered (Fig. 1).

Braille is read by gliding the fingers over the dots forming the characters. Shapes outlined by individual dots are used for mentally constructing a geometric model of the layout of the Braille characters [3]. It has also been claimed that the reading of Braille is mainly based on variations in dot spacing and density [4]. This is the case especially when longer texts are read instead of individual characters.

Nowadays, mechanical Braille displays are used alongside traditional Braille, which is embossed on paper. Braille displays are devices that usually have up to 80 Braille cells. Each cell typically has six pins controlled by individual electromechanical actuators. Textual information, for example, in a document or in a menu, is transmitted via screen reader software to a Braille display. Although current Braille displays are widely used, two major drawbacks hinder the use of these devices in everyday life: their price and poor portability.

According to Roberts et al. [3], Levesque et al. [5], and Ramstein [6], the price of current Braille displays is a major obstacle for potential users. A standard Braille display for desktop computers typically costs between 5,000 and 15,000 USD. For this reason, there has been research on alternative approaches to cut down the cost of such devices. One common way has been to reduce the number of actuators. Instead of placing individual actuators for each dot, displays with fewer electromechanical parts have been built.

Roberts et al. [3] simplified the mechanical design by creating a Braille display which was based on a rotating wheel with the characters molded around its surface. Users

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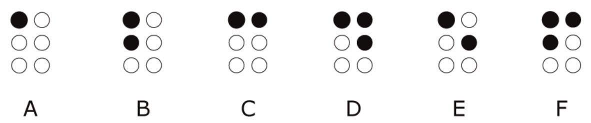

Fig. 1. Examples of six-dot Braille characters where black dots represent raised dots.

placed their fingers against the wheel and thereby received an impression of a continuous line of Braille characters without actually moving their fingers. In another approach, Levesque et al. [5] created a virtual Braille display by applying lateral skin deformation to the fingertip. By creating an impression of objects sliding on the skin, pairs of two Braille dots could be presented at a time. In a later study, Levesque et al. [7] extended their work to present six-dot Braille by applying lateral skin deformation two dimensionally. This presentation technique was shown to be legible as participants read 69 percent of meaningful five-letter words correctly with an average duration of 9 seconds per word. When reading meaningless strings of five letters, reading accuracy of 57 percent and average duration of 12 seconds per string were measured.

However, these less expensive alternatives to traditional Braille displays, e.g., [3], [5], [7], require custom-built devices and cannot be easily miniaturized for mobile use. Nonetheless, the portability of Braille reading devices has lately become an important factor as the use of technical devices shifts toward mobile contexts: there is a growing need to acquire information by using touch regardless of the user's location. Manufacturers have become aware of this, and more compact Braille displays for mobile use, e.g., [8], [9], [10], have already been developed. These displays are typically equipped with 12-40 Braille cells and have a wireless connection to mobile phones or handheld devices.

Although this has been a major step forward, external Braille displays for mobile devices may be inconvenient to use if the amount of information is limited. In mobile use, this is often the case when users would like, for example, to browse their contacts or read a short text message. If these few characters and words could be read without first having to attach external displays, the usability of mobile devices would improve significantly. Moreover, any external appliances shorten the already limited battery life of the host device even more. Therefore, we believe that it is important to investigate alternative solutions to transmit information based on Braille coding without using additional and expensive aids.

1.2 Tactile Actuators for Mobile Devices

Recently, there has been a major increase in the number of solutions available for producing tactile feedback for mobile devices. Earlier, virtually only vibration motors with eccentric rotating weights were used in devices such as mobile phones to provide coarse vibrotactile feedback to the user. It is characteristic of this actuator type that the vibration resonates through the entire device and that it has a very limited capacity to modify the feedback. In addition, making the rotating weight both speed up and slow down causes notable latencies in presenting the feedback, thereby making the actuator inappropriate for certain purposes where accurate and varying feedback is required.

Better actuators capable of producing more fine-grained tactile feedback have lately been used. Among the first were Fukumoto and Sugimura [11] who placed a voice coil actuator on the back panel of a handheld device. Because of the low latency of the actuator, the impression of manipulating real buttons on the screen was strong [12]. The downside of using voice coils is their limited frequency and amplitude range, which make it difficult to create complex feedback patterns.

Luk et al. [13] and Pasquero et al. [14] introduced a handheld device with a small tactile display based on piezoelectric actuators. A vertically aligned line of eight piezoelectric bending actuators was used for applying lateral skin stretch to the user's thumb. Similar actuators are used, for example, in most current Braille displays in horizontal orientation to raise the pins. The thumb display is a more portable, compact, and lightweight version of its predecessor, the virtual Braille display, by Levesque et al. [5]. In the handheld prototype, the tactile display was mounted on a slider located on the left side of the device. The slider was pressure sensitive and thus could also be used as an input device.

Moreover, Poupyrev et al. [12] created a tactile display using a piezoelectric actuator. Tactile feedback was provided to the hand holding the device through the back panel. In a later study, Poupyrev and Maruyama [15] embedded the piezoelectric actuator right underneath the screen of a handheld device to create a direct tactile display where the feedback was felt right under the current contact point on the display. Similar direct feedback displays based on piezoelectric actuators have been used successfully in several other studies, e.g., [16], [17], [18], and have proven to be particularly suitable for mobile devices. This is due to their durability and their ability to offer efficient and versatile actuation [18].

The actuators introduced above provide new opportunities to create more robust and localized tactile feedback. This promotes the use of haptic feedback for communicating complex information on mobile devices (e.g., characters and geometric forms) as the stimuli patterns can be made more distinguishable and mapped spatially when used together with a touchscreen.

1.3 Toward Vibrotactile Braille Presentation

Looking for a novel and widely usable way to convey information in tactile form, we started to investigate whether Braille characters could be presented in mobile devices. We propose a different approach from the expensive and external Braille displays: to utilize tactile actuators not specifically designed to present Braille. This research was motivated by an initial user requirement study carried out among the visually impaired, revealing the need for a way to read Braille characters without additional displays. The respondents suggested that Braille could be used in mobile devices, for example, to provide numerical or alphabetical cues to make the user more confident when navigating in complex menu structures. In addition, single Braille characters could be used for choosing any kind of options in the software. Thus, the amount of information that needs to be read via haptics is not

Fig. 2. Nokia 770 internet tablet.

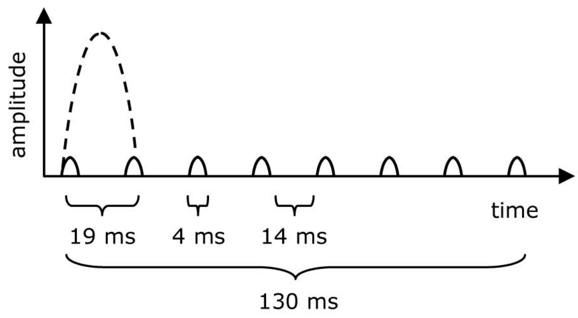

Fig. 3. An illustration of pulse shapes and durations of tactile feedback for presenting raised (broken line) and lowered (solid line) Braille dots.

necessarily large, but the option would nevertheless be very helpful. Currently, most mobile devices provide the visually impaired with only little or no information at all on the state of the device.

The aim of this study was to make it possible to read single Braille characters using a piezoelectric actuator solution embedded under the touchscreen of a mobile device. Users read characters dot by dot, either by exploring the dots based on traditional character layouts or by sensing the dots via a tactile rhythm at the point of contact on the screen. In all three methods, the Braille characters were placed on the screen in relation to the location where the user first touched the screen. For raised dots, tactile feedback representing a bump was produced. Lowered dots were represented with less powerful vibration-like tactile patterns to indicate blank space.

Although traditional Braille is based on reading multiple characters consecutively, the focus in this paper is on presenting single characters. Our main goal was to investigate whether it was possible for blind users to recognize Braille characters using only a touchscreen augmented with temporal tactile feedback. The use of single characters was chosen for this purpose.

We start by describing the design and implementation process of our Braille reading methods where each of the three methods and their use are introduced in detail. We then report the results of two experiments conducted with five blind participants. Finally, we conclude by discussing the findings and future plans in light of the present work.

2 Presentation Methods

We developed the Braille presentation methods using a prototype device based on the Nokia 770 Internet Tablet (Fig. 2; http://europe.nokia.com/770). Nokia 770 is a handheld tablet which has a large touchscreen (800 pixels $\times$ 480 pixels or 90 mm $\times$ 55 mm). The prototype was equipped with a piezoelectric actuator solution which was embedded under the touchscreen of the device. By utilizing this actuator technology, we were able to produce tactile feedback on the touchscreen with various pulse shapes and displacement amplitudes. The sharpness of the feedback pulses was controlled by the current fed to the piezoelectric actuator and the displacement amplitude by the driving voltage [19]. This control method expanded the variability of the tactile stimuli enabling much more freedom for haptic stimuli design compared to the actuator solutions (e.g., vibration motors) commonly used in mobile devices [16]. For a more detailed description of the piezoelectric actuator solution, see earlier research by Laitinen and Mäenpää [16] and Tikka and Laitinen [18].

The tactile feedback created by the device cannot be targeted at any specific location on the screen. As the entire display vibrates, the traditional layout of six simultaneously presented physical dots could not be used. Instead, Braille characters were read by perceiving each dot individually. This created an impression of localized feedback: When a user touched the screen, the feedback was felt to be located right under the contact point. Thus, we could effectively produce location-specific tactile feedback to provide spatiotemporal information.

2.1 Design of the Tactile Feedback

We used the piezoelectric actuator for creating tactile feedback for raised and lowered Braille dots. We designed the feedback in an iterative process and validated the designs by pilot testing with sighted users. Initially, we tried to create the feedback by varying only the amplitude of the stimuli. It was immediately found that the feedback for raised and lowered dots could not be reliably differentiated in this way. It was especially difficult for the users to recognize if the first dot of a character was raised or lowered before being able to compare it with the feedback of the other dots.

In the next design, we strove for more differentiable feedback. The tactile feedback for raised dots (broken line in Fig. 3) consisted of a single pulse, which was set to be as noticeable as possible using the maximum amplitude of 30 μm. The duration of this feedback was 19 ms. The lowered dots were composed of separate lower amplitude pulses (solid line in Fig. 3). Eight individual pulses with a duration of 4 ms were separated using intervals of 14 ms. Thus, the overall duration of the feedback for lowered dots was approximately 130 ms. This was chosen to be the final design as the feedback was recognized accurately by our pilot users.

After having designed the feedback, we carried out iterative constructive research on a successful presentation method. First, we divided the screen area roughly into six blocks representing the distribution of the six Braille dots in a 2 $\times$ 3 matrix. Users could freely explore the matrix of Braille dots and tactile feedback was provided when touch input was detected in one of the six areas. As the sizes of the areas (i.e., individual dots) were very large, it soon became apparent that it would be neither easy nor practical to read

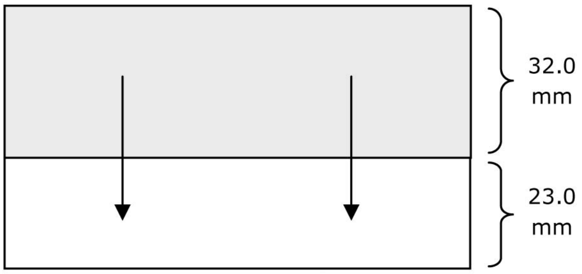

Fig. 4. Examples of allowed scan gestures starting from the gray activation area (55 mm × 32 mm or 800 pixels × 280 pixels).

characters by explicitly pointing the fixed areas one at a time. We decided to make the characters smaller and benefit from the large screen area by adjusting the dots according to the initial point of contact on the screen. This iterative research phase led to a set of three separate presentation methods. In our later implementations, the screen could be touched at any desired location assuming that the method-specific boundary conditions were met. Either a stylus or finger could be used with the methods. For simplicity, we use stylus in the following subsections where the methods and their limitations are explained in more detail.

2.2 Braille Scan

The Braille scan method used the traditional six-dot Braille layout where the dots are placed in a 2 × 3 matrix. Characters were read by moving a stylus on the screen from dot to dot starting from dot 1 in the top left corner of the character. The standard numbering of Braille dots is presented in Fig. 5. The dots were available for reading from the moment the stylus was placed on the screen until it was lifted off. Because of this the six dots must be read with a single gesture. On the following touches, the dot positions were readjusted.

The reading was started by placing the stylus at a random point on the upper part of the screen (Fig. 4). The allowed starting region was defined as a rectangle of dimensions 90 mm × 32 mm (800 pixels × 280 pixels). Braille characters were positioned downward from the touch location, and a minimum downward movement of 23.0 mm (200 pixels) was needed to read all three dots in a column. Tactile feedback was produced only once for each dot. Thus, it was not possible to move backward but the whole character had to be read again.

In the initial version of the scan method, the first dot was presented as soon as the screen was touched. After the first column had been read by moving downward, the stylus had to be moved upward until it reached the vertical height of the first dot. After that, the fourth dot was again immediately presented. In addition to moving upward, the stylus had to be moved a minimum of one pixel to the right to symbolize the change of column after the third dot. However, in the pilot tests, we found problems in moving the stylus in the designed manner. The change of columns between the third and the fourth dots particularly seemed to cause difficulties. Besides, as the feedback was produced immediately when a touch was recognized, users felt that they were not yet prepared and in many cases, they completely missed the first dot. This applied to the first dot in the second column (dot 4) as well.

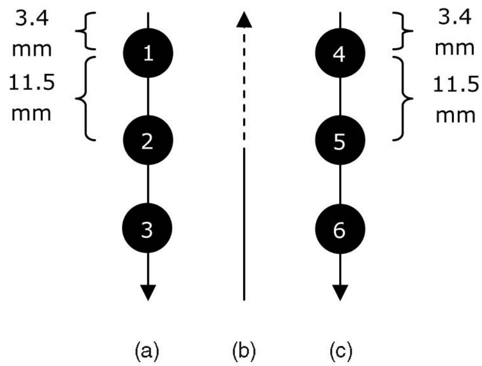

Fig. 5. The use of the scan method. After (a) reading the first three dots, the (b) stylus was moved at least one step upward to (c) read the last three dots.

Based on the findings, we optimized the scan method to make it more usable. Fig. 5 illustrates the final version of the scan method. The stylus had to be moved 3.4 mm (30 pixels) downward from the initial point of contact before the first dot was presented (Fig. 5a). The two following dots were read by moving downward two 11.5 mm (100 pixels) steps. After reading the left column, the stylus was moved upward at least one step 11.5 mm (100 pixels) from the level of dot 3 (Fig. 5b). Horizontal movement was no longer needed to access the second column of dots. The application recognized when the upward movement stopped and placed the fourth dot 3.4 mm (30 pixels) below this turning point (Fig. 5c). In this way, the feedback of the fourth dot did not come unexpectedly and users had more control over reading. The fifth and the sixth dots were read by moving two steps downward.

The pilot studies showed that the standard Braille dimensions where the dots are placed in a grid defined by a 2.5 mm distance would be virtually impossible to use. This was due to the fact that the reading gestures could not be made precise enough to differentiate between individual dots. During piloting with different dimensions, we found the dot density to be suitable when the normal dot distance was multiplied by 4.6, thus making the gaps between dots 11.5 mm long.

2.3 Braille Sweep

In the Braille sweep method, the dots were laid out horizontally instead of the standard matrix. The layout was adopted from Braille writers using a similar six-key layout to form characters. On the keyboard, the left-hand controls dots 3, 2, and 1 (corresponding to ring finger, middle finger, and index finger, respectively) and the right-hand controls dots 4, 5, and 6 (index finger, middle finger, and ring finger, respectively). It was an open question how this representation of inputting Braille would transfer to reading the characters.

The reading direction in the sweep method was determined depending on whether the gesture was started inside the left or the right activation area, namely, 35.5 mm × 55 mm (310 pixels × 480 pixels) in dimensions (Fig. 6).

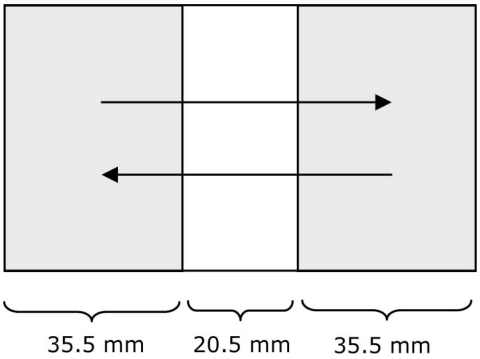

Fig. 6. Examples of allowed sweep gestures starting from the gray activation areas (35.5 mm × 55 mm or 310 pixels × 480 pixels).

To read the six dots, a minimum of 56 mm (490 pixels) of screen space was required in the horizontal direction. Fig. 7 illustrates the sweep gesture where a character is read from left to right. Similar to the scan method, the dots were lined up so that the first dot (dot 3) was placed horizontally 3.5 mm (30 pixels) away from the initial point of contact. The next two dots (dots 2 and 1) were placed to the right in 9.2 mm (80 pixels) steps. After the third dot, the next one (dot 4) was placed 16.1 mm (140 pixels) to the right to divide the dots into two groups as in Braille writers. The fifth and the sixth dots were located two smaller steps to the right. The distances between dots were decided upon after several iterations with different dot spacing.

Compared to the scan method, the stylus movements were easier in the sweep method as all the dots could be read with a simple horizontal gesture from left to right or vice versa. The vertical dimension did not affect the reading, and diagonal movements were also possible.

2.4 Braille Rhythm

The Braille rhythm method enabled reading Braille characters as temporal tactile patterns by holding the stylus on the screen. Here, characters were composed of consecutively produced tactile pulses where Braille dots were presented in a numerical order (i.e., different from the order used with the sweep method). Reading was accomplished by touching the screen at any location to start the feedback and by keeping the stylus on the screen until feedback for all six dots was presented. The rhythm was selected as one method because of some promising earlier results on tactile perception of rhythmic patterns (e.g., [20], [21], and [22]). However, it was unclear how such temporal patterns could be used and understood in coding character-based information.

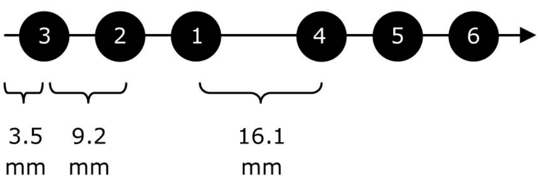

Fig. 7. The use of the sweep method for reading horizontally aligned Braille dots.

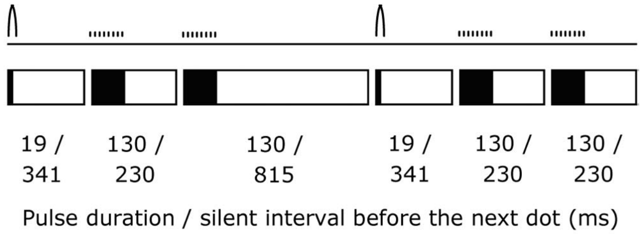

Fig. 8. The feedback pattern for letter "c" which is represented by dots 1 and 4 in Braille. The first and the fourth dots are raised (higher pulse shapes) and the other four lowered (lower pulse shapes).

Fig. 8 shows the feedback provided for letter "c" using the rhythm method. To avoid the problem caused by the first dot being felt immediately after contact, an onset delay of 360 ms was defined. The same value was used as an interval between the feedback onsets of two successive dots. Thus, the 19 ms feedback for the raised dot was followed by a silent interval of 341 ms. For the 130 ms feedback of the lowered dot, the silent interval was 230 ms. The same formula was applied to the remaining dots with the exception that the interval was 2.6 times longer (945 ms) between the third and the fourth dots. Again, this was done to divide the dots into two groups to make it easier to distinguish the dot columns.

The rhythm method was not based on any of the traditional, spatial Braille representations such as the standard 2 × 3 matrix in the scan method or the horizontal Braille writer layout in the sweep method. Instead, all the dots were felt at the same location and temporal coding was used to separate them. Consequently, users could not control the presentation rate of the feedback by movement but it was provided with fixed intervals. These intervals were determined on the basis of pilot studies where usable values between dots and columns were found. With interval values of 360 and 945 ms, the total duration of a character was either 2,404 or 2,515 ms depending on whether the last dot was raised or lowered.

3 Experiment 1

The purpose of Experiment 1 was to find out whether readers of Braille can recognize single characters using the three presentation methods. We used three sessions in the experiment to monitor the possible improvements of performance over a short period of time as well as the stability of the presentation methods.

3.1 Methods

3.1.1 Participants

Six volunteers (three females and three males) participated in the experiment (mean age 35 years, range 26-50). All of the participants were blind and had no additional impairments. The participants were experienced Braille readers (mean number of years reading Braille was 24, range 19-39). All six participants had previous experience of Braille writers or note takers using six horizontally aligned keys to input Braille characters. One of the participants was left handed and five of them were right handed by their own report. One right-handed female participant was excluded

Fig. 9. Experimental settings of Experiment 1 consisting of the prototype device, hearing protector headphones, experimenter's Bluetooth keyboard, and microphone.

from the analysis due to misunderstanding of instructions. Thus, the results are based on data from five participants.

3.1.2 Technical Settings

The prototype device based on the Nokia 770 Internet Tablet was used in the experiment. The device was on a table top during the experiment. To avoid accidental presses of hardware buttons located on the left side of the device (see Fig. 2), a piece of cardboard was attached to the device. The touchscreen of the device was used with a stylus. The stylus was chosen for Experiment 1 because the use of fingers was observed to cause interruptions and skips in the gestural touch input due to friction. The participants were instructed to use their dominant hand to hold the stylus and their nondominant hand to hold the device on the table top (Fig. 9).

In order to block the noise of the piezoelectric actuator, the participants listened to pink noise via hearing protector headphones. A microphone was used for giving instructions and verbal feedback to the participants through the headphones. The experimenter used a Bluetooth keyboard for logging verbal answers. The character presentation was controlled by an application written in C programming language and run on the Linux environment of the device. Reading times of individual characters were measured from stylus down to stylus up events. Thus, the results did not contain the reaction time of the experimenter.

3.1.3 Stimuli

The six-dot Braille characters used in the experiment were letters of the Finnish alphabet. In each block, the participants were presented with all 29 letters once in a random order. The participants read a total of 87 (3×29) characters in one session and 261 (3×87) characters in three sessions. In the scan and sweep methods, the duration of a character was determined by the speed of the reading gesture. In the rhythm method, the duration of a character was fixed so that the interval between the feedback onsets of two successive dots was 360 ms.

3.1.4 Procedure

The experiment was a 3×3 (session $\times$ presentation method) within-subject repeated measures design consisting of three separate sessions. Each session was divided into three blocks according to the three presentation methods. The order of the blocks was balanced between the participants so that each participant used the methods in a different order. In each block, the task was to recognize single Braille characters.

The first session began with an instruction phase where the participants explored the dimensions of the device and its display with their hands. After this, the stylus was picked up and held on the touchscreen while the experimenter presented the feedback twice for both raised and lowered dots.

Each block started off with practice trials using the given method. The participants read a specific training character (dots 1, 2, and 3 were lowered and dots 4, 5, and 6 were raised) ten times at their own pace. After practicing, the participants continued to the character recognition task which proceeded as follows: the participants heard a beep sound via the headphones signaling that the first character could be read. Each character could be read either one or two times. If the stylus was accidentally raised from the touchscreen during a reading gesture, the failed gesture was not counted and the reading could be repeated. The participants gave their answers verbally. There was no time limit set for answering. If the participants could not recognize the character, they were instructed to say "next letter." After each answer, the experimenter told the participant which character the device had presented. When an answer was logged, the next character was initiated after a 3 second interval followed by the beep sound.

There was a short break between the blocks during which the participants could take the headphones off and rest. The same procedure including the training trials and the character recognition task was applied to the following two blocks. After completing all three blocks, the participants were asked to rate their subjective experiences of the presentation methods using six nine-point bipolar scales ranging from -4 to $+4$. These subjective evaluations were collected only after the first and the third sessions. Ratings were requested for the following scales: general evaluation (bad-good), easiness (difficult-easy), speed (slow-fast), accuracy (inaccurate-accurate), pleasantness (unpleasant-pleasant), and efficiency (inefficient-efficient). On each of the scales, the middle of the scale represented neutral experience (e.g., neither bad nor good).

3.1.5 Data Analysis

Repeated measures analysis of variance (ANOVA) was used for statistical analysis. If the sphericity assumption of the data was violated, Greenhouse-Geisser corrected degrees of freedom were used to validate the F statistic. Pairwise Bonferroni corrected t-tests were used for post hoc tests. Both correct and incorrect responses were included in the reading time analysis. The rhythm method was not included in the reading time analysis because the feedback was provided at a fixed speed. Thus, the time from stylus down to stylus up was practically constant.

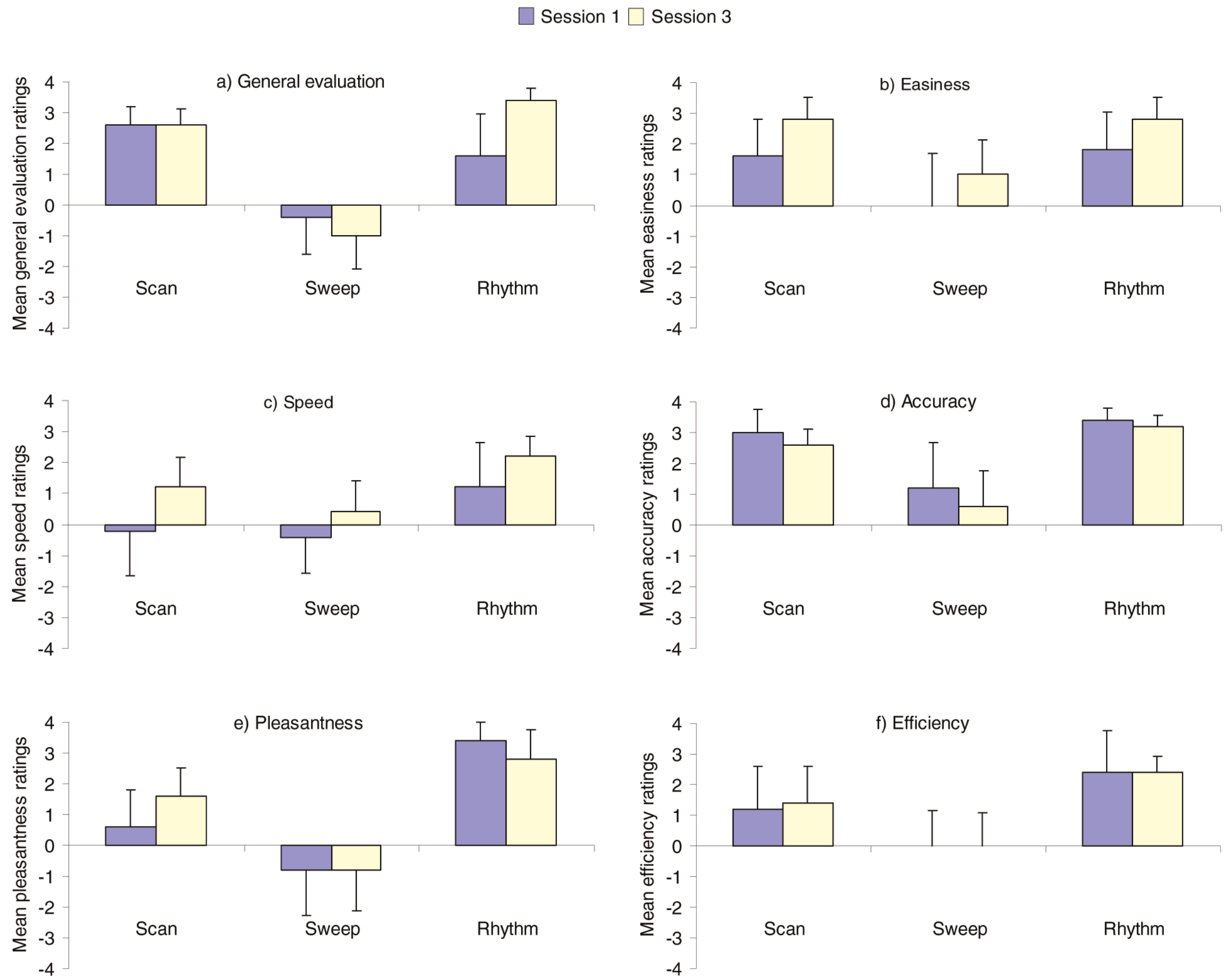

Fig. 10. Mean ratings and SEMs for the subjective evaluations of the presentation methods after sessions 1 and 3.

3.2 Results

3.2.1 Subjective Ratings

Mean subjective ratings and standard error of the means (SEMs) are presented in Fig. 10. Nine separate two-way 2×3 (session $\times$ presentation method) ANOVAs did not show significant main effects or interaction effects of the main effects for the ratings of general evaluation, easiness, speed, accuracy, pleasantness, and efficiency (see Fig. 10).

3.2.2 Recognition Accuracy

For the recognition accuracy (see Fig. 11), a two-way 3×3 (session $\times$ presentation method) ANOVA showed a statistically significant main effect of the session $F(2, 8) = 5.0, p \leq 0.05$. However, post hoc pairwise comparisons did not show significant differences between the sessions. The main effect of the presentation method and the interaction of the main effects were not statistically significant.

3.2.3 Reading Time

For the reading time (see Fig. 12), a two-way 3×2 (session $\times$ presentation method) ANOVA did not show significant main effects or interaction effects of the main effects.

3.3 Discussion

Mean recognition accuracies after three sessions were 97 percent for the scan, 91 percent for the sweep, and 92 percent for the rhythm method. In practice, over 9 out of 10 characters were recognized with two reading gestures. Although there were no statistically significant results between different presentation methods and sessions, an improving trend for recognition accuracy and reading time

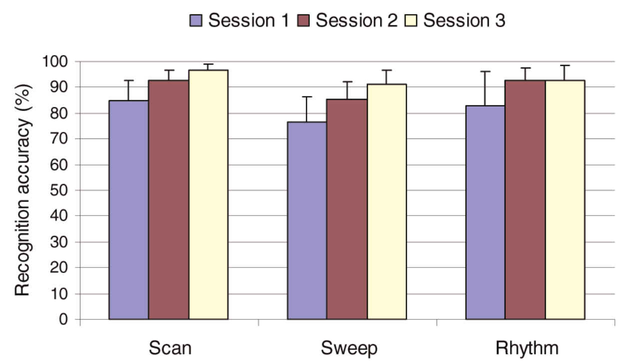

Fig. 11. Mean recognition accuracies and SEMs of Braille characters by presentation method and session.

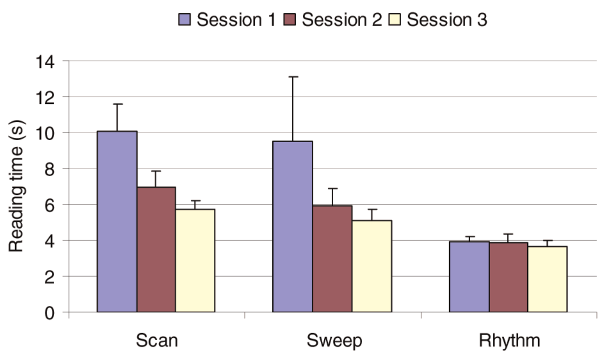

Fig. 12. Mean reading times and SEMs of Braille characters by presentation method and session. The rhythm method was excluded from the statistical analysis due to its different nature.

was observed. The initial performance in the first session was already at a relatively high level as mean recognition accuracies of 76-85 percent were measured. The results indicate that single Braille characters could be recognized by experienced Braille readers without extensive practicing. Furthermore, although the three methods required translation between temporal and traditional spatial representation of Braille, information could still be conveyed. A note of caution must, however, be made due to the fact that the number of experimental participants was relatively low. Handedness of the participants had no noticeable effect on the reading as the one left-handed participant performed just as well as the others.

After three sessions, the mean reading times (from stylus down to stylus up) for single characters were as follows: 5.7 seconds for the scan, 5.1 seconds for the sweep, and 3.7 seconds for the rhythm method. Translated into characters per second (cps), the measured speeds were as follows: 0.18 cps for the scan, 0.20 cps for the sweep, and 0.27 cps for the rhythm method. It should be noted, however, that the reading time of the rhythm method was constant as the dots were presented using a fixed interval.

In comparison to reading printed Braille or using speech synthesizers, the reading speeds measured for the three methods were considerably slow. The average reading speed using printed Braille has been reported to be around 5.8 cps or 70 words per minute (wpm) [23]. Furthermore, in a study by Legge et al. [24], reading speeds between 5.4 cps (65 wpm) and 15.4 cps (185 wpm) were found. Default listening rates for speech synthesizers are usually around 15 cps (180 wpm) although those accustomed to speech synthesis can use listening rates three times the default rate [25]. However, to the best of our knowledge, there are no previous investigations on reading Braille dot by dot or by using solely temporal tactile feedback. Due to the interaction methods being original innovations [26] intended for mobile use with touchscreens, comparisons with earlier studies are not feasible.

Although the differences were not statistically significant, subjective ratings indicated that the participants tended to evaluate the scan and the rhythm methods more positively than the sweep method. The ratings remained fairly constant throughout the sessions. In the postexperimental interview, the participants reported that the horizontal reading gesture in the sweep method was easy to use as the movement required was simple. On the other hand, the order of the dots (3-2-1-4-5-6 from left to right) caused difficulties for some participants, suggesting that the transformation of the representation from inputting to reading was not entirely straightforward. Despite the initial challenges, the results of the sweep method were positive, as the recognition accuracy was comparable to the other presentation methods.

In contrast, the dot layout in the scan method was the closest to the standard Braille dot layout, which might explain the relatively positive subjective evaluations. The main drawback of the scan method was partially caused by the use of the stylus. The participants felt that the stylus was unnatural and clumsy. Especially in the first session, the stylus movements were not steady, and therefore reading was inconvenient. The participants commented that they had to press the stylus quite heavily on the touchscreen, which caused stress on the reading hand.

Four out of five participants would have chosen the rhythm method for their personal use. This may be due to the fact that there was no need to concentrate on moving the stylus from dot to dot on the screen. Although the rhythm method was found to be the fastest of the three, the participants proposed higher presentation rates. Furthermore, the rhythm method was found to be the most suitable for use without a stylus as the friction caused by fingers would not be an issue from the technical point of view.

4 Experiment 2

In light of the encouraging results of the first experiment, we conducted a follow-up experiment with the rhythm method. The rhythm method was shown to be the most efficient as well as the most positively received of the three methods by our users. Furthermore, it became evident that the presentation rate of the rhythm method could be increased by adjusting the intervals between individual dots. The character duration used in the first experiment was not optimized in terms of presentation rate but to ensure that it was suitable for all the participants. Our main goal in the second experiment was therefore to evaluate how the participants performed when the character duration was shorter than in Experiment 1.

4.1 Methods

4.1.1 Participants

The five volunteers from Experiment 1 also took part in the second experiment. We decided to continue with the same participants; due to their previous experience in using the methods, they could effortlessly try the rhythm with faster presentation rates.

4.1.2 Technical Settings

The technical settings were otherwise identical to those in Experiment 1 but the participants used the index finger of their preferred Braille reading hand instead of a stylus. This change was made as the first experiment proved the stylus to be unnatural for this purpose. In addition, the rhythm method could be used with bare fingers because it required no movement between dots on the touchscreen, thus avoiding problems in losing touch contact.

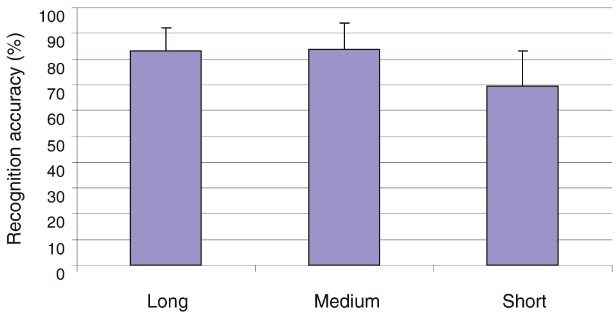

Fig. 13. Mean recognition accuracies and SEMs of Braille characters by character duration.

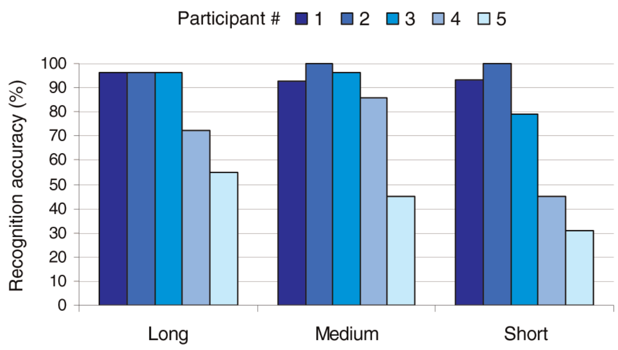

Fig. 14. Mean recognition accuracies of Braille characters by participant and character duration.

4.1.3 Stimuli

The character durations in the rhythm method varied in each block. The original character duration from Experiment 1, 2.45 seconds, was used as a starting point. This duration was measured from the onset of the first dot to the offset of the last dot. The other two respective durations were 1.85 and 1.25 seconds. The durations were selected based on preliminary evaluations with one blind pilot participant. The same letters of the Finnish alphabet were used but now the total number of letters presented to one participant was 87 (3×29).

4.1.4 Procedure

There were four differences from Experiment 1 in the procedure. First, only one test session was used. Second, in each of the three blocks, the participants used different character durations of the rhythm method instead of the three different methods. Third, the order of test blocks was not randomized but was the same for all participants; each one started with the longest and ended with the shortest character duration, making the task progressively more difficult. Fourth, the participants were allowed to read each character only once before answering.

4.1.5 Data Analysis

A repeated measures ANOVA was used for statistical analysis.

4.2 Results

Mean recognition accuracies and SEMs are presented in Fig. 13. For the recognition accuracy, a one-way ANOVA did not show a statistically significant effect of the stimulus duration $F(2, 8) = 3.68$, $p = 0.074$.

4.3 Discussion

The mean recognition accuracies for different character durations were as follows: 83 percent for the long (2.45 seconds per character), 84 percent for the medium (1.85 seconds per character), and 70 percent for the short (1.25 seconds per character) duration. The mean recognition accuracy for the long duration was 9 percent lower than in the last session of the first experiment. This could be because some months elapsed between the experiments. In addition, the participants were allowed to read each character only once. The option to read each character twice was removed to simplify the experimental setup and data analysis.

Interestingly, there were practically no differences in mean recognition accuracies between the long and medium character durations. This implies that the standard presentation rate of the rhythm method could be increased without affecting character recognition. A 14 percent drop in mean recognition accuracy was measured with the short character duration compared to the medium duration. Taking into consideration that the short duration is approximately half of the long duration, the decrease in recognition accuracy is quite moderate. This promotes the view that the rhythm method has potential in terms of shorter reading times compared to the other two presentation methods. A hypothetical reading speed of 0.8 cps can be calculated using a character duration of 1.25 seconds. Even though this is still far from those of normal Braille reading, in mobile contexts where the amount of information to be acquired is limited (e.g., single characters, words, and short messages), the current speed could well be adequate.

Fig. 14 shows that there were wide variations in recognition accuracies between participants. When using the short character duration, mean recognition accuracies of 31-100 percent were measured. Encouragingly, three of the participants also performed particularly well (79-100 percent) with the shortest duration, suggesting that 1.25 seconds per character may not necessarily be the minimum value of understandable rhythmic presentation. For some of the users, even shorter character durations could be recognizable. In practical use, the character duration should be adjustable so that all readers could use their own preferences and start with lower presentation rates if necessary.

Four out of the five participants preferred using the index finger to the stylus. It was more natural and thus less of a strain on the reading hand. Only one participant preferred the stylus because he was able to sense the raised dots more accurately through the plastic pen in the first experiment. Several of the participants commented that the tactile feedback could be slightly stronger. We used the highest possible amplitude of the piezoelectric actuator but as the presentation methods are not limited to a specific hardware solution, alternative and stronger tactile feedback could also be used. In general, the participants stated that efficient use of the rhythm method would be possible through learning.

5 Applicability of the Results

We have shown that single Braille characters can be presented in a mobile device using spatiotemporal (i.e., scan and sweep) and temporal (i.e., rhythm) tactile feedback. We used an approach different from those based on building nonportable mechanical devices, e.g., [3], [6], [7], to overcome the problem of expensive Braille readers. Our current aim was to make it possible for visually impaired people to read single characters one at a time without an additional Braille device. The findings of Experiment 1 revealed that experienced Braille readers recognized characters accurately (91-97 percent) without prior experience. Further, reading time analysis showed that the use especially of the scan and the sweep methods is time-consuming compared to reading printed Braille or using normal Braille displays. It took over 5 seconds on average to read a character. On the other hand, in Experiment 2, where the rhythm method was used with a character duration of 1.25 seconds, the participants were still able to recognize 70 percent of the characters correctly.

In generalizing the findings, we found that the rhythm method was the most promising of the three in terms of reading time and user satisfaction when reading single-character data. In a real context of use, the rhythm method could provide single numerical or alphabetical cues while accessing information on a mobile device. When using a menu, the user could automatically receive the first letter of each menu option to make navigation more fluent. Furthermore, short words or number sequences could be read one character at a time, for example, to make sure that a phone number has been typed in correctly. Alternatively, the user could confirm private information such as a PIN number in a more secure way compared to using speech. What is noteworthy while considering the use contexts for the findings is that Braille code has undergone continuous modification over the years. One of the results of this progress is abbreviations for common words (e.g., afternoon = afn, necessary = nec). If the rhythm method were adopted for reading words, shorter representations common in modern messaging could be used to create informative expressions with only a few characters, thereby improving the efficiency of use.

We experimented with two alternative ways to use the touchscreen; the stylus was found to be feasible for the scan and sweep methods because of the better contact on the touchscreen, whereas in the rhythm, the index finger was preferred. This study showed that the use of bare fingers is preferred by visually impaired people for sensing tactile feedback. It would also be possible to use the palm of the hand for reading as the rhythm method does not necessarily require the device to be equipped with a touchscreen. In general, any sufficiently precise tactile actuators capable of creating distinguishable feedback could be used to provide the Braille coding to the body of a device. Instead of touching the screen to start the feedback, a hardware button could be used.

Each of the participants in our experiments reported that the use of the presentation methods required intensive concentration on the reading task. Because of the nature of the new temporal Braille representation, users need to parse Braille characters one dot at a time. The cognitive requirements for remembering dot positions and mentally forming characters out of individual feedback were different from standard Braille reading. Similar to our finding, Levesque et al. [7] reported that reading using nonfamiliar Braille representation demanded great concentration from the readers. Further studies would be needed in order to find out how practical experience in using the methods affects reading and whether the required level of concentration declines while learning.

In extreme simplification, it can be stated that tactile-specific sensory memory and working memory have a crucial role in comparing the series of individual vibrations with the internal model for reading traditional Braille characters stored in long-term memory. One of the participants commented that while reading, he was constantly anticipating the next dot on the basis of dots already presented. This suggests that experienced readers were able to hold dots in their working memory and thus facilitate reading by limiting the number of possible characters. Tan [27] reported a similar finding with letters when studying tactual and auditory reception of Morse code.

Our results show that visually impaired people could utilize their prior skills in reading Braille although the representation used in this study was different. This suggests that the new reading methods suit the preexisting models in long-term memory for reading traditional Braille. What kinds of cognitive processes were required to recode the vibrotactile patterns to match with the representation of traditional Braille cannot, however, be explained through these series of experiments. Although an interesting research question, the psychological processes were not the main focus of the present study. Even so, the results demonstrated the flexibility and potential of the human brain which could be utilized in providing new haptic interaction methods for visually impaired people. We therefore believe that it is valuable to investigate more versatile and mobile alternatives to traditional Braille to improve the nonvisual accessibility of mobile devices.

Looking from the perspective of traditional Braille reading, we cannot yet draw definite conclusions on how these methods would perform in reading multiple consecutive Braille characters. However, when considering the findings of this study as well as the technological development of different actuator solutions, the possibilities are obvious. As we were successful in showing that characters can be read via temporal tactile feedback and Braille coding, there are various paths that can be taken to enable the use of these methods in reading multiple Braille characters. The next step for us will include thorough research on how the present results could be utilized for accessing serial information as well as user evaluations of the new implementations. One possible direction in which to proceed on this topic would be to use the touchscreen for moving between multiple characters and to present characters with the rhythm method when a touch input is detected in a certain location.

Interestingly, when discussing the representation used in the rhythm method on a more general level, we can identify similarities to Morse code, which uses two elements to form characters. Although traditionally transmitted through auditory senses, there has been research on using Morse via a tactile channel. In a study by Tan [27], four participants recognized over 95 percent of single letters correctly using vibrotactile Morse at a presentation rate of 1.3 cps (16 wpm). Thus, due to the similar nature of these two tactual representations, commonalities might also be possible in terms of efficiency. A longitudinal study should be conducted in order to measure the efficiency levels of expert readers using the rhythm method.

We have proposed three alternative presentation methods to external Braille displays for cases where these displays are either impractical or not available at all. The novel presentation methods based on temporal Braille coding showed promise in accessing limited amounts of information (i.e., single characters) on mobile devices. As research on different tactile actuators has resulted in viable solutions, e.g., [12], [13], [14], [15], [16], [18], the use of alternative Braille presentation methods on mobile devices can also become a reality in consumer products. In this respect, the rhythm method especially has potential as it can be used with devices with no touchscreen. Furthermore, in future, the rhythm method can be utilized in reading serial information based on Braille coding. Compared to mounting physical Braille cells in a limited number of mobile devices, tactile actuators coupled with Braille reading software is a reasonable choice in terms of cost-effectiveness and universal access with any compliant device.

6 Summary

In this paper, we have introduced and studied three novel methods for presenting six-dot Braille characters using only a touchscreen augmented with tactile feedback. To the best of our knowledge, there were no previous solutions for reading Braille without additional displays attached to mobile devices. The results of the first experiment proved that experienced Braille readers could accurately recognize characters using all three methods, although reading speeds were slow compared to normal Braille reading. In the second experiment, the reading speed using the rhythm method approached 1 second per character, while the recognition accuracy remained at a usable level. In light of the insights gained through this study, we recommend the rhythm method to be used for providing a low-cost and portable way to read small amounts of information using mobile devices with precise enough tactile actuators. As the findings of this first study proved the new representation of Braille to be practicable, the next step will be to enable the rhythm method to be used for reading multiple Braille characters consecutively.

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