

BezelBraille: A Braille-Inspired Bezel-Guided Virtual Keyboard for Low Vision and Blind Users

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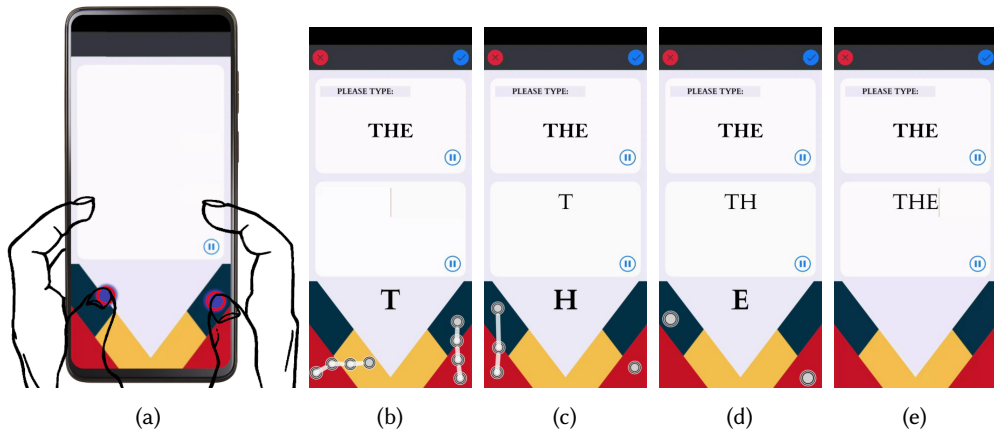


Fig. 1. The process of entering the word “THE” with BezelBraille. The user holds the device with both hands and performs gestures using the thumbs. To enter each letter, the user simultaneously performs left and right gestures corresponding to the braille columns. Users can also perform the gestures sequentially and use a confirmation step while learning the method.

We present BezelBraille a novel eyes-free, braille-inspired text entry technique for blind and low vision users. It maps the left and right columns of the braille cell to gestures performed with the left and right thumbs, using the smartphone’s bottom corners as tactile landmarks. Gestures are flexible in both direction and size, can be initiated from any direction, and may be performed sequentially or simultaneously, as long as they pass through the intended zones, reducing the need for precise target selection. We evaluated BezelBraille with 12 visually impaired participants of varying braille proficiency in eight short sessions. Despite the limited training time, entry speed improved from 3 wpm in the first session to 4.2 wpm in the last, reaching 6.9 wpm without the confirmation step used for novice training. Braille proficiency improved significantly, especially among novices (from 12% to 79%). Participants rated BezelBraille as easy to learn, accurate, and suitable for regular use, underscoring its potential as both an accessible text entry method and a promising tool for braille learning.

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CCS Concepts: • **Human-centered computing** → **Text input**; **Gestural input**; **Empirical studies in HCI**; **Empirical studies in accessibility**; *Accessibility technologies*.

Additional Key Words and Phrases: Text Entry, Braille, Smartphone, Low Vision, Sight, Blindness, Impairment, Input

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1 Introduction

According to the 2023 American Community Survey (ACS), approximately 8.7 million people in the United States are blind or have serious difficulty seeing, even while wearing corrective lenses [19]. Despite this, there is still no dominant character-based input method designed specifically to meet the needs of this group. Mainstream solutions such as virtual Qwerty keyboards with screen readers, voice dictation, and gesture-based systems each have limitations. Virtual keyboards require precise touch targeting, which can be slow and error-prone without visual feedback. Many alternative methods use novel approaches that do not support skill transfer to or from other accessibility technologies, while others rely on external devices that must be carried separately [26]. Voice input, although fast, is often unreliable in noisy environments and is not suitable for private communication due to privacy concerns and limited error correction options [37]. Many have proposed braille-based text entry techniques to address these challenges (Section 2.1). Braille is a tactile writing system composed of six raised dots arranged in cells, with different combinations representing letters, numbers, and symbols, enabling literacy through touch [40]. However, most existing braille-based input techniques assume prior braille knowledge and lack scaffolding for novices, which can hinder adoption, especially since fewer than 10% of legally blind individuals in the United States are braille literate [35]. Furthermore, some techniques require precise target selection or awkward device orientations, further reducing usability and user acceptance.

In this work, we present BezelBraille, a braille-inspired, eyes-free text entry method that uses the bottom corners of a smartphone as tactile landmarks for entering braille characters. The left and right columns of the braille cell are mapped to gestures performed by the left and right thumbs, respectively. These gestures are flexible in both direction and size. Users can initiate them from any direction and perform them at any length, provided they pass through the intended zones. This flexibility reduces the need for precise target selection. This design also supports various holding postures, accommodating different user preferences. To input a letter, users perform the corresponding gestures either sequentially or simultaneously with their thumbs, a flexibility that can aid in learning and ease of use.

Table 1. Summary of studies conducted in this work, including sample size, participant population, and study purpose.

Studies	N	Population	Investigation
Focus Group	4	Blind	<i>Validating the idea</i>
Pilot Study	5	Low Vision & Blind	<i>Testing the final prototype</i>
User Study 1	12	Low Vision & Blind	<i>Evaluating BezelBraille</i>

The contribution of this work is the design and evaluation of BezelBraille through multiple user studies (Table 1), demonstrating its effectiveness as a braille-inspired, character-based text

Table 2. Performance summary of braille-based text entry techniques for mobile devices. Entry speed is reported in words per minute (wpm), and error rate (ER) is reported using standard error rate metrics (Section 6.5.1), except for values marked with ‘†’, which indicate total error rate [41], a metric that accounts for both remaining and corrected errors in the transcribed text. Rows marked with ‘*’ indicate that performance values were recalculated from plots presented in the original paper. The table also lists training and experimental tasks used in each study, where ‘m’ denotes minutes, the number following ‘×’ indicates the number of sessions, and ‘n’ indicates that the number of phrases was not reported. ‘N’ indicates sample size, and the braille column indicates participants’ braille proficiency. For studies reporting only last-session performance, earlier sessions are included in the training column.

Method	Training	Task	N	Sample Braille	Performance Speed	ER
BrailleType [36]	10 to 15 m × 1	5 phrases × 1	15	Proficient	1.45 wpm	8.91%
BrailleEnter [1]	15 m + 2 phrases × 1	12 phrases × 1	6	Proficient	2.45 wpm	7.80%
BrailleTap [24]	20 m × 1	n phrases × 3	5	–	3.36 wpm	5.05%
EdgeBraille [33]	5 m + 15 phrases × 1	1 two-word phrase × 1	14	Proficient	3.97 wpm	8.43%
	5 m + 15 phrases + 16 phrases × 14	5 two-word phrases × 1	7	Proficient	7.17 wpm	–
SingleTapBraille [2]	20 m × 1	14 phrases × 1	7	Proficient	4.71 wpm	11.23%†
Perkinput [11]	30 m + 2 phrases + 5 m × 7	30 m as many phrases × 7	8	Proficient	6.05 wpm	12.23%
TypeInBraille [31, 32]	20 m × 1	500 phrases × 1	7	Proficient	6.30 wpm	3.00%
BrailleSketch* [29]	10 m + 15 m × 5	3 phrases × 5	10	Proficient	9.87 wpm	21.80%†
BrailleTouch* [42]	10 phrases + 20 m × 4	20 m as many phrases × 1	11	Proficient	17.87 wpm	28.97%†

entry method for blind and low vision users with varying levels of braille proficiency. While many braille-based input methods exist, the novelty of BezelBraille lies in its use of the smartphone’s bottom corners as tactile landmarks, its compatibility with both portrait and landscape orientations, and its support for both simultaneous and sequential gestures. Although not the primary focus of this work, BezelBraille was also found to significantly improve braille proficiency, highlighting its potential as both a practical input method and a tool for braille learning.

2 Related Work

This section reviews mobile text entry techniques developed and evaluated for low vision and blind users. It excludes methods intended for non-mobile platforms, and those that require external devices, sensors, or wearables to operate.

2.1 Braille-based Methods

Braille-based virtual keyboards are designed to replicate the braille writing system for people with low vision and blindness. On mobile devices, these methods tend to use sequential input, multi-touch gestures, or chording, typically followed by auditory feedback. BrailleType [36], for example, divides the screen into six large targets representing the braille dots, allowing users to long-tap each target to enter the desired letter. BrailleEnter [1] also follows a sequential input model, where users perform a long tap for active dots and a short tap for inactive ones anywhere on the screen. SingleTapBraille [2] counts the number of taps and analyzes the distance between them to infer the intended braille dot pattern. Perkinput [11], by contrast, uses a chording approach in which users enter one column of the braille cell at a time: first selecting the left three dots, then the right three. BrailleTouch [42] allows users to input braille characters using six fingers and both hands, much like a traditional braille keyboard, but requires holding the device with the screen facing away, which may be unintuitive or uncomfortable for some users.

Many methods adopt gestural approaches, as gestures offer a larger interaction area and are often more accessible than taps. TypeInBraille [31, 32], for example, allows users to enter letters by

performing taps and gestures by mapping distinct gestures to the four possible combinations of dots in a single braille row. BrailleSketch [29] also uses gestural input, enabling users to draw a path through braille dots on the touchscreen, with each gesture forming a character, similar to gesture typing on a Qwerty keyboard. EdgeBraille [33], on the contrary, places braille dots along the edges and corners of the screen, where users swipe across the regions to input the corresponding letters. Some other methods have also taken advantage of physical attributes of the device. BrailleTap [24], for instance, assigns each of the six braille dots to a dedicated key on a mobile keypad, with additional keys for Enter and Space.

A common limitation of these methods is that they assume users are already literate in braille, offering little to no scaffolding for novices. Many also require a series of actions to enter a single letter, increasing the risk of fatigue, discomfort, and cognitive load [21]. Some rely on hardware features, such as physical keypads, that are no longer standard on modern smartphones. Table 2 presents a summary of these methods in terms of speed and accuracy, as well as participant characteristics and the training and experimental tasks used in each study.

2.2 Character-based Methods

Several mobile text entry techniques for low vision and blind users do not rely on braille. Instead, they employ novel approaches to enable eyes-free text entry. A well-known example is NavTap [24], which divides the alphabet into five horizontal rows, each starting with a vowel. Users navigate through the rows using the directional keys on a mobile keypad. In a study with a representative user group, NavTap achieved an average speed of 1.25 wpm with a 10% error rate. A similar method designed for smartphones is NavTouch [23], which replaces physical keys with directional swipes to navigate the alphabet. In a study with blind users, it achieved 1.79 wpm with a 4% error rate. Another gesture-based method, No-Look Notes [14], arranges the alphabet into an eight-segment circular pie menu, with each segment containing a subset of letters. To input a letter, users swipe toward the appropriate segment, split-tap to select it, drag to the desired letter, and perform another split-tap to confirm. In a study with visually impaired participants, the average text entry speed was 1.32 wpm with an 11% error rate. Continuing with directional gestures, ThumbStroke [27] is a virtual keyboard optimized for continuous thumb input. Users first swipe in one of eight directions to select a letter group, then extend the stroke toward the specific letter within that group. In a study with sighted users, ThumbStroke achieved an average speed of 9.43 wpm with a 7.78% error rate.

Senorita [39], on the contrary, employs a chording approach with two-thumb interaction, designed specifically for eyes-free text entry. For novice users, the system supports a split-tap method: the first tap selects a group of letters, and the second tap selects the desired letter from the opposite side. Expert users, however, can simply perform a chord by tapping both thumbs simultaneously on opposite sides of the keyboard to enter a letter. In a study with participants with vision impairments, Senorita achieved an average speed of 5.5 wpm with a 5.46% error rate. SpatialTouch [22], on the other hand, replicates a Qwerty keyboard layout on a tablet using multi-touch interaction. Users rest one finger on a designated “home key” and explore the keyboard with the other. To enter a letter, users simply lift the exploring finger. In a study with visually impaired users, SpatialTouch reached an average speed of 3 wpm with an 11.52% error rate.

One major issue with many of these methods is that they are highly novel and often designed or optimized for a specific form factor. As a result, users are unable to transfer existing skills from other systems to these methods, or apply the skills acquired through them to other technologies. In contrast, braille-based methods offer greater potential for skill transfer. Braille-literate users can directly apply their existing knowledge, while those new to braille can potentially carry the skills they acquire through these methods to other braille-based technologies.

2.3 Word-based Methods

Word-based methods allow users to input entire words, sometimes even multiple words at once, typically through recognition or prediction techniques, such as gesture typing, speech, or character-based input combined with word prediction. One such approach is AGTex [13], which enables blind users to slide a finger across a virtual Qwerty keyboard to form a word, while receiving auditory feedback (similar to voice-guided gesture typing). The method uses a combination of a spatial gesture model and a language model to support prediction. In a study, blind users achieved an average speed of 5.66 wpm with an error rate of 14.87%. Methods like this can be cognitively demanding, as they usually require users to memorize gesture traces or input patterns for more efficient use [21]. There are also some speech-based text entry methods that have been specifically designed for blind users [34, 38].

These methods can be fast, but they also present several challenges. Recognition-based approaches, such as speech input, are often unreliable in noisy environments. There are also concerns about security and privacy, particularly when using speech in public spaces [37]. Predictive systems, on the other hand, can limit user input by making it difficult to select intended words from the prediction list. They often struggle with out-of-vocabulary (OOV) words, such as proper nouns, alphanumeric text, foreign terms, or jargon. Furthermore, correcting errors in both recognition and predictive systems is difficult [4]. One study found that blind users spent nearly 80% of their time with predictive text entry reviewing and correcting errors in dictated input [10].

3 Focus Group

We conducted a focus group to evaluate the feasibility of the idea and inform the design of the system.

3.1 Participants

Four volunteers participated in the study. They all self-identified as having profound visual impairment with Snellen visual acuity of 20/500 or worse [3]. Three identified as female and one as male. Their age ranged from 32 to 68 years ($M = 53$, $SD = 17.2$). Three were right-handed and one left-handed. Two participants had more than 15 years of experience teaching accessibility technologies to blind individuals. Each participant received a US \$20 Amazon gift card for their participation.



Fig. 2. Two participants taking part in the focus group.

3.2 Procedure

The focus group took place at a local association for blind individuals. We began by explaining the concept to participants and then introduced specific topics and questions for discussion. Rather than using a functional prototype, participants were instructed to use their own smartphones as reference (Fig. 2). A moderator presented each topic, invited participants to respond in turn, and then facilitated an open group discussion. The discussion focused on four main topics: (1) the perceived usefulness of the idea, (2) willingness to learn and use a new character-based method despite access to speech and other word-level input methods, (3) motivations for adopting such a technique, and (4) preferred device-holding postures and features to enhance performance. The study was reviewed and approved by the Institutional Review Board (IRB).

3.3 Results

The responses were overwhelmingly positive. We had expected some reluctance as learning a new method requires time and effort [15]. However, participants explained that blind users often need to learn new tools because accessibility technologies evolve quickly. They added that mastering this technique could be especially beneficial, as the skills could be transferred to other braille-based technologies.

All participants appreciated the gestural approach, describing it as more accessible than tap-based methods. They indicated that they would use the method predominantly ($N = 2$) or occasionally ($N = 2$) despite having other input options, although their motivations differed. Participants without braille knowledge saw it as an opportunity to learn braille, while the proficient user saw it as an easy transition by transferring existing skills.

When asked about their use of speech input, the participants reported using it frequently for voice commands but not for text entry. The primary reasons were privacy concerns and the lack of effective error correction. They explained that using speech in public places is not only unreliable, but also uncomfortable for sending personal messages, aligning with previous findings [37]. They also noted that correcting misrecognized words is often difficult or even impossible with speech-based methods. As a result, they felt that an effective character-based method is essential in situations where recognition and predictive systems are unreliable, as the ability to spell out words provides greater control over text entry.

Regarding holding posture, participants slightly preferred holding the device in portrait orientation. They were not in favor of holding it facing the back of the device [42] or placing it on a flat surface to use all the fingers of both hands [11], as these felt unnatural. However, they were comfortable using the bezels as spatial guides and were indifferent to using one or both hands. When asked to demonstrate, all participants could initiate gestures from the correct positions. They also performed simultaneous gestures from the top, middle, and bottom of the screen, expressing greater comfort with the middle and bottom areas. These preferences were incorporated into the design of the system.

We also collected feedback on speech feedback speed and vibration intensity. Participants noted that these settings depend on individual preference, so both were made adjustable in the prototype. In general, the focus group validated the concept and provided valuable design insights for prototype development.

4 BezelBraille

BezelBraille enables users with low vision and blindness to enter text on smartphones by performing simultaneous or sequential gestures with their thumbs, mapping the left and right columns of braille dots to gestures performed by the left and right thumbs, respectively. For spatial reference,

the system uses the bottom two corners of the device. Gestures can be initiated either above or to the sides of these corners, eliminating the need for visual cues. The design of the system is described below.

4.1 Gesture Mapping

BezelBraille maps the three dots in the left column and the three dots in the right column of a braille cell to an angular layout positioned in the bottom-left and bottom-right corners of the phone (Fig. 1). In each corner, the top dot is located above the corner, the middle dot at the corner, and the bottom dot on the side (left or right, depending on the column).

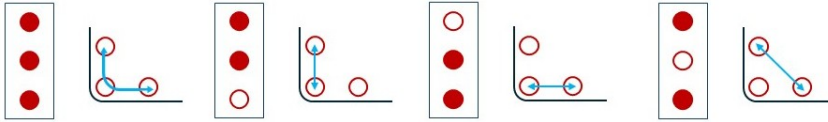


Fig. 3. Gesture mapping convention used in BezelBraille, shown here for the left column only. The right column uses a mirror image of these mappings. Double-headed arrows indicate bidirectional gestures that can begin above, beside, or directly on the phone’s corners and can be of any size, as long as they go over the intended zones..

To enter a dot sequence, users connect the dots for the left or right column using their corresponding thumb. The bezel and bottom corners serve as tactile landmarks, helping users initiate gestures from or near the bezel while keeping the corner as a spatial reference. When a dot combination does not include the middle dot (such as in the letter ‘k’), users skip it by performing a diagonal gesture connecting the top and bottom dots. To enter a single dot (such as in the letter ‘a’), users tap its corresponding position, either above or on the side of the corner. Gestures and taps for the two columns can be performed simultaneously (often called “chording”, preferred for better performance) or sequentially (common among novice users). Fig. 3 illustrates the convention used to map gestures to the braille alphabet, and Fig. 4 presents the complete gesture set for all letters.

We arrived at this convention through an iterative design process and numerous lab trials. During early explorations, we considered vertically arranging the dots along the left and right bezels or horizontally along the bottom and top bezels. However, these layouts made it difficult to distinguish whether all three dots in a column or only the first and last dots were selected without relying on predictive methods. Based on the findings of the focus group (Section 3), a primary design goal was to create a method that operates without word prediction or suggestions, providing users with greater control over text entry. Laboratory trials also revealed that these arrangements were inadequate in different display sizes, as it is difficult to predict how far a user’s finger will extend on various devices, which requires fine-tuning for each individual. We also considered a purely tapping-based approach, as explored in previous studies [42], but found it unsuitable, as tapping with three fingers of each hand is impractical in natural smartphone-holding postures. Allowing sequential taps reduced this difficulty, but significantly increased the number of actions per character, leading to finger fatigue and reduced text entry performance. For these reasons, we eventually settled on the current design.

4.1.1 Gesture Characteristics. Gestures in BezelBraille are bidirectional and are not constrained to a fixed size. Users can initiate a gesture from above, from the side, or from the bottom corner bezel (Fig. 3), and it can be any size as long as it passes through the zones containing the target dots. For this, each bottom corner (left and right) is divided into three zones, for a total of six zones, as shown in Fig. 1. This flexibility allows users to rely on the bottom corners as tactile reference points.

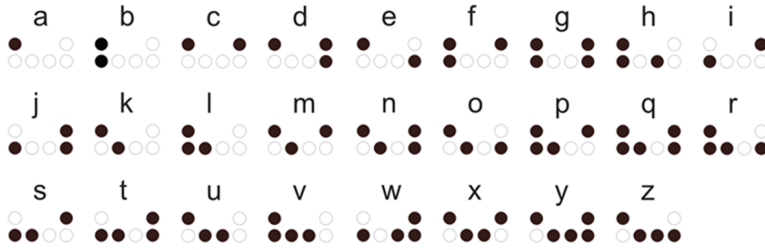


Fig. 4. Gesture set for the 26 letters of the English alphabet.

In addition, each gesture is recognized only when the finger is lifted, allowing users to correct it on the fly. For example, if a user moves their finger from the top to the bottom corner and then to the side, but realizes that they intended a top-to-side gesture instead, they can move back to the first dot and complete a diagonal gesture without lifting the thumb. Depending on user preference and skill level, gestures for the two columns may be executed simultaneously for greater efficiency or sequentially for ease of learning.

4.1.2 Corrective and Mode Gestures. In addition to gestures for the dots in the left and right columns of a braille cell, the system supports gestures for common editing and mode-switching actions: a left-stroke for backspace, a right-stroke for space, an up-stroke for Enter, and a down-stroke for Shift. These gestures can be performed anywhere on the display, provided that they do not touch the bezel. We selected these gestures because they have proven effective for text entry with blind [39] and sighted users [8] in previous work.

4.1.3 Confirmation Gesture. For this investigation, we used double-tap as a confirmation action to input a letter. As shown in Fig. 1, each letter is first displayed in the layout and read aloud to the user. If it matches the intended letter, the user performs a double-tap to confirm and enter it into the input area. We included this feature because most of our participants were novice braille users or had no braille skills (Section 6.4.3). It allowed them to explore and test gestures until they found the correct one for the target letter, reducing the need for frequent error correction. This feature can be gradually removed as users become more proficient with the method and gestures, enabling faster text entry.

4.2 Haptic Feedback

The system provides haptic feedback when a user's finger enters a zone, signaling both the event and the specific zone entered. Android supports vibration intensities from 0 (no vibration) to 255 (maximum), but in lab tests, we found that values above 250 are uncomfortably strong. We therefore defined three intensity levels: Level 1 (50, 100, 150), Level 2 (100, 150, 200), and Level 3 (150, 200, 250), corresponding to the upper, corner, and side zones, respectively. The duration of the vibration was fixed at 100 ms, based on laboratory tests that evaluated durations from 50 to 500 ms and found 100 ms to be the most comfortable while allowing for a clear distinction between the three intensity values at each level (also reported in the literature [28]). Following feedback from the focus group (Section 3), the application allowed users to adjust the intensity of the vibration. In the study, the default was set to Level 2, although 42% of the participants ($N = 5$) opted for the highest intensity, Level 3.

4.3 Auditory Feedback

The system provided several types of auditory feedback. First, it read aloud the presented text for participants to transcribe. Users could re-hear the presented text at any time by long-tapping on the lower part of the screen. For confirmation, when a letter was recognized, the system immediately announced it, and likewise provided auditory feedback on actions such as backspace, enter, or space. For current input feedback, users could tap on the upper part of the screen to hear the text entered so far or long-tap to hear the complete letter-by-letter transcription.

The application used Google Text-to-Speech AI¹ (standard female voice en-US-Standard-H²) for the read-aloud feature. The default speaking rate was 1×, but based on the feedback from the focus group (Section 3), we allowed users to adjust it from 0.25× to 2× in increments 0.25×. In the study, two-thirds of the participants ($N = 8$, 67%) kept the default rate, while two participants (16.5%) preferred a faster rate of 1.75×, and the remaining two participants (16.5%) preferred a slower rate of 0.75×.

4.4 Visual Feedback

Although BezelBraille is designed as an eyes-free keyboard, we incorporated visual feedback to support low vision users with light or color perception, as well as sighted users interested in learning the method. The interface uses a high-contrast color palette: pure black, white, red, and yellow, as recommended for accessibility [20]. It also used large fonts to enhance readability. To support interaction, the system displays a cursor to indicate input mode and renders thick visual traces of touch and gestures on the touchscreen (Fig. 1).

5 Pilot Study

We conducted a pilot study to gather initial feedback on the design of the final prototype. Five participants volunteered for the study, none of whom had taken part in the focus group. They all were legally blind but did not know their exact visual acuity. Four identified as female and one as male. Their ages ranged from 19 to 79 years ($M = 55$ years, $SD = 22.3$). One participant reported knowing some braille letters, while the others had no prior braille experience.

5.1 Procedure

In the study, we first demonstrated BezelBraille to the participants, then allowed them to use it for 5-10 minutes for free-form text input. We did not record performance metrics, instead focusing on participants' first impressions of the system and any usability issues they identified. In particular, we sought to determine whether there were application issues that needed fixing and how to improve overall usability. Participants were also asked for feedback on the application, along with any comments or recommendations for improvement. Furthermore, they rated on a five-point Likert scale (1 = definitely not, 5 = definitely yes) whether they would learn and use the method as one of their primary text input methods on mobile devices. All participants used the method while sitting, holding the experimental device (Section 6.2) with both hands in portrait position (Fig. 5). The study procedures were reviewed and approved by the Institutional Review Board (IRB).

5.2 Results

All participants reported enjoying the method and did not offer any major suggestions for changes. Similarly to the focus group, they felt the method would be effective in certain situations and would provide them with greater control over their input. Participants particularly appreciated

¹Google Cloud Text-to-Speech API: <https://cloud.google.com/text-to-speech>.

²Supported Voices & Languages: <https://cloud.google.com/text-to-speech/docs/list-voices-and-types>.



Fig. 5. Two participants taking part in the pilot study.

the division of zones, the flexibility to initiate gestures anywhere on the screen, and the vibratory feedback as a cue for zone changes. One participant, who had both blindness and motor impairment, suggested using stronger vibrations. When the option was shown, she welcomed it and adjusted the vibration strength to her preference.

In response to whether they would learn and use BezelBraille as one of their primary text input methods, four participants answered “*definitely yes*” (a score of 5), while one participant, who experienced initial difficulty due to motor impairment, gave a neutral rating of 3. This resulted in an average score of 4.6 ($SD = 0.89$), indicating strong user acceptance of the prototype, thus validating the effectiveness of the design process.

6 User Study

We conducted a five-day user study, consisting of multiple sessions, to evaluate BezelBraille. The goals were to evaluate its performance and learning with a representative population varying in braille proficiency, compare its speed and accuracy to the methods they were already using, and explore whether the use of BezelBraille led to improvements in braille skills.

6.1 Participants

Initially, we recruited 16 participants with low vision or blindness. However, four were unable to complete the study for personal reasons, resulting in a final sample of 12 participants. Six participants self-identified as having severe visual impairment with Snellen visual acuity between 20/200 and 20/400 (we refer to them as low vision users). The remaining six participants identified as having profound visual impairment with no light perception, corresponding to a Snellen visual acuity of 20/500 or worse [3] (referred to here as blind users). Six participants identified as female and six as male, with ages ranging from 18 to 63 years ($M = 35.42$, $SD = 13.58$). Ten participants were right-handed, one left-handed, and one was ambidextrous. All had at least a high school education and reported full or native professional English proficiency.

All participants were smartphone owners with a minimum of six years of ownership ($M = 11.4$ years, $SD = 3.9$). All blind participants used built-in screen readers (TalkBack on Android or VoiceOver on iOS) to input and interact with their smartphones. Among participants with low vision, two used screen readers, while three used magnifiers and high contrast color settings. None of the participants used external devices or third-party accessibility tools. All had at least two years of experience entering text on smartphones using virtual Qwerty with their preferred built-in accessibility features ($M = 8.1$ years, $SD = 3.4$). Seven participants also reported using speech commands for certain tasks, but, as in the focus group (Section 3), none used speech predominantly

for text entry. All participants, including those who withdrew, received a compensation of US \$150 for their participation.

6.2 Apparatus

We used a Motorola Moto G Power 5G smartphone ($163.1 \times 74.8 \times 8.5$ mm, 185 g), featuring a 102.0 cm^2 display with a resolution of 1080×2400 pixels. The device runs on Android 14 and is equipped with 128 GB of internal storage and 4 GB of RAM.

The experimental application was developed using Android Studio v2025.1.1 Narwhal, the official integrated development environment (IDE) for Android. The interface was built with Jetpack Compose, Android's recommended toolkit for creating native UIs, and the backend was implemented in Kotlin, which fully interoperates with the IDE. The application automatically calculated and recorded all relevant performance metrics.

6.3 Design & Procedure

Participants scheduled their five study days over a three-week period within a wider two-month availability window. To maintain continuity in learning, we allowed a maximum gap of five days between sessions involving different tasks and a one-day gap between sessions involving the same tasks. On each study day, participants completed between two and four sessions, all of which involved the same set of tasks. A mandatory five-minute break was provided between sessions, with the option to extend it to fifteen minutes upon request. However, only three participants requested extended breaks. The study procedures were reviewed and approved by the Institutional Review Board (IRB).

The study activities were organized into three categories: pre-evaluation activities, evaluation activities, and post-evaluation activities. In the following sections, we describe the procedures, designs, and specific tasks associated with each phase of the study.

6.4 Pre-evaluation Activities

These activities were scheduled over the first three study days. They included introducing the research to participants, collecting demographic information, and gathering details about their experience with mobile text entry. These days also included assessing participants' performance with the virtual Qwerty keyboard they use on their own devices with their preferred accessibility features enabled, evaluating their braille skills, and providing a demonstration and training session for BezelBraille.

6.4.1 Introduction & Demographics. Participants were introduced to the research during the recruitment and scheduling process. However, on the first day of the study, we reiterated the purpose of the study, reviewed the informed consent form, and addressed any questions they had. After obtaining their consent, participants completed a demographic questionnaire that asked about their personal background, level of vision, use of mobile devices, and experience with mobile text entry. We then proceeded to the next activity.

6.4.2 Baseline Performance. In this session, we evaluated participants' performance using the character-based input method they typically use on their smartphones. We clarified that this could include virtual keyboards or external physical devices, such as Bluetooth keyboards, and instructed participants in advance to bring any external device they regularly use. However, all participants reported using the default virtual Qwerty keyboard on their device with built-in accessibility features enabled (Section 6.1).

Participants were asked to type 12 random phrases from a commonly used corpus [30] on their own devices using their preferred text entry methods. A researcher read each phrase aloud, and

participants were instructed to transcribe it as quickly and accurately as possible. They were allowed to repeat the phrase before starting, but once typing began, no further repetitions were given. Error correction was encouraged, but not mandatory. Text entry performance was measured using WebTEM [7], an open-source tool for capturing text entry metrics.

6.4.3 Braille Assessment. In this session, we evaluated participants' ability to read and write in braille. For this purpose, we used the UEB/EBAE³ inventory recommended by the Braille Authority of North America (BANA) [12]. The complete inventory covers a wide range of braille skills, but for the purposes of this study, we focused only on reading and writing the 26 letters of the English alphabet.

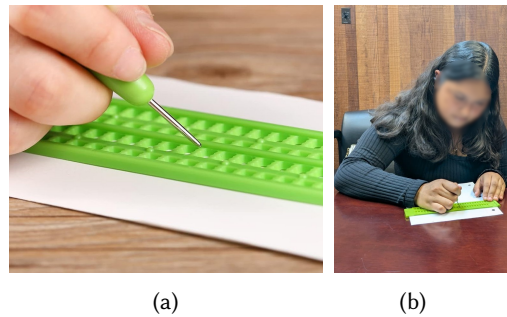


Fig. 6. (a) The braille slate and stylus used in the study. (b) A participant completing the braille writing assessment.

For the writing assessment, we used a four-line 28-cell Frienda Braille Slate and Stylus (Fig. 6). The slate provides a writing area of approximately $21.8 \times 4.4 \times 0.7$ cm, and the stylus is approximately 1.75 cm in length. Participants were also given thick, heavyweight white cut-sheet braille paper. During the writing test, they were asked to write the 26 letters of the English alphabet in random order. A researcher dictated each letter, and the participant wrote it using the slate and stylus.

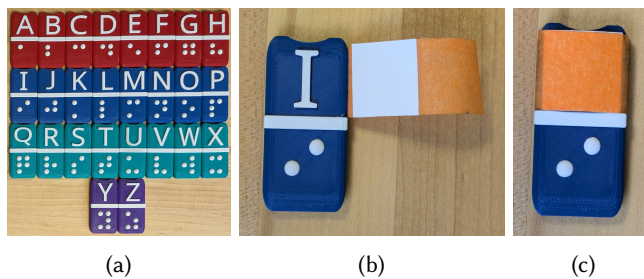


Fig. 7. (a) The alphabet tiles used in the study. (b) and (c) show the letter section of the tile for the letter 'I' covered with art paper and tape.

For the reading assessment, we used braille alphabet tiles with raised dots that allow tactile identification (Fig. 7). These tiles, originally designed for braille learning, feature two sections: the top with raised print letters and the bottom with the corresponding braille dots. To use them for

³UEB (Unified English Braille) is a standardized Braille code that has largely replaced EBAE (English Braille American Edition) in the United States.

testing, we covered the letter section with art paper and tape (Fig. 7c). During the test, a researcher presented one tile at a time in random order and the participants were asked to identify the letter by touch.

The reading and writing assessments were counterbalanced among the participants, with different randomized orders used for each task. Upon completion, we combined the reading and writing scores and calculated an overall accuracy percentage using the formula: $\frac{(S_r + S_w)}{26 \times 2} \times 100$, where S_r and S_w represent the number of correctly identified letters in the reading and writing tasks, respectively.

Results. In the assessment, six participants scored between 0% and 19% ($M = 12\%$, $SD = 6.77$), and six participants scored between 20% and 100% ($M = 83\%$, $SD = 24.61$). Only two participants achieved a perfect score of 100%. Based on these scores, participants were categorized into two skill levels: *novice* ($\leq 20\%$) and *moderate* ($> 20\%$). This classification was derived from the sample distribution to balance participant skill levels, rather than relying on any standardized braille proficiency scale. Since only two participants achieved perfect scores, we did not create a separate expert group.

6.4.4 Demonstration & Training. In this session, we first introduced the braille writing system to all participants. Although two of them were already trained in braille, we included this introduction for everyone to avoid potential confounds. We used the same alphabet tiles from the braille assessment (Section 6.4.3) to explain the logic behind the braille dot assignments.

We showed participants how the first ten letters of the alphabet use only the upper four dot positions (black dots in Fig. 8), with simpler patterns assigned to the first three letters and the first three vowels. The next ten letters mirror the first ten but include an additional dot at position 3 (red dots in Fig. 8). The final five letters (excluding 'W', which was added later to accommodate the English alphabet) follow the same pattern, with additional dots at both positions 3 and 6 (green dots in Fig. 8). This introduction was designed to support memorization and recall of the braille alphabet. The session lasted approximately 10–30 minutes per participant.

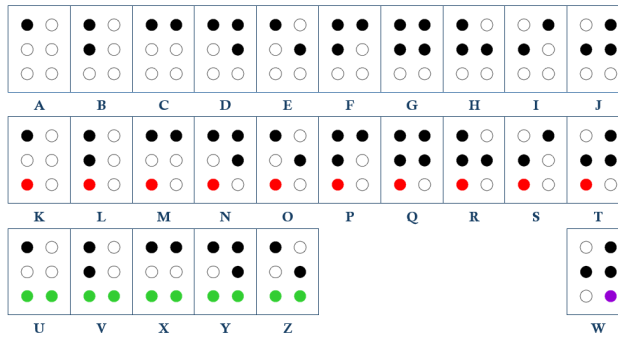


Fig. 8. Color-coded representation of the derivation of the 26 braille letters in the basic Latin alphabet.

Once participants were familiar with braille, we introduced them to BezelBraille. We demonstrated how the two columns of braille dots are represented through continuous gestures and how these could be performed either sequentially or concurrently using both thumbs (chording). We also explained all system features, including the gestures for space, backspace, and enter, as well as the options for customizing speech output speed and vibration intensity. Special emphasis was placed on using the phone's bottom edges as tactile landmarks to guide finger movement across gesture zones. Participants were shown that gestures could be initiated and ended anywhere on

the screen, as long as they passed through the relevant zones, thus minimizing the need for precise target selection.

Once familiar with the keyboard layout, participants were asked to enter all 26 letters of the English alphabet at least three times using BezelBraille. The custom training module guided them through this process, prompting them to enter one letter at a time and providing immediate feedback on correctness. If a letter was entered incorrectly, participants were asked to refer to the corresponding braille tile to reinforce the correct pattern. If a participant was not confident after three rounds, they were allowed to continue practicing for up to two additional rounds (five total). In our study, only those unfamiliar with braille opted for the extended training. Once this practice phase was completed, we concluded the training session.

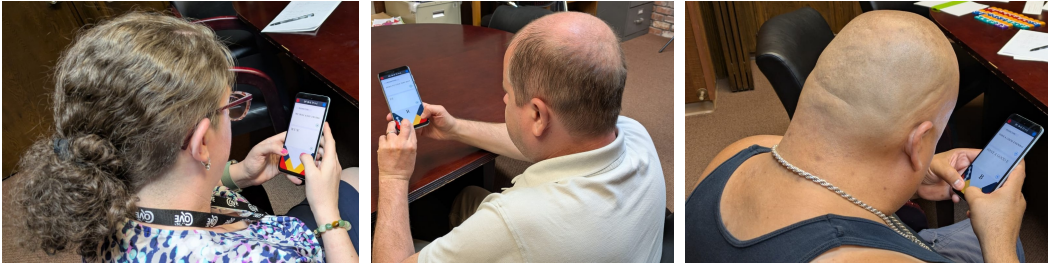


Fig. 9. Three study participants engaged in the evaluation activity.

6.5 Evaluation Activities

The main study activities involved transcribing text using BezelBraille in eight sessions, each lasting 12 minutes. We chose not to assign a fixed number of words or phrases per session, as entry speed could vary significantly between participants. This approach is often used in similar research to maintain consistent session durations (Table 2).

In the first four sessions, participants transcribed random words containing at least four characters from the 600 most frequently used words [16]. In the last four sessions, they transcribed short phrases consisting of 3–5 words each, randomly drawn from the Enron corpus [43]. All selected words and phrases excluded proper nouns, numbers, punctuation, and symbols. This word-to-phrase structure provided a gradual increase in difficulty.

The system read aloud one word or phrase at a time, which participants could replay by long-tapping on the bottom of the display. Once ready, they began transcribing. Each letter was confirmed aloud as entered. Participants could tap on the upper part of the screen to hear the current input or long-tap to hear the complete letter-by-letter transcription. Error correction was encouraged, but not forced. Participants used the method in a seated position and were instructed to hold the device with both hands, using their thumbs to perform the gestures (Fig. 9).

Each session ended automatically at the 12-minute mark, however, participants were allowed to finish transcribing the current word or phrase if it had already been started. As noted earlier, a mandatory five-minute break was provided between the same-day sessions (up to four per day), with the option to extend to fifteen minutes upon request. However, only three participants requested extended breaks.

6.5.1 Independent & Dependent Variables. The independent variables were the level of sight (two levels: low vision, blind), braille skill (two levels: novice, moderate) and the training session (eight sessions). The dependent variables were the following commonly used text entry performance metrics:

- **Words per Minute (wpm)** measures the number of words transcribed per minute, where one word is defined as five characters, including spaces [9]. The timing includes all actions, such as error correction, hearing or re-hearing the input, and performing the confirmation action. It is important to note that the confirmation action was optional and primarily intended for training, thus the reported wpm reflects a learning-mode configuration rather than regular use. To provide an estimate of entry speed without this training aid, we also calculated wpm excluding the confirmation action, denoted with an asterisk (wpm*).
- **Error Rate (ER, %)** represents the average percentage of errors remaining in the transcribed text, calculated as the ratio of incorrect characters to the total number of characters in the transcribed text.
- **Actions per Character (APC)** indicates the average number of actions performed to enter a single character or letter, excluding the confirmation action. This metric is comparable to the keystrokes-per-character (KSPC) metric commonly used in text entry research.

6.6 Post-evaluation Activities

These activities were scheduled on the last day of the study. They included reassessing participants' braille skills and collecting their feedback through questionnaires.

6.6.1 Braille Re-assessment. To investigate whether using BezelBraille facilitated braille learning, we re-assessed the braille skills of the participants using the same procedure described in Section 6.4.3.

6.6.2 Questionnaires. We concluded the study by administering the following two questionnaires to gather feedback from participants on usability, perceived workload, general impressions, and any additional comments they wished to share.

- **Usability:** We used a custom five-item questionnaire to gather user feedback on BezelBraille's perceived speed, accuracy, usability (*"easy to use"*), learnability (*"easy to learn"*), and overall preference (*"would prefer to use on a smartphone"*). The responses were recorded on a 7-point Likert scale.
- **Perceived Workload:** We also administered the widely used NASA-TLX questionnaire to assess the perceived workload of using BezelBraille. We used the raw version of the questionnaire, which is common in usability research [25]. It rates six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration, on a 20-point scale where 1 represents *"very low"* and 20 represents *"very high,"* except for performance, where 1 represents *"perfect"* and 20 represents *"failure."*

7 Results

A Shapiro-Wilk test confirmed that residuals of the response variables were normally distributed, and Mauchly's test indicated that the assumption of sphericity was met. Therefore, we used a two-way mixed-design ANOVA with within-subjects factors *practice* (8 sessions) and/or *intervention* (pre and post), and between-subjects factors *sight* (low vision vs. blind) and *proficiency* (novice vs. moderate) for hypothesis testing. To compare performance with the baseline, we conducted a repeated-measures ANOVA with a single within-subjects factor *method* (BezelBraille vs. baseline), using data from the final session only. For all statistically significant effects, we report effect sizes using eta-squared (η^2), where values of 0.01, 0.06, and 0.14 correspond to small, medium, and large effects, respectively, following Cohen's guidelines [18].

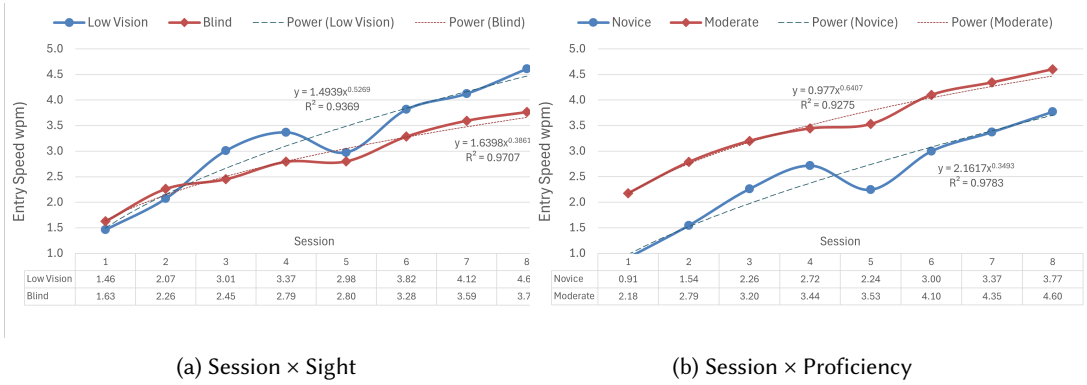


Fig. 10. Mean entry speed (wpm) across sessions by (a) level of sight and (b) braille proficiency, with power trendlines fitted to the data.

7.1 Entry Speed

On average, BezelBraille yielded an entry speed of 3 wpm ($SE = 0.4$). In the final session, the average entry speed reached 4.19 wpm ($SE = 0.44$). An ANOVA revealed a significant main effect of practice on entry speed ($F_{7,56} = 29.04$, $p < .0001$, $\eta^2 = 0.30$), indicating an improvement over time. We also estimated entry speed without the time spent on the confirmation action, yielding an average of 6.86 wpm* ($SE = 0.92$). In the final session, entry speed without the confirmation action reached 8.85 wpm* ($SE = 0.94$).

7.1.1 Level of Sight. An ANOVA did not find a significant main effect of sight ($F_{1,56} = 1.54$, $p = .25$). Participants with low vision averaged 3.18 wpm ($SE = 0.73$), while blind participants averaged 2.82 wpm ($SE = 0.46$). In addition, there was no significant practice $\times$ sight interaction effect ($F_{7,56} = 1.12$, $p = .36$). However, a post hoc Tukey-Kramer test revealed three distinct session groupings based on entry speed for both low vision: {1, 2, 3, 4, 5}, {6, 7}, {8}, and blind participants: {1, 2, 3}, {4, 5, 6}, {7, 8}, with both groups reaching significantly higher entry speeds in the final grouping. Fig. 10a illustrates the average entry speed across sessions by level of sight, with power trendlines fitted to the data.

7.1.2 Braille Proficiency. An ANOVA did not identify a significant main effect of proficiency ($F_{1,56} = 4.18$, $p = .07$). On average, novice participants achieved 2.48 wpm ($SE = 0.56$), while moderate participants achieved 3.52 wpm ($SE = 0.58$). There was also no significant practice $\times$ proficiency interaction effect ($F_{7,56} = 0.18$, $p = .99$). However, a post hoc Tukey-Kramer test identified four distinct session groups for novice participants: {1, 2, 3}, {4, 5}, {6}, {7, 8}, and three groups for moderate participants: {1, 2, 3}, {4, 5, 6, 7}, {8}, with both proficiency groups achieving significantly higher entry speeds in their final group. Fig. 10b illustrates the average entry speed between sessions by braille proficiency, with power trendlines fitted to the data.

7.1.3 Comparison with Baseline. Participants achieved an average of 17.99 wpm ($SE = 4.24$) in the baseline condition. Low vision participants averaged 28.20 wpm ($SE = 5.98$), while blind participants averaged 7.77 wpm ($SE = 1.18$). This was substantially faster than their performance with BezelBraille, which is not unexpected, as the baseline condition involved the text entry method they regularly use on their smartphones, whereas BezelBraille performance reflects only a short practice period. When comparing the last session of BezelBraille with the baseline, an ANOVA revealed significant main effects of method ($F_{1,10} = 20.13$, $p < .005$, $\eta^2 = 0.32$) and sight ($F_{1,10} = 11.87$, $p < .01$, $\eta^2 =$

0.19), as well as a significant method $\times$ sight interaction ($F_{1,10} = 10.13, p < .01, \eta^2 = 0.16$). However, interestingly, a post hoc Tukey-Kramer test showed that low vision participants performed significantly faster in the baseline condition than with BezelBraille, while no significant difference was found for blind participants.

It is important to note that in the baseline condition, participants were asked to enter 12 phrases if possible. Almost all low vision participants (5 out of 6) completed all 12 phrases, whereas none of the blind participants did. All blind participants requested to end the session early due to stress and difficulty with the task, transcribing between 5 and 10 phrases ($M = 8, SD = 2.2$).

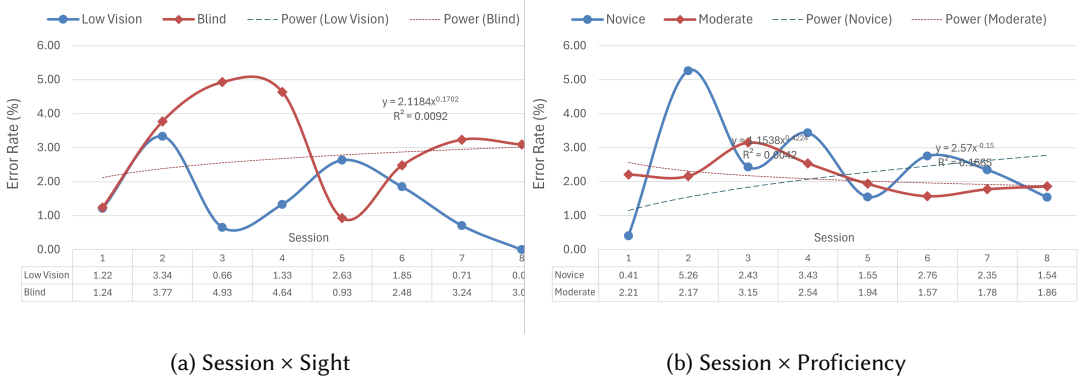


Fig. 11. Mean error rate (%) across sessions by (a) level of sight and (b) braille proficiency, with power trendlines fitted to the data.

7.2 Accuracy

On average, participants committed 2.31% errors ($SE = 0.89$) while transcribing text with BezelBraille. An ANOVA did not reveal a significant main effect of practice on error rate ($F_{7,56} = 0.94, p = .48$).

7.2.1 Level of Sight. There was no significant main effect of sight ($F_{1,56} = 0.82, p = .39$). Low vision and blind participants committed an average of 1.45% ($SE = 1.1$) and 3.12% ($SE = 1.3$) errors, respectively. However, there was a significant interaction effect between practice and sight ($F_{7,56} = 2.30, p < .05, \eta^2 = 0.10$). A post hoc Newman-Keuls test suggested that the improvement observed among blind participants primarily contributed to this interaction. It identified four statistically distinct session groupings for blind participants: {1}, {2,3,4}, {5,6}, and {7,8}, with each subsequent group yielding a significantly lower average error rate than the previous one. Interestingly, in session 5, blind participants showed a sharp drop in error rate. However, this is likely due to chance, as no clear pattern or explanation emerged from our analysis. In contrast, low vision participants maintained a consistently low error rate throughout the study (Fig. 11a).

7.2.2 Braille Proficiency. There was no significant main effect of proficiency on accuracy ($F_{1,56} = 0.01, p = .94$). Novice and moderate participants committed an average of 2.45% ($SE = 1.50$) and 2.17% ($SE = 0.97$) errors, respectively. The analysis also did not identify a significant practice $\times$ proficiency interaction effect ($F_{7,56} = 1.54, p = .17$). Both novice and moderate participants consistently maintained low error rates (Fig. 11b).

7.2.3 Comparison with Baseline. An ANOVA revealed a significant main effect of method on error rate ($F_{1,10} = 8.00, p < .05, \eta^2 = 0.27$). Results showed that participants committed significantly more errors in the baseline condition (7.88%, $SE = 2.72$) compared to BezelBraille (2.31%, $SE = 0.89$).

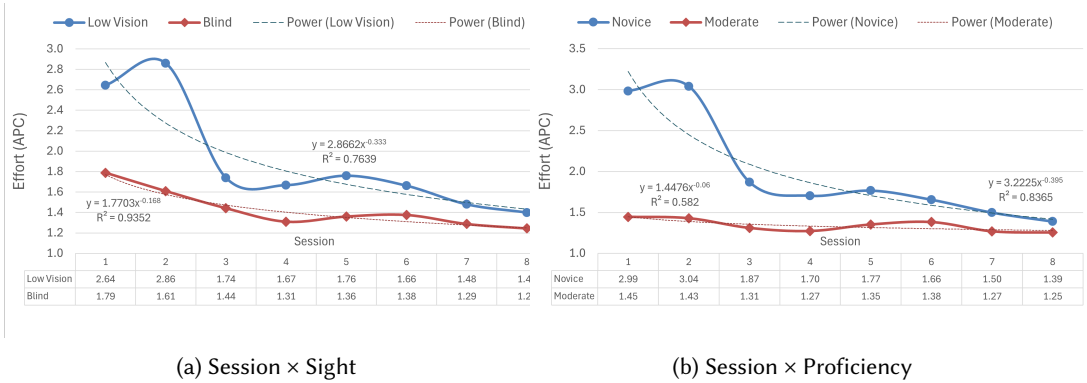


Fig. 12. Mean effort, measured as actions per character (APC), across sessions by (a) level of sight and (b) Braille proficiency, with power trendlines fitted to the data.

7.3 Effort

On average, participants performed 1.66 actions ($SE = 0.32$) to enter a single character using BezelBraille. In the final session, actions per character decreased to 1.32 ($SE = 0.10$). An ANOVA revealed a significant main effect of practice on actions per character ($F_{7,56} = 2.52, p < .05, \eta^2 = 0.31$).

7.3.1 Level of Sight. Participants with low vision performed an average of 1.90 actions ($SE = 0.61$) per character, while blind participants averaged 1.43 actions ($SE = 0.18$). However, the ANOVA did not reveal a significant main effect of sight ($F_{1,56} = 0.26, p = .62$) or a significant practice $\times$ sight interaction ($F_{7,56} = 0.32, p = .94$). A post hoc Tukey-Kramer test identified the same three distinct APC session groupings for both low vision and blind participants: {1, 2}, {3, 4, 5, 6}, {7, 8}. Fig. 12a illustrates the average actions per character across sessions by level of sight, with power trend lines fitted to the data.

7.3.2 Braille Proficiency. Novice and moderate participants performed an average of 1.99 actions ($SE = 0.61$) and 1.34 actions ($SE = 0.12$) per character, respectively, when using BezelBraille. An ANOVA did not find a significant main effect of proficiency ($F_{1,56} = 0.94, p = .36$) nor a significant practice $\times$ proficiency interaction ($F_{7,56} = .71, p = .13$). Interestingly, a post hoc Tukey-Kramer test revealed three different APC session groupings for novice participants: {1, 2}, {3, 4, 5, 6}, {7, 8}, while no such groupings were found for moderate participants. Fig. 12b shows the average actions per character in sessions by proficiency, with power trend lines fitted to the data.

7.3.3 Comparison with Baseline. An ANOVA did not reveal a significant main effect of method on actions per character. Participants performed a comparable number of actions with BezelBraille ($M = 1.66, SE = 0.32$) and with the baseline methods ($M = 1.10, SE = 0.05$).

7.4 Letter-Level Confusion Analysis

To better understand which letters were easier or more difficult to enter, and which were most frequently confused, we conducted a letter-level confusion analysis, illustrated in Fig. 13. The analysis used data only from the final session of the study. Any letter entered incorrectly on the first attempt was counted as an error, regardless of whether it was later corrected.

The results showed that the letters ‘Q’ and ‘Z’ were the most difficult to enter and the most frequently confused. Notably, both letters involve a large number of dots (five and four, respectively)

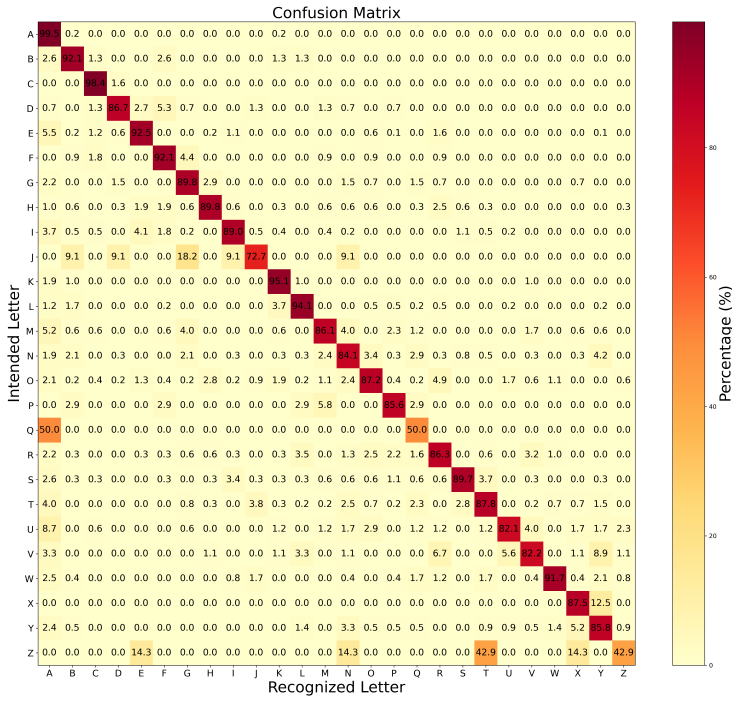


Fig. 13. Letter-level confusion matrix for BezelBraille based on data from the final study session.

distributed across both columns. Overall, the confusion matrix suggests that error likelihood increased with the number of dots involved and with gestures requiring coordination across both sides of the device. In particular, ‘Z’ was most commonly confused with ‘T’, likely because both use similar gesture patterns that differ primarily in direction. More generally, letters with similar gesture structures were occasionally confused with one another, whereas letters composed of simpler one-dot gestures were entered with the highest accuracy (e.g., ‘A’ and ‘C’). These findings could help inform future predictive or error-correction mechanisms for BezelBraille.

7.5 Learning Braille

An ANOVA revealed a significant main effect of intervention on braille skills ($F_{1,10} = 45.33, p < .0001, \eta^2 = 0.32$). There was also a significant interaction effect between initial proficiency and intervention ($F_{1,10} = 16.15, p < .005, \eta^2 = 0.12$).

The results showed that the braille skills of novice participants improved by 583% after the intervention (from 12% to 79%), while moderate participants showed an improvement of 20% (from 83% to a perfect 100%). Fig. 14 illustrates these changes. A post hoc Tukey-Kramer multiple comparison test revealed a significant difference between pre-intervention and post-intervention scores for novice participants. However, no significant differences were found for moderate participants.

7.6 Subjective Evaluation

For questionnaire data, we used a one-sample Wilcoxon signed-rank test to assess whether median ratings for each measure differed from the neutral midpoint. This non-parametric test, suitable for ordinal Likert data, compares participant scores to the midpoint and evaluates whether the

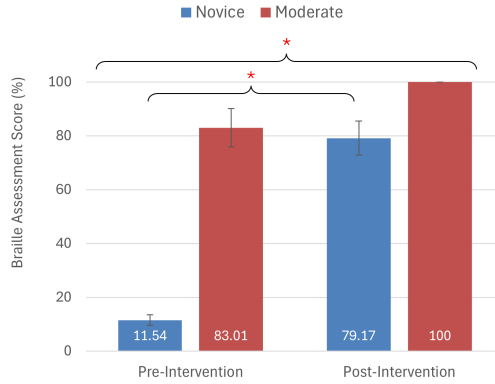


Fig. 14. Mean braille proficiency scores on the BANA inventory for novice and moderate participants, before and after the intervention. Error bars represent ± 1 standard error. Red asterisks indicate statistically significant differences.

distribution of differences is symmetric around zero, indicating significantly higher or lower ratings [6]. We also calculated effect sizes (r) using rank-biserial correlation from the test statistics to gauge the magnitude of these differences, where $r = 0.71$ constitutes a large effect [5].

7.6.1 Usability. The results revealed that all five measures were rated significantly higher than the neutral midpoint, with large effect sizes in every case. Perceived Speed ($W = 0.0, p < .001, r = 0.89$), Perceived Accuracy ($W = 0.0, p < .005, r = 0.89$), Usability ($W = 3.5, p < .05, r = 0.75$), Learnability ($W = 0.0, p < .005, r = 0.89$), and Preference ($W = 5.0, p < .01, r = 0.75$) all showed r values well above 0.7. These results indicate not only statistically significant but also substantial differences from neutral, suggesting participants perceived the system as fast, accurate, easy to use, easy to learn, and preferable overall. Fig. 15 shows the mean participant ratings for the questionnaire items.

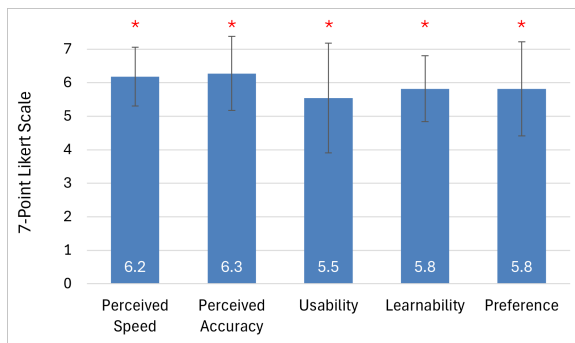


Fig. 15. Mean participant ratings for the five usability questionnaire items on a 7-point Likert scale. Error bars represent ± 1 standard deviation. Red asterisks indicate measures with median ratings significantly higher than the neutral midpoint.

7.6.2 Perceived Workload. The results showed that Performance was rated significantly lower than the midpoint ($W = 0.0, p < .005$), with a large effect size ($r = 0.88$), indicating that participants

perceived their performance as substantially better (lower scores indicate better performance). While Temporal Demand ($W = 9.5, p = .12, r = 0.51$) and Frustration ($W = 11.5, p = 0.07, r = 0.58$) did not reach statistical significance, both showed large effect sizes, suggesting a tendency toward lower-than-neutral ratings. The remaining measures, Mental Demand ($W = 9.0, p = .40, r = 0.32$), Physical Demand ($W = 8.5, p = .67, r = 0.17$), and Effort ($W = 17.5, p = .55, r = 0.20$), did not significantly differ from the midpoint and showed small-to-moderate effect sizes, indicating ratings closer to the neutral level. Fig. 16 shows the mean participant ratings for the NASA-TLX questionnaire items.

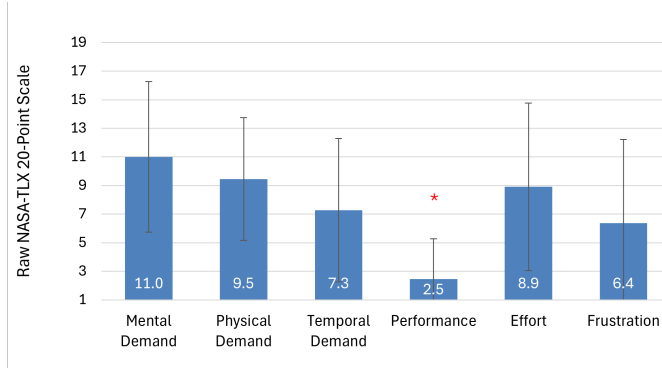


Fig. 16. Mean participant ratings for the six NASA-TLX questionnaire items on a 20-point scale. Error bars represent ± 1 standard deviation, and red asterisks mark items with median ratings significantly different from the neutral midpoint.

8 Discussion

8.1 Speed & Accuracy

BezelBraille yielded an average entry speed of 3 wpm, which increased to 4.2 wpm in the final session. The fastest participant (female, 18 years old), who scored 44% on the braille assessment, achieved 7.7 wpm in the last session. Although Table 2 shows the performance of BezelBraille in the middle range compared to existing braille-based mobile text entry methods, this comparison is not entirely fair. All studies in the table involved experienced braille users who did not require braille learning, while in our study 83% of the participants were not proficient in braille and 50% had almost no prior skills. To support these users, we included an exploration feature that allowed them to test gestures when uncertain about the correct input. While beneficial for novices, this feature slowed text entry, but could be removed for expert users to improve speed. As a result, the reported speeds reflect a learning-mode configuration rather than typical use, and should therefore be interpreted with caution. To approximate performance without this training aid, we recalculated wpm excluding the confirmation action. Without this step, the average entry speed increased to 6.9 wpm*, with the final session reaching an average of 8.9 wpm*. Yet, this analysis was conducted post hoc, and further studies are needed to validate these findings.

The fastest methods in Table 2, those exceeding 20 wpm, were evaluated after extended training sessions focused on the method itself. In contrast, much of our training time was spent introducing braille, followed by having participants enter the English alphabet just 3-5 times using the method. Also, unlike some prior studies, our participants were not instructed to practice braille between sessions and only used it during the study itself. Hence, we expect that with more training, participants could achieve substantially higher speeds. Evidence of continued learning is clear. Both low

vision and blind participants improved steadily throughout the study, fitting well to the power law of practice ($R^2 > 0.9$) [15]. The entry speeds of the low vision and blind participants increased by 216% and 131%, respectively, from the first to the last session, with post hoc analyses showing that the latter session groups significantly outperformed the earlier ones (Fig. 10a). Similarly, novice and moderately proficient braille users improved by 314% and 111%, respectively, also fitting well to the power law of practice and showing significant differences between the earlier and the latter session groups (Fig. 10b). In all cases, the learning curves had not plateaued, indicating the potential for further improvement.

Finally, when comparing BezelBraille with the baseline method in the last session, an ANOVA did not show a significant effect of method. Although non-significant results do not provide definitive conclusions, they suggest that the test did not detect a difference. It is also important to note that in the baseline condition, none of the blind participants completed all 12 phrases due to stress and task difficulty, transcribing on average only eight phrases each. The same option to end the session early was provided for BezelBraille, yet none of the participants chose to do so.

There was no significant effect of level of sight or braille proficiency on accuracy (Fig. 11). Participants consistently maintained a low error rate throughout the study, probably due to a speed-accuracy trade-off. Because they started at a slower and steady pace while learning the method, they likely made fewer mistakes. Notably, participants committed significantly more errors with the baseline method (7.9%) compared to BezelBraille (2.3%). However, differences in the study setups between conditions should also be considered when interpreting these results. In the baseline condition, participants used their own devices with varying hardware and screen reader configurations, whereas BezelBraille used a standardized Motorola device. Similarly, phrases were read aloud by a researcher in the baseline condition, while BezelBraille provided the auditory prompts automatically. We therefore encourage further investigation under more controlled and comparable conditions to enable a more rigorous comparison.

8.2 Effort & Chording

On average, participants performed 1.66 actions per character (APC) when using BezelBraille, with no significant difference compared to the baseline. There were also no significant differences in APC between participants with different levels of sight or braille proficiency. However, learning effects were evident across all groups (Fig. 12). Overall, participants' APC decreased by 41% from the first to the last session. Both low vision and blind participants showed improvement, fitting moderately well ($R^2 = 0.87$) and well ($R^2 = 0.93$), respectively, to the power law of practice. Low vision participants reduced their APC by 47%, while blind participants reduced theirs by 31% over the course of the study. Post hoc analyses confirmed that both groups performed significantly fewer actions per character in latter sessions compared to earlier ones.

A similar trend was observed for braille proficiency. Novice and moderately proficient braille users both fit well to the power law of practice ($R^2 > 0.9$), with APC reductions of 54% and 14%, respectively. The smaller reduction for moderate users is likely because they began with fewer actions per character, benefiting from prior braille knowledge.

These findings suggest that participants became more efficient with practice, performing fewer exploratory actions and making fewer corrections over time. They also indicate an increasing tendency to perform gestures simultaneously (chording) rather than sequentially. In an ideal case, where users always chord and make no errors, the APC would be 1.0. For comparison, the calculated APC for sequential-only gestures in the study's text was 1.83. The observed average of 1.66 supports the conclusion that participants were already beginning to chord. With continued learning, APC could approach 1.0, resulting in higher text entry speeds.

The letter-level confusion analysis showed that letters requiring more dots and coordination across both sides of the device were generally more difficult to enter and more frequently confused. In particular, ‘Q’ and ‘Z’ exhibited the highest error rates, with ‘Z’ most often confused with ‘T’ due to their similar gesture patterns. In contrast, simpler one-dot letters, such as ‘A’ and ‘C’, were entered with the highest accuracy. These findings could inform future predictive or error-correction mechanisms for BezelBraille.

8.3 Learning Braille

There was a significant effect of the intervention (using BezelBraille) on braille proficiency, as well as a significant interaction between initial proficiency and the intervention. A paired-samples t-test confirmed these findings ($t_{(11)} = -4.37, p < .001, d = -1.26$), with the effect size exceeding the threshold for a large effect ($d = 0.8$) [17]. Novice participants showed a remarkable 583% improvement in braille skills, increasing from an average score of 12% to 79%, while moderately proficient participants improved by 20%, rising from an average score of 83% to a perfect 100% (Fig. 14). In general, 50% of the participants ($N = 6$) achieved a perfect score, and another 33% ($N = 4$) scored between 80% and 98%. These results demonstrate that using BezelBraille can improve braille proficiency, enabling skills that may transfer to other braille-based technologies. However, we acknowledge that the observed rate of improvement may not be entirely attributable to BezelBraille, as activities prior to and during the study, including the training sessions, may also have contributed. A longer-term study is therefore needed to more fully investigate this effect.

8.4 User Feedback

All participants found BezelBraille easy to learn and use. Most (67%, $N = 8$) rated it as moderately demanding in terms of mental, physical, and temporal demands, as well as effort (scores < 10), while the remaining 33% ($N = 4$) rated it as demanding. This is not surprising, as these four participants had low braille proficiency and likely needed more effort to learn the method. Despite this, participants perceived the method as both fast and accurate, contrary to our expectation of negative ratings. Interestingly, performance and frustration ratings were favorable, with performance ratings significantly above the neutral midpoint. This was likely because participants recognized that their performance improved over time. As a result, all participants expressed interest in continuing to use the method as one of their primary text entry options.

8.4.1 Interaction Design. Participants generally responded positively to the interface design of BezelBraille, particularly appreciating the use of spatially aligned braille gestures and vibration feedback. Several participants reported that the layout became easier with use, with one participant noting that they “developed muscle memory for the letters” after typing a few times, while another said they “liked the app once [they] could remember all the braille combination.” Participants also praised the overall concept, commenting that “the idea of aligning the letters is great,” and that the “vibration feedback for locating the regions is well designed for the blind or low vision people.”

8.4.2 Suggested Improvements. At the same time, participants identified several design aspects that could be improved. Multiple participants mentioned difficulties with reaching or locating the bottom zones, particularly when performing diagonal gestures or accessing the right-side zones. One participant explained that “it takes a little time to get used to the alignment of the dots,” while another noted that “sometimes it is difficult to type a few letters and reaching the right zone.” Some participants suggested that placing “the keyboard a little higher would help,” since “holding the phone and at the same time reaching the bottom area is a bit difficult.” Others suggested that “landscape position might help holding and better typing.” Although BezelBraille also supports landscape orientation, we did not evaluate it in the study based on feedback from the focus group.

Participants also expressed interest in stronger or richer tactile guidance, recommending “*more intense vibration*” and suggesting that “*a physical bump or dot on the surface will help more reaching the right zones than just vibration.*” Additional feedback included requests for automatic auditory feedback after spaces. In the current implementation, this required a long press.

9 Limitations

We acknowledge several limitations of this work. The final study included only 12 participants, primarily due to the difficulty in recruiting visually impaired individuals in a small town setting. Furthermore, we were unable to recruit enough expert braille users to achieve our initial goal of having an equal representation of novice, intermediate, and expert participants. Despite these constraints, the large effect sizes observed for all statistically significant results suggest that our findings are likely transferable to a broader population.

10 Conclusion

This work introduced BezelBraille, a braille-inspired, eyes-free text entry method for blind and low vision users that exploits the smartphone’s physical bezel corners as tactile landmarks for spatial reference. Through an iterative design process and evaluation with 12 visually impaired participants, we demonstrated that BezelBraille enables accurate text entry, significantly improves braille proficiency, and is well-received by users. Despite limited prior practice and varying levels of braille literacy among participants, the method achieved competitive performance compared to existing braille-based systems. Moreover, BezelBraille offers users greater control by minimizing the need for precise target selection, supporting a range of preferred holding postures, and functioning independently of predictive text systems. These findings suggest that BezelBraille is a promising character-based mobile input method that supports both effective communication, and potentially, the development of braille literacy.

11 Future Work

We plan to extend this study to examine expert performance and verify whether the projected speeds after 10 hours of training align with actual results. We will also explore the integration of predictive features such as word completion and suggestions. While these were intentionally excluded in the present study to measure the method’s raw performance, we acknowledge that predictive features could further enhance text entry speed and accuracy. In addition, recent advances in generative AI and large language models (LLMs) present opportunities for phrase completion and next-phrase prediction, which we aim to investigate.

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