BraillePlay: Educational Smartphone Games for Blind Children

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ABSTRACT

There are many educational smartphone games for children, but few are accessible to blind children. We present BraillePlay, a suite of accessible games for smartphones that teach Braille character encodings to promote Braille literacy. The BraillePlay games are based on VBraille, a method for displaying Braille characters on a smartphone. BraillePlay includes four games of varying levels of difficulty: VBReader and VBWriter simulate Braille flashcards, and VBHangman and VBGhost incorporate Braille character identification and recall into word games. We evaluated BraillePlay with a longitudinal study in the wild with eight blind children. Through logged usage data and extensive interviews, we found that all but one participant were able to play the games independently and found them enjoyable. We also found evidence that some children learned Braille concepts. We distill implications for the design of games for blind children and discuss lessons learned.

Categories and Subject Descriptors

H.5.2 [Information Interfaces and Presentation] User Interfaces-Haptic I/O. K.3.0 [Computers and Education]. K.4.2 [Computers and Society]: Social Issues-assistive technologies for persons with disabilities.

General Terms

Human Factors, Design, Experimentation.

Keywords

Accessibility; educational games; blind; children.

1. INTRODUCTION

Smartphones offer an appealing and increasingly popular platform for educational games for children. Digital games in general have been shown to be effective learning tools [12,33]. Smartphones in particular offer advantages over traditional computers because they are mobile (people can use them anywhere) and have additional sensors (*e.g.*, a touchscreen and a vibration motor). Many children already use smartphones on a regular basis [12], and educational smartphone games have generated substantial interest in industry and academia. There are currently 65,000 education applications in the Apple AppStore [6], many of which are games targeted towards children [18].

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Figure 1. The VBraille interface for "reading" and "writing" Braille characters (left) and a menu from the VBHangman game that is based on the word game Hangman (right).

While smartphone games have the potential to significantly impact children's education, they are largely inaccessible to blind children. Smartphones are generally accessible to blind people with built-in screen readers such as iOS's VoiceOver [5] and Android's TalkBack [4]. These screen readers work well with text-based interfaces that use standard UI widgets. Games, by contrast, usually have custom widgets with images rather than text. Moreover, they commonly require users to hit visual targets under time constraints, making them inaccessible. Blind children are thus unable to participate in and benefit from these promising educational tools.

In this paper, we present *BraillePlay*, a suite of educational smartphone games for blind children. Our goal was to design games that (1) were accessible and engaging to blind children and (2) promoted Braille concepts. We focused on Braille because in recent years there has been a sharp decline in Braille literacy. According to the National Federation of the Blind, only 10 percent of blind children in the US are learning Braille despite the fact that Braille literacy has been strongly linked with a higher education level, a better chance of employment, and a higher income for blind adults [29]. We designed our games for children who are 5 years old or older, so they can learn Braille concepts at the same age that their sighted peers are learning to read.

The BraillePlay suite includes four applications that use the VBraille interface [19, 28] through which the user can identify (*i.e.*, "read") and enter (*i.e.*, "write") Braille characters (see Figure 1). The BraillePlay games help children learn and memorize Braille character encodings, which is a critical aspect of learning how to read Braille. Two of the games simulate Braille flashcards, testing children's ability to identify and enter characters while the other two incorporate the VBraille interface into word games. The games have speech output with high-contrast but minimal graphics, large print, and gestures that follow accessible design guidelines [20, 21].

To evaluate our games, we conducted a longitudinal study in the wild with eight blind children (ages 5 – 8). We asked participants to play instrumented versions of the games at least four times a week for four weeks. Throughout the study, we surveyed and interviewed participants and their parents. We found that most participants were able to play the games independently with minimal training. Several of the children found the games enjoyable and were motivated to play them for long periods of time, and several of the parents felt that the games helped their children learn Braille.

In summary, our contributions include:

i. The BraillePlay games, a set of free iOS[1] and Android[2] applications that are available online, as well as the code for the games, which is available in our online repository[3].

ii. Empirical findings from our longitudinal study that show how children interacted with the games.

iii. Design implications for accessible smartphone games for children.

iv. A discussion of lessons learned that provide guidance for researchers interested in conducting studies with children in the wild.

2. RELATED WORK

To our knowledge, BraillePlay games are the first educational smartphone games for blind children. The design of the VBGhost game was first presented in a poster [28], but the current paper describes all the games in detail and the longitudinal study. Our work draws from prior work on (1) representing Braille on smartphones, (2) educational games for sighted children, and (3) accessible games.

2.1 Representing Braille on Smartphones

Since BraillePlay teaches Braille concepts, we discuss several approaches to representing Braille on smartphones. People commonly read Braille on specialized devices called Braille displays [2] that display a row of characters at once. However, Braille displays cost hundreds or thousands of dollars.

BraillePlay games use Jayant *et al.*'s VBraille [19], a method of reading characters on a smartphone with no visual or audio output. VBraille displays one character on the screen at a time. The screen is divided into 3 rows and 2 columns like a Braille cell and the phone vibrates when the user touches regions that correspond to the raised dots in the current character. Jayant *et al.* argue that VBraille can be a useful output method for deaf-blind mobile device users, since VBraille only provides haptic feedback. When using VBraille in our games, we added speech output that tells the user which dot she is touching. We also created a VBraille interface for entering characters, where the user double taps regions of the screen to raise the corresponding dots. Al-Qudah *et al.* [1] also present a method where characters are output through haptic feedback only. They use a vibration pattern for each character that is based on its Braille representation.

There has also been much work on Braille-based methods for input on a smartphone. BrailleTouch [14], Perkinput [10], and TypeInBraille [25] use multi-touch input to enter characters. These methods are likely to be difficult for young children who are not as coordinated or dexterous as adults. BrailleType [30,31] is similar to the VBraille input method we use in BraillePlay. Unlike VBraille, BrailleType users single tap the regions of the screen to raise dots. BrailleType is likely to be faster than VBraille but also more error-prone, especially for children who are learning Braille.

2.2 Accessible Digital Games

Researchers have created recreational digital games for traditional computers as well as various other hardware platforms [7, 8, 11, 16, 27, 34, 37]. McElligott *et al.* [26] conducted co-design with blind children and developed several computer games with audio feedback. They emphasized the importance of using existing, mainstream platforms and designing games that can be played autonomously and cooperatively. Researchers in the TiM project [7, 11] also designed accessible games that used audio feedback, but they required speakers for surround-sound and tactile overlays for a computer screen. Some researchers have laid out guidelines in building accessible games for blind games [3, 9, 15, 26, 32]. These guidelines have inspired us to use a universal design approach to the games by providing both audio output, and visual output with contrast for low-vision users.

There are a few accessible games designed for smartphones. Both Tapbeats [22], and the Audio Flashlight [36] use the audio interface of the smartphone to be accessible to blind people. Neither game is designed for children or for educational purposes.

2.3 Educational Games

There is a body of literature enumerating the potential benefits of using digital games for education [12,13,33]. Games can be valuable learning tools because they are engaging and motivate users to improve their gameplay skills. However, it is difficult to isolate the learning effects of games, and there is little direct evidence in the literature that games teach certain concepts [13], and results have been mixed in studies measuring the empirical evidence of learning using educational games [17,23].

There are few educational games designed for blind people. Song *et al.* [35] developed two audio-based learning games on TeacherMate, an inexpensive mobile device designed for people in developing countries. They found that children enjoyed playing their games individually and in groups, working together on challenging parts of the game. Sánchez *et al.* [34] also developed an accessible game on a custom hardware platform called MOVA3D, which teaches children orientation and mobility skills.

[1] https://itunes.apple.com/us/artist/mobile-accessibility/id692203637

[2] https://play.google.com/store/apps/developer?id=Mobile+Accessibility

[3] https://code.google.com/p/mobileaccessibility/

Figure 2. A two-finger swipe to the right allows users to submit a character entered in VBWriter or move to the letter input screen in VBReader.

3. BRAILLEPLAY GAMES

3.1 Design Principles

We designed the BraillePlay games to be (1) educational, (2) accessible, (3) accommodate a variety of skill levels, and (4) available for mainstream devices.

Educational. We created games to promote Braille literacy, which is in rapid decline despite the fact that it is important for success in both school and the workplace [29]. Early exposure to Braille concepts is crucial for blind children [24]. Just like their sighted peers, blind children must begin learning reading and writing concepts in preschool, and there are a variety of games and avenues to aid with this. To read Braille, children must both know the Braille dot patterns and be able to discern these dot patterns tactilely. Because it can be difficult and frustrating for children to discern the patterns using the small standard Braille cell, the Braille alphabet is often taught using over-sized stand-ins including plastic eggs in egg cartons and tennis balls in muffin tins [24].

The VBraille interface differs from standard Braille in two ways: it is much larger, and it uses vibration instead of raised bumps to represent the characters. Because of these differences, it cannot help children develop the tactile sensitivity needed to read a standard Braille cell. However, VBraille can help children learn Braille encodings, a critical component of learning how to read. Teachers already use large representations of Braille characters that they make out of egg cartons and muffin tins.

Accessible. To be accessible, the games had to be (1) age appropriate for children aged 5 years old and older and (2) accessible for people who are sighted, low-vision, and blind.

To accommodate the developing motor skills of young children, we used simple gestures such as single and double taps and swipes (Figure 2). When possible, we gave users the ability to use either the smartphone's keypad or a touchscreen gesture to complete an action. For example, users can either double tap on the touchscreen or use numbers 1-6 on the keypad to raise or lower dots in VBWriter. We chose a large representation of Braille so that young children could easily distinguish between dots in nearby rows or columns. We also used a representation that has the same spatial layout as a Braille cell, as opposed to a purely temporal representation like the one developed by Al-Qudah *et al.* [1], making it easier for young children to make the connection to Braille characters. Additionally, our games do not rely on timing. Instead they are self-paced, and children can hear information about the state of the game as many times as they want.

To ensure the games were accessible for people with all levels of vision, we used high contrast and large fonts as well as audio and haptic feedback. We also relied on simple gestures and VoiceOver-like interaction techniques with menus (single tap to hear an option and double tap to select it) in line with earlier accessibility work [20, 21]

Accommodate Different Skill Levels. We wanted to design games that worked for children 5 years old and older and accommodated varying levels of Braille, vocabulary, and spelling skills. We thus created simple flashcard games (VBReader and VBWriter) for people just learning Grade 1 Braille characters, and more complex word games (VBHangman and VBGhost), which require a larger vocabulary and spelling ability. We hoped that children would begin using VBReader and VBWriter and be motivated to "graduate" to the more complex word games.

Available on Mainstream Devices. Finally, we wanted to design games that could be played using a mainstream device instead of specialized assistive technology. As smartphones become increasingly pervasive in our culture, the ability to use a smartphone is, in itself, a crucial skill. It is therefore important that blind children gain exposure and experience using smartphones just like their sighted peers.

3.2 Description of Games

We designed four BraillePlay games: VBReader, VBWriter, VBHangman and VBGhost. All four games are available for the Android platform (1176 downloads from the Play Store from August 2013 to August 2014), and VBReader, VBWriter and VBGhost are available on the iOS platform (4,471 downloads from the App Store from August 2013 to August 2014). There are minor differences between the two platforms, and in this paper, we describe the Android versions, since those were the games used in the longitudinal study.

VBReader. VBReader is a simple flashcard game in which a user identifies VBraille characters. A VBraille character is presented on the screen. When the user determines which character is presented, she uses a two-finger swipe to the right (Figure 2) or presses the trackball to load the character entry screen. Using the menu button, the user can choose between three options to enter a character: (1) a Qwerty keyboard, which presents a Qwerty keyboard in landscape orientation, which can be navigated with a VoiceOver-like gestures, (2) a two-column alphabetical keyboard, navigated in the same way, or (3) a tapping progression through the alphabet, in which a user can cycle through the alphabet with a single tap to move to the next letter and a double tap to select a letter. After the user selects a letter, the application tells the user whether the input was correct or not and presents a new VBraille letter. If the user exits the application, VBReader tells the user how many characters were identified correctly out of the total number: "You entered 5 out of 10 characters correctly!"

VBWriter. VBWriter is another simple flashcard game in which a single character is spoken aloud ("Enter A as in Alpha"), and the user must input that character using the VBraille interface. The user can press the menu button to hear the letter again. After raising the desired dots in the VBraille screen, the user can submit the character with a two-finger swipe to the right or a tap on the trackball. If the character was entered correctly, the application congratulates the user and presents anther character. If the letter was not entered correctly, the application tells the user what letter was entered and displays the correct letter on the VBraille interface. When the user exits the game, VBWriter announces the number of correctly entered characters out of the total number attempted.

VBHangman. VBHangman is based on the word game Hangman. In Hangman, the user must determine what a word is, given the length of the word and a limited number of guesses as to which letters are in the word. With each guess, the user is told whether the letter is in the word, and, if it is, where the letter is in the word. For example, if the word was "banana" and a user guessed the letter "A," she would be told "blank-A-blank-A-blank-A." Hangman is typically played between two people.

In VBHangman, the user plays against the "computer." At the start of a game, the user chooses the length of the word she would like to play using a menu. The smartphone randomly selects a word of that length, then displays the main menu (Figure 1). In the main menu, the user can choose to hear (1) the word so far ("blank-A-blank-A-blank-A"), (2) the number of trials left ("You have four trials left"), (3) the letters guessed so far ("Letters guessed: 'A' as in alpha, 'C' as in Charlie"), or (4) the instructions for the game. The menu also includes an option to enter another letter. The user enters letters through the VBraille interface, and uses a two-finger swipe to the right to submit her guess. She is given a chance to verify her guess: "You entered the letter 'B' as in bravo, swipe right with two fingers if that is correct." After each guess, the game will tell her if the letter is in the word: "Good guess, 'B' is in the word. The word so far is 'B-A-blank-A-blank-A.'" If the user successfully completes the word, the game will congratulate her and read the completed word aloud. If the user uses up all her guesses and does not correctly identify the word, the game informs her that she has lost and tells her what the word was.

VBGhost. VBGhost [28] is a slightly more complicated game, based on the word game Ghost, in which users take turns adding letters onto a word fragment. If a user adds a letter that spells out a complete word then she loses (*e.g.*, if the current word fragment is "gam," the user will lose if she adds the letter "e" because she will spell "game"). A user also loses if she adds a letter to the word fragment that makes the word fragment invalid (*e.g.*, if she adds the letter "z" to the word fragment "gam," "gamz" is no longer the start to any word).

In VBGhost, the user indicates whether she wants to play the game against the smartphone or against a co-located friend. If she plays against the smartphone, the user is taken to the VBraille screen where she can enter the first letter of the game. After entering a letter, the user swipes with two fingers to the right, and the game tells her (1) if she entered a non-alphabetic character (she is presented with a blank VBraille screen again), (2) if the letter creates an invalid word fragment or completes a word: "I am sorry, you lost, "gamz" is an invalid word fragment" (she is then presented with the main menu screen), or (3) if the letter is a valid play. If the letter is a valid play (part of a valid word fragment), the smartphone selects a letter to add to the word fragment (the smartphone will sometimes complete a word and therefore lose at this point). If the smartphone loses the game by completing a word, it informs the user of her victory and takes her to the main menu screen. Otherwise, the phone adds a letter onto the word fragment, and the user can read the letter using the VBraille interface.

In the multi-player mode, users pass the smartphone back and forth to enter letters. After one user adds a letter to the word fragment, the other user can chose to (1) enter her own letter, (2) listen to the word fragment so far or (3) challenge the previous letter entered by her opponent as either completing a word or creating an invalid word fragment. The smartphone checks whether the challenge is correct and announces which user won based on the outcome of the challenge. We chose to include a more complex, multi-player game in the suite of BraillePlay games to facilitate collaborative learning.

4. EVALUATION

To evaluate BraillePlay, we conducted a longitudinal study with eight blind children and their parents over a four-week period. Participants were recruited from across the United States and Panama. We chose to perform a longitudinal study in the wild because we wanted to observe gameplay patterns over time that reflected natural use. We conducted the study remotely because there are few blind children locally that were willing to participate in the study.

We sought to answer three research questions:

1. Are BraillePlay games *accessible* to blind children?
2. Are BraillePlay games *engaging* for blind children?
3. Are BraillePlay games *effective* teaching tools?

4.1 Method

4.1.1 Participants

We recruited eight sets of participants (children and parents) for this study from around the United States and Panama (Table 1) through email lists related to raising and caring for blind children. We required that the children (1) be between the ages of 5 and 13 and (2) they identify as either blind or low-vision. The mean age of the child participants was 6 years old (age range was 5 to 8). There was a wide range in the children's knowledge of Braille, as some children were learning how to read single letters, while others were learning Grade 2 contractions. Participants were compensated with a $50 Amazon gift card.

Table 1. Participants in Longitudinal Study

ID	Age	Gender	Degree of Vision	Braille Knowledge	Note
P1	6	F	Light perception	Grade 1	-
P2	6	F	Low-vision	Some contractions	-
P3	5	F	No functional vision	Some letters	-
P4	6	M	No functional vision	Some letters	Language delays
P5	8	M	Light perception	Some contractions	-
P6	7	F	Light perception	Some letters	English as a second language
P7	7	F	No functional vision	Some letters	Cerebral palsy
P8	6	M	Low-vision	Some letters	Language and motor delays

4.1.2 Apparatus

We used 5 Android G1 phones with three games: VBReader, VBWriter and VBHangman (Figure 1). We did not include VBGhost because of the age range and literacy level of our participants: most participants were learning individual letters and had not progressed yet to spelling words. We included VBHangman for the participants with higher literacy skills, but the mechanics of VBGhost seemed too complex for our participants. We installed two versions of each game: one for the parent and one for the child, because we wanted to have one instrumented version that the children played exclusively ("child version") and one version that the parents could use to become familiar with the games ("parent version"). The parent and child versions of the games were identical, except that the child versions were instrumented, and the parent versions were labeled as such (*e.g.*, "Parent VBReader" vs. "VBReader"). Logged information from the child version was sent to the researchers' server when the phone was connected to the Internet and saved to a log file on the phone otherwise.

4.1.3 Procedure

Throughout the study, we conducted a preliminary survey, weekly semi-structured interviews, and a final exit interview and survey with each set of participants. The preliminary survey included questions about demographic information about the child along with information about the child's vision, siblings, and Braille knowledge. Each family was then sent a phone as described above. We instructed the families to take a few days to become familiar with the applications and the phones, using the parent version of the applications. After the orientation period, we conducted 30-minute training sessions over a video-conferencing system with each family to answer questions. The participants were then instructed to play the games for 30-minute sessions four times a week for four consecutive weeks. We encouraged families to maintain a weekly average of two hours of gameplay, but were flexible in how they did this due to differing attention spans and schedules. Because of the varying developmental stages and experience with Braille, we did not define how much we wanted the participants to play each game, and, instead, hoped each participant would play the games best suited to their ability and preference. At the end of the study, we conducted a final set of 30-minute semi-structured interviews with the parents and children.

4.1.4 Design and Analysis

We transcribed and coded the interviews and preliminary surveys. For the quantitative data, we explored two measures: accuracy and time to enter each letter. For both VBReader and VBWriter, accuracy for each letter was binary: either the user entered the letter correctly or not. To measure the length of time to enter each letter, we measured the period of time between the time the letter was presented to the user (either loaded onto the VBraille interface for VBReader or spoken aloud in VBWriter) until the time the user double-swiped to submit a character in VBWriter or selected an answer from the menu in VBReader. For analysis, we excluded extreme outliers.

Our analysis did not include entry times and accuracy measures from VBHangman. We could not compute accuracy rates because there was no way to determine what letter the user *intended* to enter in VBHangman. We had no reliable measure of entry time because the time spent in the character entry screen included the time spent *thinking* about what letter to enter.

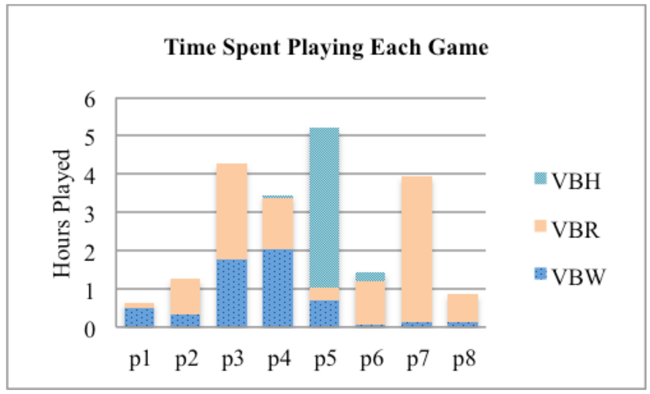

Figure 3. Time spent by participants playing VBHangman (VBH), VBReader (VBR), and VBWriter (VBW).

4.2 Results

4.2.1 Gameplay Patterns

The children collectively played the games for 21 hours (Figure 3), in which they read over 360 letters in VBReader and entered over 598 letters in VBWriter. The total time a child spent playing the games ranged from 37 minutes to 5 hours and 12 minutes (Figure 3).

Entry time and accuracy varied widely for the children (Figure 4). We could not find any visible trends in the data. We believe the variability is likely due to the differing ages, skill levels, abilities, and knowledge of Braille of the children, as well as differences in the amount of parental supervision children received while playing the games.

P4 (age 6) achieved the highest accuracy rates, entering characters correctly 96% of the time with VBReader and 90% with VBWriter. P4 did not play VBHangman. Interestingly, P4 also had the longest average entry rates on both VBReader and VBWriter, with an average of 63.3 seconds to identify a character on VBReader and 67.6 seconds to enter a character on VBWriter. P6 (age 7) achieve the lowest accuracy rates, with an average accuracy of 11% on VBReader and 8% on VBWriter. She took on average of 18.6 seconds to identify letters on VBReader and 12.6 seconds to enter letters on VBWriter. Her parent explained that she had difficulty understanding the screen reader since she was learning English as a second language.

P5 (age 8) was the only child who played VBHangman consistently. He was the oldest child in the study and had relatively advanced Braille skills.

4.2.2 Interviews and Observations

With the exception of P8 who had difficulty playing the games due to motor impairments, parents and children were enthusiastic about the games in the initial and exit interviews. In the preliminary surveys, we found a strong desire for and interest in accessible smartphone games. Five out of eight children either had their own smart device (either an iPod Touch or an iPad) or used their parent's smartphone to play games, listen to music, or listen to audiobooks. Three of those five parents mentioned (unprompted) that they had not found any accessible Braille applications. Four parents said that they had difficulty motivating their child to learn Braille concepts, signaling a need for fun Braille-based games.

From the exit interviews with the children, we found that most of the children were able to interact autonomously and enjoyed playing with the BraillePlay games. Seven children were able to

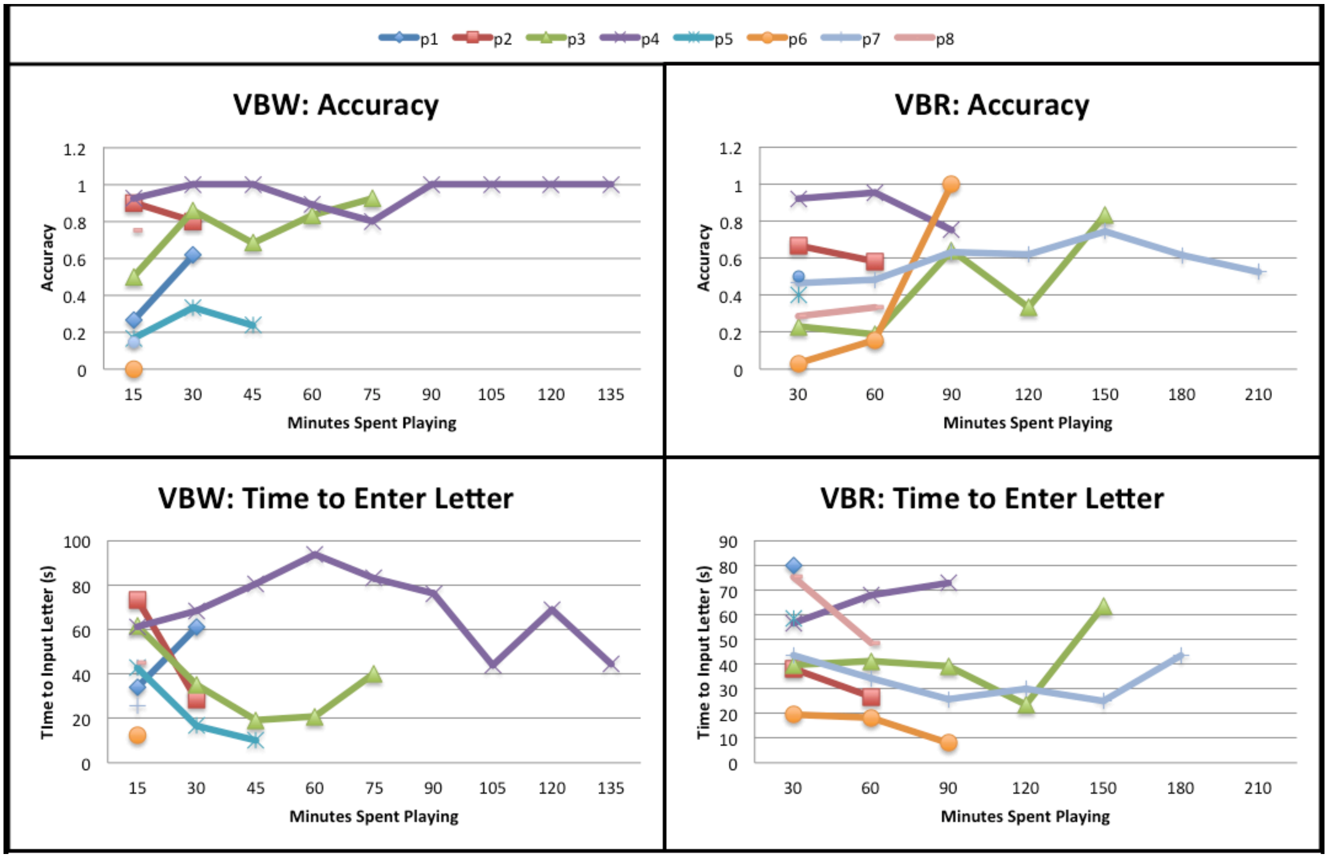

Figure 4. Gameplay patterns for all participants in the study. The top two plots show accuracy rates for participants over time for VBWriter (left) and VBReader (right). Bottom two plots show the average time to enter a letter for VBWriter (left) and VBReader (right). Accuracy rates and letter entry are computed for every 15 minutes of gameplay for VBWriter (VBW) and 30 minutes for VBReader (VBR). There is high variability and no visible trends.

play the games by themselves, while P8 needed assistance because of motor impairments. P1 – P7 reported that they had no problems holding the phone, using buttons or exploring the screen with one finger. However, three participants reported having some difficulty with the two-finger swipe, indicating that multi-touch gestures may not be suitable for children. Most importantly, all seven children (except for P8) reported liking the games.

Interestingly, we found slightly different results from the interviews with the parents: only six parents felt that their child was able to consistently play the games without help after the first few sessions of the study. P1's parent reported that her child had "problems getting the double tap to work" and the "reading with one finger on the screen was too confusing," although P1 reported that she was able to play the games autonomously.

We also found evidence that some children were able to learn Braille concepts with the Braille games. Three children thought that the games helped them learn Braille letters. Additionally, three parents reported that the games helped their child improve his or her ability to read and write Braille letters. P5's parent elaborated:

> *It helped him to remember that there are six dots in a cell as opposed to a whole shape and to remember which dots made up the letters. I think he loved having something on the phone that he could do in Braille.*

Three parents reported that they were not sure if the games helped their children in their current stage in development, but thought it would help their child at some point. The parent of P3 said,

> *I'm not sure if it helped her specifically… it was an exciting app for me as a parent…I think at some point in her development, it could help a lot.*

The parents of the two participants (P1 and P8) who did not think the BraillePlay games were or would be helpful stated that they had difficulty getting their children to play the games. The parent of P1 said, "No, she didn't play them enough." Figures 3 and 4 show that P1 spent little time playing the games.

4.3 Discussion

4.3.1 Research Questions

Using both the gameplay patterns and information from the interviews, we were able to answer our three research questions:

Are BraillePlay games *accessible* to blind children? For the most part, we found that the children were able to play the games autonomously. P8 had difficulty navigating the games due to a motor impairment. P1 had trouble understanding the vibration output of the phone and performing some of the more complex gestures such as the double tap or two-finger swipe. In the exit interviews, all the parents thought that their children were able to understand the concept of the vibrating dots representing the raised dots of a Braille cell. We found that only one child regularly played VBHangman; in our interviews with the parents, it appeared that this was because the children were not yet fluent enough in Braille to spell out words and were instead focused on learning the Braille character patterns.

Are BraillePlay games *engaging* for blind children? We found that most of the children enjoyed playing the BraillePlay games, but they did not play them for as long as we had hoped. The children each played the games for an average of 2.6 hours over the course of the study; this is significantly lower than the encouraged 8 hours. Interest in the games dwindled at the end of the study for many of the children, indicating that we did not design the games to have the optimal balance of challenge and success needed for game flow [33]. This is likely because two of the three games used in the study were the simple flashcard games. The only child that consistently played VBHangman was the oldest child in the study (P5) and also logged the most total hours playing the games (Figure 3). Using the VBraille interface to build more difficult word games or include contractions in the future might lead to more engaging games. Although we did not include VBGhost in the study, P5 expressed interest in playing more word games and might have enjoyed the more difficult game. Our results are similar to findings from prior work. A study with sighted children playing a literacy game over a period of two weeks found that children only played for 10 minutes at a time and interest dwindled after a few days of playing [12]. In future studies, we recommend a shorter playing period and a wider variety of games.

Are BraillePlay games *effective* teaching tools? Evidence from the final interviews with parents and children suggests that some of the children learned from the games, but these findings are only preliminary. In general, it is difficult to evaluate learning, and similar studies on educational games often have mixed results when trying to show evidence of learning [13, 17, 18, 23, 32].

The BraillePlay games seem best suited for slightly older children than most of our participants (7 - 8 years old). The three sets of parents who thought the games helped their child learn Braille concepts were the parents of P5, P6 and P7, the oldest children in the study. Interestingly, we found that the BraillePlay games helped some of the parents learn Braille. Of the six parents who played the games with their child, four said that they learned Braille characters from the games (the other two already knew all of the characters).

4.3.2 Design Implications
We distill implications for the design of educational games for blind children.

Design for collaborative play: We found that many of the participants engaged in collaborative play with their sighted siblings and parents during the study. Games should be designed for collaborative play to engage children and allow their parents and sighted peers to also learn Braille concepts and identify with blind children.

Design for blind, low-vision, and sighted children: Parents of children with low-vision in the study suggested using more exciting graphics. Games should be designed for children with all degrees of vision. This will both encourage sighted siblings and peers to play and make the games more appealing for children with some functional vision.

Design for developing motor skills: We found that many of the children had difficulty using multi-finger gestures, such as a two-finger swipe (used to submit letters), so applications for games should include single finger gestures.

4.3.3 Lessons Learned
In conducting a four-week longitudinal study in the wild with children over a large geographic area, we learned a number of lessons that will help others in the community conduct similar studies.

We found the amount of time children played the games varied wildly week to week and that 30-minute-long sessions for young children was too long. This was similar to what Chiong *et al.* [12] reported with their study of literacy games for sighted children. They found that children were only able to play mobile games for 10 minutes at a time. Instead, we recommend that researchers ask participants to do a larger number of short sessions throughout a week and have bi-weekly planned video conferencing sessions scheduled with the children to watch them interact with the games.

We also recommend that researchers studying educational games either make games complex enough to have novelty throughout the study or make different games available at different times throughout the study to aid in analysis and to mitigate some of the loss of interest in the games at the end of the study. In order to accommodate the varying ages and levels of ability of our participants, we allowed them to choose which games to play and when. This extra freedom let us know which games different children found most enjoyable, but it made data analysis difficult, as children could play one game exclusively at the beginning of the study and another at the end, making it harder to pick out trends over time. This may indicate that educational games should constantly introduce novelty if developers want them to be played for long periods of time.

5. FUTURE WORK AND CONCLUSION
Our results show that there is a compelling need and desire for educational games for blind children: both parents and children were excited about the BraillePlay games, and many participants mentioned that they were not aware of any accessible Braille-based games for the smartphone. Our longitudinal study indicates that you can create accessible ways to interact with Braille characters on a touchscreen, and that this interface can be used and understood by children. Although most of the children reported that they enjoyed playing the games, we found it was difficult to make games that continued to engage children over a four-week period. However, many additional word games can be developed with the VBraille interface, maintaining children's interest as they continue to improve their Braille skills. Our work demonstrates that there is great potential for fun and educational games for blind children on mainstream devices.

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