BrailleBlocks: Computational Braille Toys for Collaborative Learning

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ABSTRACT
Braille literacy has fallen in recent years, and many blind children now grow up without learning Braille. However, learning Braille can increase employment chances and improve literacy skills. We introduce BrailleBlocks, a system to help visually impaired children learn and practice Braille alongside a sighted parent. BrailleBlocks comprises a set of tangible blocks and pegs, each block representing a Braille cell, and an associated application with games. The system automatically tracks and recognizes the blocks so that parents can follow along even if they cannot read Braille. We conducted a user study to test BrailleBlocks with five families, with five parents and six visually impaired children. The contributions of this work are a novel approach to Braille education toys, observations of how visually impaired children and sighted parents used this system together, their insights on current issues with Braille educational tools, and actionable feedback for future Braille-based learning tools.

Author Keywords
Accessibility; blind; visually impaired; education; Braille; children; collaboration.

CSS CONCEPTS
Human-centered computing → Accessibility systems

INTRODUCTION
Braille literacy is declining among students in the United States. BrailleWorks reports that in 1960, over 50% of blind US students were Braille literate [5]. In 2017, only 7.8% of blind students surveyed by the American Printing House for the Blind identified as Braille readers [1]. Education experts have expressed alarm at the drop in literacy rates, calling it the "Braille literacy crisis" [19].

There is ample evidence that learning Braille is beneficial to blind and visually impaired children, even when other forms of accessible media are available. Learning Braille provides access to a vast collection of reading materials and resources. Because Braille is low-tech and read tactilely, it can be used even when computers are unavailable and when listening to synthesized speech is impractical, such as in a noisy classroom [7]. Braille literacy has also been found to increase chances of employment and to improve literacy skills such as reading comprehension and reading proficiency [25].

Figure 1. A participant family use the BrailleBlocks prototype. The children are writing animal names in Braille while their mother monitors and encourages them.

Despite these benefits, the Braille literacy rate has continued to fall. One catalyst for the decline in Braille literacy appears to be the rise of audiobooks and accessible computing technology such as text-to-speech [24, 29]. These resources provide access to information without the effort needed to learn Braille, but may lead to a lack of interest in developing Braille literacy skills. Another barrier to Braille education is the fact that learning to read Braille is difficult and time consuming. Braille is more difficult to learn than printed text, and visually impaired children often lag behind their sighted peers when learning to read [30]. Guerreiro et al. [9] outlined the following challenges in current Braille education: lack of interactivity in Braille learning materials, lack of available learning resources, lack of perceived purpose in learning Braille, and lack of motivation. With these challenges in mind, it is clear that Braille education tools must both properly teach Braille as well as address the difficulty and motivation challenges encountered while learning Braille.In this paper, we explore the creation of educational tools and toys to support visually impaired children in learning Braille. To explore the possibilities for more engaging and inclusive Braille tools, we introduce BrailleBlocks, a tangible block set and a collection of associated, cooperative games (Figure 1). Additionally, we present a graphical user interface that enables sighted parents, teachers, and other collaborators to

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play with, support, and learn Braille alongside a blind or visually impaired child. BrailleBlocks supports interactive games that can be controlled by physically assembling Braille letters and words, and provides audio and multimedia feedback about words as they are constructed.

We evaluated the BrailleBlocks prototype through individual study sessions with five families (with five sighted parents and six visually impaired children total). During the hourlong study sessions, we introduced the blocks to the child and the computer interface to the parent. We observed how parents and children collaborated to learn Braille, studied the strategies parents employed to teach Braille, and gathered feedback about their use of the prototype BrailleBlocks system. Through these studies, we aimed to address the following research questions:

1) Do interactive tangible blocks support collaborative Braille learning?
2) Which aspects of our prototype (tangible blocks, games, sound effects) are effective in engaging children and parents?

How can we improve and extend the BrailleBlocks system?The contributions of this work are: 1) a new approach to Braille education through a set of interactive, tangible, Braille-based games; 2) observations of how the system was used by pairs of visually impaired children and sighted parents; and 3) insights from interviews about experiences with current Braille education technologies and the future potential of tools like BrailleBlocks.

RELATED WORK

Braille Education Tools and Toys

Children learning Braille today can access a variety of low-tech toys and games. PlanToys produces Braille toys such as alphabet and number blocks [21]. For example, the *Braille Alphabet A-Z Set* includes thin rounded square blocks with indented alphabets along with the alphabet's Grade 1 Braille representation on the bottom of the block.

BrailleBricks, a proof-of-concept prototype, comprises a set of Lego-like blocks with a slightly enlarged Braille representation on their surface [4]. Each block represents a single letter. Kids can play with the blocks by sticking them onto an included Lego mat to create words and sentences. This prototype inspired a commercial product, also called Braille Bricks, that will be released in 2020 [15]. Tack-Tiles, another block-based educational toy, uses small Lego-sized blocks with an enlarged Braille representation embossed onto the surface [28]. Kwon and Kang [14] proposed a modular Braille system in which blocks contained holes that children could fill with pegs, thus creating letters by assembling Braille "dots" [14]. Although these blocks do not incorporate computing elements, they demonstrate the desirability of tangible Braille toys.

Perhaps due in part to the limited availability of commercial Braille toys, educators have also created Do-It-Yourself (DIY) tools and toys as alternatives to commercial products [10]. Hurst presents a collection of DIY tangible toys made by educators across the United States, including creative examples such as using baking tins to represent enlarged Braille cells and baking edible Braille cell pizzas [11]. These projects demonstrate that there are a variety of ways to incorporate Braille into children's play, but that the burden of providing these tools currently rests on educators.

Our project, BrailleBlocks, aims to introduce new types of Braille educational toys. In contrast to these low-tech solutions, BrailleBlocks introduces tangible computing techniques to enable new forms of interaction between visually impaired children and their collaborators.

While most existing Braille education toys use simple, low-tech materials, researchers have explored how to create electronic Braille learning tools. Electronic Braille Blocks allows children to learn Braille through games by assembling blocks tracked via NFC tags [12]. We extend this line of research by introducing new methods for creating blocks, new applications, and a visual interface that enables sighted parents to collaborate and learn alongside their child.

Interactive Tangible Blocks in Education

Outside of Braille education, tangible blocks have often been used in education, both for blind and sighted learners. Incorporating tangible activities into education can increase engagement for learners [22, 26].

Introductory computer science tools have often used the notion of assembling modular blocks to create programs [23]. While block-based programming tools are not specifically designed to support accessibility, making blocks tangible can lead to accessible learning experiences. StoryBlocks uses tangible blocks to enable children to create audio stories [13]. Microsoft's Code Jumper uses a set of connectible pods to enable children to construct programs that represent music and other audio [17]. Each of these systems combines tactile interaction with audio output to create an engaging and accessible learning experience. BrailleBlocks builds upon the success of these systems but focuses instead on Braille learning.

Braille Games and Apps

Researchers have explored how to support Braille learning through games and applications. BraillePlay [16] is a set of smartphone games that reinforce Braille concepts for visually impaired learners through flashcards and word games such as Hangman.

BraillePlay uses a mobile phone's vibration motor to represent Braille characters, vibrating if the user touches an area of the screen that represents a Braille dot. GBraille [2] is a mobile game that encourages players to practice Braille through Hangman and a keyboard-controlled Asteroids game. mBraille [18] is an application that supports children in writing the Braille alphabet in multiple languages. As in this prior work, BrailleBlocks incentivizes children to practice Braille via word games, but incorporates tangible blocks to support more embodied learning. BrailleBlocks also focuses on collaborative learning by providing a separate interface for a sighted teacher or companion.

Cross-Ability Collaboration

Assistive technologies are often presented as a means of promoting independence, but using some assistive technologies, like screen readers, can have an isolating effect [3]. It can be difficult for people to use screen-readers while listening to or talking with other people, such as classmates and teachers, which may cause screen reader users to withdraw from discussions during group activities [7]. Due to the overhead of using assistive technologies during groupwork, some screen reader users may find it easier to use accessible interfaces alone [6]. We designed BrailleBlocks to support collaborative learning between visually impaired children and their teachers, family members, or friends.

A further obstacle to accessible and collaborative Braille learning is that a child's companion may be unfamiliar with Braille, making it difficult for them to participate meaningfully in a Braille educational activity. To address this issue, and to provide the benefits of collaborative Braille-based interactions between children and parents, BrailleBlocks provides specific instructions and feedback for sighted collaborators.

DESIGN OF BRAILLEBLOCKS

We introduce BrailleBlocks, an educational gaming system that allows children to learn and practice Braille through collaborative games. BrailleBlocks comprises three main components: (1) a tangible block and peg set, (2) a computer interface for a sighted collaborator, and (3) an overhead webcam for tracking blocks and initiating feedback.

To keep the system affordable, BrailleBlocks are made with low cost materials (wood and cardboard) and the interface can be used on systems that people may already have (laptops, tablets, etc.). The BrailleBlocks interface translates Braille into English text so that parents who don't know Braille can still participate in the activities.

Although students may learn Braille at any age, we focused our efforts on developing experiences for children who are learning Braille at an early age, approximately 5-10. Our primary learning goals with this version of BrailleBlocks were to engage children in constructing letters and words, and to engage them in word games using Braille.

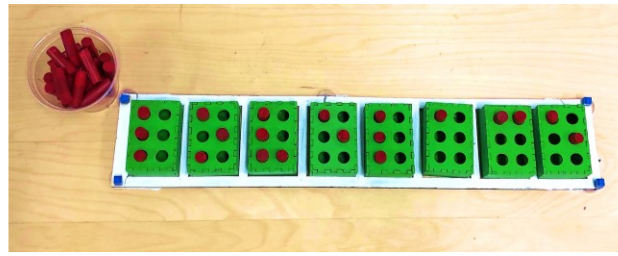

Figure 2. Tangible blocks from the BrailleBlocks prototype. Wooden blocks and pegs sit in a frame to keep them within the webcam's view. The blue Lego bricks at each corner are used to track the frame. In this image, the blocks spell "lovelace" (⠇ ⠕ ⠧ ⠑ ⠇ ⠁ ⠉ ⠑) in Braille.

Formative Design and Prototyping

We developed the BrailleBlocks system through iterative prototyping and testing with Braille educators. We first constructed a non-interactive, cardboard prototype of the blocks and play area frame. We demonstrated this prototype to a K-5 teacher and a Braille specialist who offered feedback about the size of the blocks, the choice of games, and the appropriate age levels for our prototype. Based on their feedback, we focused our initial development on supporting early-stage Braille learning activities such as tactile recognition and spelling.

Physical Setup

BrailleBlocks are a set of bright green wooden blocks, with six holes in each block, and a set of red wooden pegs representing the Braille dots (Figure 2). The dimensions of the block are 1.25 in. x 2 in. x 3 in. The pegs are 1.5 in. long. We chose red and green as high contrast colors so that children with limited visual acuity could see the blocks and pegs, and to support easy prototyping of the computer vision system.

Each block represents a single Braille cell. A child constructs a Braille letter by placing red pegs in the blocks corresponding to the raised dots of the Braille letter. For example, to create the letter "A", a user would place one peg in the top, left-most hole of the block.

To make it easier for children to form words from individual blocks, BrailleBlocks includes a tactile frame for holding the letters as they are assembled. The current prototype supports constructing words of up to eight letters long. The frame size was chosen based on the size of the blocks and the camera's field of view; longer words can be supported by changing the size of the blocks or the camera's position.

Companion Application

To support collaborative play between visually impaired children and their sighted parents, teachers, or other collaborators, BrailleBlocks includes a graphical companion application that shows a visual and text representation of the current activity. The application is presented on a laptop screen that is adjacent to the block assembly area. The companion application presents instructions and prompts for the parent, encouraging them to take part in the activity. As the child assembles blocks, the application recognizes the Braille characters that the child has written and shows the corresponding text on screen. We used HTML5, JavaScript, CSS, and Flask[1] to create the interactive web application for this system.

Games
The current version of BrailleBlocks includes an interactive tutorial and the following games: Animal Name Game, Hangman, and Word Scramble.

Tutorial
The tutorial demonstrates how letters are assembled and recognized by the system. When the parent types a letter on the keyboard, the corresponding Braille character is shown on screen. The parent asks their child to construct a letter and uses the application to check their work.

Animal Name Game
In the Animal Name Game, children attempt to guess an animal based on the sound that it makes (Figure 3). The game is intended to encourage children to use the blocks and to practice spelling in Braille.

Figure 3. Animal Name Game. Once the parent selects an animal, the system plays that animal's noise and shows the Braille representation of that animal's name.

The parent selects an animal and the system plays a sound made by that animal (e.g., a "quack" for a duck or a "baa" for the sheep.) The child is prompted to guess the appropriate animal and to write its name in Braille. The application shows the parent the Braille characters for the correct answer so that they can provide hints or support as appropriate. Once the child has finished writing the word, the parent can press the "Check Word" button to translate their child's guess from Braille to text, allowing them to see the answer as both text and Braille (Figure 4).

[1] https://github.com/pallets/flask

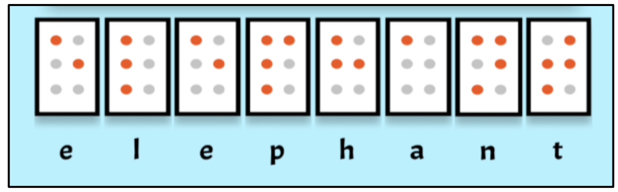

Figure 4. BrailleBlocks shows words as both Braille and text, allowing a sighted parent or teacher to participate in the activity even if they are unfamiliar with Braille.

Hangman
BrailleBlocks includes the traditional word-guessing game Hangman, as it is already known by many children and parents. Hangman can support practicing spelling skills and can promote critical thinking through guessing.

In Hangman, parents think of a word and type it into the system. The system then shows the word as both text and Braille (similar to Figure 4). To make a guess, the child assembles a word using blocks and presents it to the parent. As in the previous game, the parent can press a "Check Word" button to translate their child's guess from Braille to text. BrailleBlocks can provide audio feedback based on the child's guess, playing a "ding" sound for a correct guess and a "bzzt" sound for an incorrect guess. While this feedback could be automatically delivered, we currently rely on the parent to recognize the letter and input whether it is correct or incorrect in order to encourage them to take an active role in the game.

Word Scramble
The Word Scramble game emphasizes Braille reading skills. In this game, the parent is presented with a scrambled word and creates that word using blocks. The parent presents this word to the child, who feels the blocks and attempts to decipher a word. The child can rearrange the blocks to unscramble the word. As in the other games, the parent presses the "Check Word" to determine whether the child's solution is correct and provides them with appropriate feedback.

Block Detection and Translation
BrailleBlocks uses computer vision to track the blocks and identify the Braille letters that they represent. While we designed the games to include the parent as an active participant, automatically recognizing blocks enables parents to participate even if they cannot read Braille.

The computer vision components are written in Python and use the OpenCV library. When the parent presses the "Check Word" button, the system captures a photograph of the work area. The system locates the four corners of the frame, marked by blue Lego bricks, and crops the image. We apply a color mask to extract the positions of the red pegs and use the location of the pegs to convert the image to an equivalent text representation. This process is illustrated in Figure 5. Because the camera is placed directly above the workspace, no perspective transformations are needed, although this feature could be added in the future to support other workspace configurations.

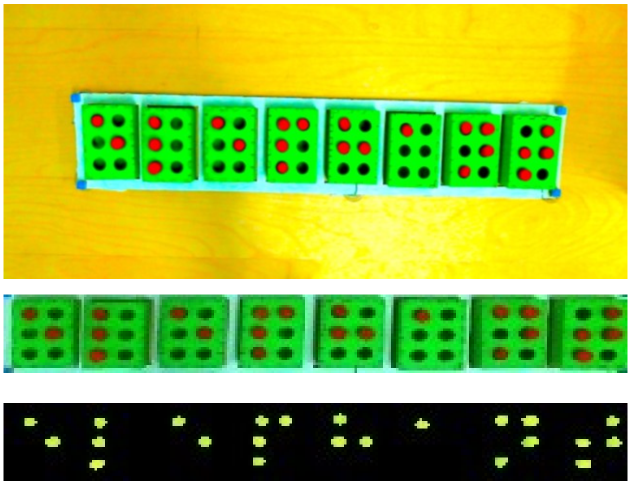

Figure 5. Image processing and Braille recognition. Top: Original image. Middle: Image has been cropped to include only the frame. Bottom: Color mask is used to extract the location of red peg pieces.

STUDY

We conducted a usability study to observe how sighted parents and blind children collaborated and learned with BrailleBlocks. The study consisted of individual sessions with each participant family and included exploratory game playing tasks and an interview. The sessions took place at various locations, including local libraries, the authors' research lab, and participants' homes. This study took place after two rounds of initial pilot testing with teachers of the visually impaired who provided feedback on the physical form, games, and age appropriateness of the system.

Participants

Our study included five participant families, with six child participants total. Four of the families included one child, while one included two children. Among the participants, all adults were sighted and all children were visually impaired. Table 1 describes our participants.

We recruited participants through our state's Department of Education and local education centers as well as through local schools for blind and visually impaired students.

Procedure

We conducted a semi-structured interview and gameplay activity with each family. Each prototype test and interview lasted around an hour, divided into 45 minutes for exploring the system and 15 minutes for the interview.

We first explained the overall structure of the study and the activities that the parent and child would be partaking in. After this, the parents and children completed consent and assent forms, respectively. Following the consent procedure, we provided a brief demonstration of how to use the blocks and pegs to build letters and words, including showing the locations of the webcam and work area. We also described the four applications that would be tested during the study: the tutorial, Animal Name Game, Hangman, and Word Scramble. In addition to the BrailleBlocks prototype, we provided a paper-based Braille reference sheet with Braille characters and their corresponding text representation.

We encouraged parents to lead the session and to use the time to reflect on how they might use the BrailleBlocks system at home. As we were interested in whether families could learn to use BrailleBlocks in its current form, we did not provide any tutorials for the games themselves other than the on-screen instructions in each game. Families were given 45 minutes to test the various games.

The last 15 minutes of the study were reserved for a semi-structured interview. We began by asking participants about their previous knowledge of Braille and the ways that they have currently or previously studied Braille. We then requested feedback about the BrailleBlocks prototype, including both the system itself and the particular games they tested. Next, we asked participants to discuss their experience of collaboration while using BrailleBlocks. Finally, we asked participants to brainstorm future uses of the BrailleBlocks system. Any remaining time in the study was left for participants to ask the research team questions or share any additional thoughts about the experience. We recorded audio and video during each session and took field notes. Each session was conducted with the first author present and a student researcher as a note taker.

Analysis

The authors transcribed the video recordings from each session. After initial discussions within the research team, the first author identified themes using open coding techniques [27]. Our themes included 1) verbal instructions, 2) physical guidance, 3) how the games were played, 4) subjective comments about learning, engagement, and fun, and 5) creative play and storytelling.

FINDINGS

Previous Experience with Braille Educational Tools

We asked participants what tools they have previously used to learn Braille at home. Participants mentioned using the Perkins Brailler [20], Swing Cell [8], and physical Braille books. In addition to these common educational tools, some families tried creating their own instructional materials. PP2 described searching internet forums for ideas, and developed homemade Braille flash cards. PP3 made cards and included both Braille and print because their child (CP3) can "still read print if its close to her face." Family 4 attempted to create their own Braille blocks by using egg cartons to represent Braille cells and cotton balls to represent the Braille dots.

We also asked families to discuss their positive and negative experiences using these Braille learning tools.

ID	Gender	Age	Vision	Knowledge of Braille
PP1	F	43	Normal	Some familiarity
CP1	M	10	No vision	Grade 1
PP2	F	42	Normal	Grade 1, learning Grade 2
CP2A	F	6	Black spots in vision, declining vision	Grade 1, learning Grade 2
CP2B	M	8	Black spots in vision, declining vision	Grade 3-4
PP3	F	32	Normal with correction	Familiar with all grades
CP3	F	6	20/300 with correction	Grade 2
PP4	F	29	Normal	Grade 1
CP4	F	5	No functional vision	Grade 1
PP5	F	25	Normal	Grade 1, learning Grade 2
CP5	F	7	No functional vision	Grade 1

Table 1. Study participants, gender, age, their vision level, and their self-reported knowledge of Braille at the time of the study. Each row represents a participant family featuring a parent participant (PP) and child participant (CP).

During the interview, Family 1 and Family 4 commented that current Braille education tools were expensive, and both mentioned that they borrowed Braille tools from the child's school when possible to save money. Family 4 expressed that there were not enough tools geared towards younger visually impaired children, particularly younger children aged 3-5.

Participants also discussed their challenges related to Braille reading and writing. Learning to write Braille presents unique challenges, such as the need to write characters backwards when using a slate and stylus. CP2B commented, "the only thing that's hard with slate and stylus is that you have to draw it backwards to get it forwards." PP5 pointed out that sighted children often have access to educational apps on their phones and tablets, but Braille readers may not, and noted that Braille learners would benefit from similar apps.

We asked participants about the qualities of a good Braille learning tool for their families. PP1 requested tools that are "easy for both a child and adult to use intuitively. Something that is a little bit flexible." PP1 also noted the importance of simplicity in the design of educational tools. PP2 commented, "for kids, definitely something that's fun. This is fun, and they will learn it better. Something that's just boring and monotonous they don't like it as much." PP3 added that good learning tools are often ones that have been tested with "actual kids who read Braille and teachers who are going to tell you how it works in practice."

Learning to Use BrailleBlocks

Before the study began, many of the child participants, and their siblings if present, explored the physical work area without prompting. Upon entering the study room, CP1 and his younger brother immediately began to feel the blocks, webcam, and frame. Shortly after sitting down, CP3 spelled out her name using the blocks and pegs, speaking each letter out loud as she pointed to the blocks. She remarked, "we do this every day at school because my vision teacher makes me write my name on every paper." CP4's sister began to place pegs in the blocks and arranged the blocks in a row.

To help familiarize their child with the blocks, parents would refer to Braille tools they had already used. A few parents compared each individual block to the Swing Cell, a physical block toy [8]. At the start of the session, parents would place their hands over their child's hands and feel the various components of the system. For example, PP5 held CP5's hand and placed it over each block and counted them out loud, so that CP5 would know how many blocks were in the frame. The participants would also feel the holes in each block and count them in order from one to six. A few parents encouraged their children to feel the overhead webcam mount so that the child would not accidentally bump into the camera during the study. All children actively touched the blocks and frame and asked questions about them, such as why the frame had Lego bricks on its corners.

Interactions Between Parents and Children

One goal in developing BrailleBlocks was to create a tool that would involve parents in their child's Braille education. During the study, we observed that parents typically took the lead in the activity, providing their child with instructions and prompts, and giving them feedback about their Braille characters. The following sections describe parents' instructional strategies during the study.

Facilitating Games and Providing Hints

While each game included its own set of instructions, parents often adapted the gameplay to best suit their child's interests and familiarity with Braille.

For example, the parent of our youngest participant, PP4, skipped the Hangman and Word Scramble games, explaining "it's probably out of her skill set right now. I'm going to go back to the intro. We are working on spelling names. She's going to Kindergarten so that's a big goal." As PP4 and CP4 placed pegs in the holes together, PP4 would say the correct dot numbers for each letter, and CP4 would often repeat them after her.

Both Family 3 and Family 5 played Hangman by guessing entire words, rather than guessing letters. During this game, PP3 gave hints such as "the name of a dog that we know." CP3 proceeded to narrow down the options by asking clarifying questions like "Is it close to a Dachshund?" Once CP3 figured out the word, she began to write the dog's name using the blocks and pegs rather than guessing verbally. Similarly, PP5 would give prompts such as "this word is your favorite food!"

For the Word Scramble, all parents assembled the scrambled Braille letters themselves, and handed the blocks to their child to guess. PP2 and PP5 told their children ahead of time what the letters were, whereas PP3 had CP3 feel the blocks and identify the letters in front of her. Parents spontaneously provided clues to help their children guess the word. For example, PP5 would provide hints like "where are you __, finish the sentence" for the word "at", or "you drink hot ___" for the word "tea".

During the Animal Name Game, parents sometimes augmented the animal sounds played by the system with their own sounds and occasional clues. Most parents played the audio sound first and then let their child guess the name, although PP5 made all the animal noises herself. When the children were unsure how to spell the name of an animal, parents would sound out the word with them.

Hand-over-Hand Guidance

Another instructional strategy that emerged was hand-over-hand guidance. Parents would place their hand over their child's hand as a strategy to help the child feel letters, orienting them to the holes on the blocks and spaces between the blocks.

For example, PP1 would guide CP1 by placing her hand over his and guiding his hand to the relevant block. During Word Scramble, PP1 held CP1's hand and moved them over each letter block. Over the course of the study, CP1 learned to ask for this kind of assistance when needed.

The level of physical guidance varied across families. CP4 was in the beginning stages of learning Braille, so PP4 placed her hand over CP4's hand for all the activities (Figure 6). PP4 would repeatedly remind CP4 to use two hands to feel the blocks and holes. As CP4 was learning

Figure 6. Parent (PP4) places both of her hands over her child's (CP4) hands to guide her to the blocks and to help her place pegs in the holes.

how to construct Braille letters, PP4 would repeat the numbers of the Braille dots as she led CP4's hand over each of the holes. After completing a letter, they would repeat the dot numbers for that letter, touching each one together.

CP5 initially had some trouble orienting herself in relation to the "top" of the blocks. As a result, CP5 would sometimes correctly say the location that a peg belonged in, but would place the peg in another hole. To help her child to orient herself, PP5 would remind her that "each one of the [blocks] has six holes in them like a regular Braille cell," and would lead her child's hand to touch each hole, saying the number of the hole while she did so.

In some cases, parents referred their children to the provided Braille reference document when they became stuck. While playing Hangman, CP3 was trying to build "Wilbur", her dog's name, but forgot how to construct the letter "U" in Braille. As CP3 is able to read large print, her mother (PP3) reminded her to use her Braille reading skills rather than reading the sheet, stating, "if you need to feel a 'U' that's fine, but don't look – no peeking! Just feel." Ultimately, CP3 decided that she did not want to use the "cheat sheet" because she wanted to "figure it out on [her] own," and instead asked her mother questions about how to write the correct letter until she figured it out.

Teaching Words

Even when children knew how to write the Braille letters, they would sometimes struggle to spell out the required word. Parents would often help their children spell the word by providing clues or encouraging them to sound out the word. For example, when CP1 did not recognize a word, his mother (PP1) would break down the word by phonetically sounding out each letter. They would then repeatedly read out the letters together, going faster and faster until CP1 was able to say the word fluidly.

During Word Scramble, when CP2A and CP2B finished building a word, PP2 would ask, "what does this spell?" The children made the letter sounds, receiving subtle feedback from their mother until they finally converged on the correct word. In another instance, CP3 easily unscrambled the letters during Word Scramble but experienced difficulty saying the complete word. PP3 repeatedly encouraged her to "sound that out, smooth it out" until she was able to correctly say the word.

Reacting to Audio

The sound effects produced by the BrailleBlocks software were intriguing and sometimes provided additional entertainment. During the Animal Name Game, some children would jump out of their chairs and yell out the animal's name after hearing each sound. After correctly guessing the entire list of animals, CP2B wanted to continue spelling other words, saying "I'm going to spell 'goat' anyway. Should we just spell 'goat' anyway?" As in the StoryBlocks system [13], participants sometimes augmented the system's sounds with their own sound effects. PP5 made each of the animal noises herself, prompting CP5 to giggle each time before saying the animal's name.

During Hangman, some children became excited at the correct buzzer sound and laughed at the incorrect buzzer sound. CP1 and CP5 would break into wide smiles every time they guessed a correct letter. Upon hearing the incorrect buzzer, CP2B exclaimed "wow that was funny!" and CP2A replied "it keeps farting!" When CP2B said "So what's next. I wanna do it again so it can fart again," PP2 told the researcher "the obvious feedback is don't make it sound like a fart." The children would purposefully guess silly things like "three!" to make the buzzer play again.

Creative Uses of BrailleBlocks

While all child participants understood that the blocks were intended to represent words, they sometimes invented creative uses for the blocks. Most of the children, and siblings if present, fidgeted with the blocks while waiting for their parent to sign consent forms and during the interview portion of the study. They stacked the blocks into towers and filling up the holes with pegs. Some children were possessive about the blocks, causing parents to remind their child to share the blocks with their siblings.

Towards the end of the study session, CP3 began to use the blocks and pegs as construction toys, creating "sandwiches" with "bread" blocks and "gummy" pegs in between (Figure 6). She stacked all the blocks together to create "12 rooms in this house because they are two houses put together." CP3 stated that, in her sculpture, the pegs represented people and dogs, and that the people took the "train" (the frame) to "work" (the webcam) every day.

Participant Feedback

After the participants played with BrailleBlocks, we asked them to share their thoughts and to provide feedback about the system, the games, audio feedback, and the design of the tangible components.

Overall, feedback about BrailleBlocks was positive. Participants enjoyed the games, particularly the ones with

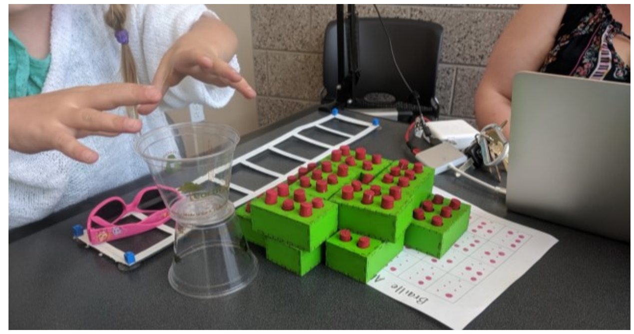

Figure 7. A "house" that CP3 built using the blocks. The pegs represent people living in the house and the cardboard frame is a train that the people take to work.

sound effects, and the parents appreciated that the tool could be used for developing skills beyond just Braille.

We asked both parents and children, "on a scale of 1 to 5 (1 being not at all engaged and 5 being extremely engaged), how engaged were you in the activities?" When possible, we asked the children to answer this question on their own, but parents sometimes interpreted their child's feedback and provided an estimated rating by proxy. Table 3 shows their responses. PP2 said "I was fairly engaged and helping them. We would definitely use this at home." PP3 noted "that was a very long time for [CP3] to sit down and concentrate on learning Braille."

Suggested Improvements to the Games

PP2, along with other parents, enjoyed the system because their children had fun playing the games. CP2A said her favorite part was "spelling animal things" while CP2B said she enjoyed Hangman the most; when asked why, she proceeded to imitate the Hangman incorrect buzzer sound.

PP2 appreciated that the system provided instructions but felt that some of the instructions could be a little easier. PP3 appreciated "the literacy part of it. I liked that you could adapt it to Grade 2 Braille." When asked what games best suited her child, PP3 said, "I like the animal one and the [tutorial] one. She can't really spell words on her own yet but I think those two are good for younger kids."

Suggested Improvements to Audio Feedback

PP4 suggested adding more auditory feedback to the blocks and the system, like "having it say the letter out loud when I type it." PP2 suggested changing some of the audio feedback like "the giggles and the farting noise. I mean they enjoy it and obviously, they should control their laughter but children obviously can't."

Suggested Improvements to the Physical Blocks

Overall, participants seemed satisfied with the size of the blocks. PP4 noted, "The pegs are great for pre-Braille skills, just being able to use two hands and everything."

However, the size, shape, and coloring of the blocks sometimes created difficulties for participants. When asked what he did not like about the blocks, CP2B stated, "It's hard to see the holes. I would just change the colors. The blocks could be white and the pegs could be blue." While changing the contrast of the blocks may help some children, PP2 noted that "every kid unfortunately sees different colors."

As noted previously, CP5 and other children sometimes had difficulty identifying the correct orientation of the blocks. When constructing a letter, CP5 would sometimes place some pegs in one block and some pegs in another block (an *alignment error)*. In other cases, she would correctly state which hole a peg belonged in, but would then place the peg in a different hole (a *placement error).* During the interview, her mother (PP5) noted that the most difficult task for her daughter was "figuring out the exact hole for the Braille cell." Several parents noted the potential difficulty of orienting a block and suggested adding tactile markers to indicate the block's orientation.

Participants were also occasionally confused by the spacing between blocks. PP1 said that CP1 had a "hard time figuring out each individual cell at first". PP4 noted that, "I think the space in between threw her off. She's not as familiar with this so I think that it's harder to differentiate between the holes and the spaces in between." PP4 suggested that permanently affixing the blocks to the frame, rather than allowing them to move freely, might help some children understand the spacing.

Target Audience

We asked all parent participants what age groups they thought BrailleBlocks would be useful for. Most parents agreed that BrailleBlocks would be most useful for early Braille learners: "early readers, first grade or under" (PP1). PP3 and PP5 suggested that BrailleBlocks would be useful for children aged five and older, while PP2 suggested that BrailleBlocks would be suitable for children up to age 10. PP4 suggested that the basic spelling activities contained in the tutorial would be best for children aged three to six, while the more advanced games could be useful for children between kindergarten and first grade (approximately five to seven).

Ideas for Future Versions

We asked participants how this technology might be useful in other areas. Parents agreed that the system would work well for teaching spelling and vocabulary. PP1 noted, "Over the summer, we have like 100 words we are learning, so it would be cool to incorporate this." PP2 said, "This would be helpful if [CP2B] is spelling words and [CP2A] is Brailling them. … It's hard to practice at home because we don't have that much to practice with, so this would be incredible."

When asked about other potential applications, PP1 and PP3 noted that the system would also work well with fill-in-the-blank type games. PP5 thought it would be fun to adapt the system to play tic-tac-toe or a spelling bee game. CP5 suggested a game in which the child is presented with an assembled letter and has to identify it by touch.

When asked about other useful features, several parents suggested that future versions of BrailleBlocks could include better reporting for parents. PP5 suggested that the system should track how often the child is correct or incorrect. PP1 noted, "It's helpful to know if we try [spelling] dog 5 times, he got it right 4 times." PP4 suggested that the system could document progress for parents to review later, stating, "If she's identifying letters more correctly or more accurately, even if it was tracking how she's using her hands together ... that would be huge."

DISCUSSION

In our initial evaluation of BrailleBlocks, we learned that a tangible, game-based approach to learning Braille can be engaging for both visually impaired children and sighted parents. Parents could envision making BrailleBlocks part of their at-home learning practices. Children (including sighted siblings) were drawn to the tangible blocks, using them for creative play and building. Building on our iterative design process and the user evaluation, here we discuss the design decisions we made while developing BrailleBlocks, and how these decisions impacted the system's use.

Physical Form

We chose to make enlarged Braille blocks, as opposed to standard sized blocks, both for ease of technical implementation and to support early Braille learners, who often work with enlarged representations. When a child became confused, their parents often encouraged them to slow down and feel the blocks. Overall, parents were positive about the use of enlarged blocks, and likened the BrailleBlocks to other Braille education tools such as the Swing Cell, a commonly used Braille learning tool [8].

While the size of the blocks and pegs seemed appropriate for most participants, our child participants were sometimes

Participant	Age	Engagement (scale 1-5)
PP1	43	3
CP1	10	2*
PP2	42	5
CP2A	6	5
CP2B	8	between 4 and 5
PP3	32	5
CP3	6	4*
PP4	29	5
CP4	5	2*
PP5	25	5
CP5	7	5

Table 2. Participants rated their own engagement on a 5-point Likert Scale (5 is better). Responses marked with an asterisk (*) were made by the parent on behalf of their child.

confused about the orientation of the blocks and about boundaries between the blocks. These issues could likely be addressed by adding additional tactile feedback to the blocks to indicate their orientation and boundaries.

In our initial design work, we experimented with several ways to assemble letters into words, including having freeform blocks on a surface or having a permanently attached set of blocks. Ultimately, we chose a solution that balanced flexibility and guidance, providing a frame that blocks could be placed into. While this approach made the implementation of the computer vision system easier, some children were confused by the relationship between the blocks and the frame, and sometimes misjudged the spacing between blocks. In the future we may go back to explore these initial ideas, although these issues might also be solved by keeping the frame as-is while improving the tactile features of the blocks themselves.

Learning through Gaming

In designing the initial set of games and applications, we drew from prior work in creating Braille-based educational games, and also considered how each game could support collaboration between children and their parents. Unsurprisingly, some children found some of the games too difficult, while others found some of the games too simple. We were pleasantly surprised to see that families were often able to adapt the activities to an appropriate difficulty level.

While our study sessions were too brief to assess the effectiveness of BrailleBlocks as a learning tool, participants seemed to genuinely enjoy playing the games, and parents noted that their children spent a significant amount of time using and thinking about Braille during the study activity. We are optimistic that BrailleBlocks can serve as a complement to other Braille learning tools and activities. After testing BrailleBlocks, participants also suggested that it might be useful as a way of integrating Braille into other learning activities such as spelling and critical thinking.

Engagement and Creative Play

Both visually impaired children and their sighted siblings found BrailleBlocks to be interesting, often reaching out and starting to play with the blocks before the study began. Some participants used the blocks for imaginative storytelling. Even without the computational aspect of the system, BrailleBlocks presents opportunity for tactile play. Given the physical similarity of BrailleBlocks and other educational toys, it is not surprising that children would be eager to play with them. By combining an approachable form factor with engaging interactive activities, we hope that BrailleBlocks can become a useful and engaging tool for young Braille learners and their families.

When testing the prototype games, it quickly became clear that augmenting tangible interaction with audio facilitated greater engagement. While the brailleblocks prototype offered limited audio feedback, families engaged with the audio in several ways, laughing at humorous sound effects and contributing their own sounds to the games. As shown by prior systems such as code jumper [17] and storyblocks [13] and duplicated here, the combination of audio and tactile interactions was helpful in supporting engagement and creative play.

FUTURE WORK

Our user study identified areas where we can improve BrailleBlocks, such as the tactile design of the blocks and additional audio feedback, but also revealed opportunities to extend the existing system to explore new areas. In particular, we are interested in extending BrailleBlocks to support interactions with larger groups, including other family members, and expanding BrailleBlocks to include more diverse and creative educational activities.

In addition to extending the system’s capabilities, we are interested in using BrailleBlocks as a platform to explore other issues in accessible education such as collaborative learning. While we designed BrailleBlocks to support collaboration between family members, we have not yet explored how aspects of the system can facilitate collaboration and interdependence between visually impaired children and their friends and classmates.

Finally, our initial version of BrailleBlocks has focused on a particular group size and learning activity: a visually impaired child practicing Braille with a sighted parent. In the future we will explore how our system’s core features can be adapted to different group configurations and learning styles, such as supporting play between multiple visually impaired children, or supporting children in independently learning and practicing concepts.

CONCLUSION

Sighted children have an abundance of toys and activities to help them learn to read, but visually impaired children have far more limited options. While Braille can be a valuable tool for blind and visually impaired children, its adoption may be hindered by the quantity and quality of educational resources. We developed BrailleBlocks to explore the possibilities of creating more engaging Braille-based toys and activities. Our BrailleBlocks prototype and its evaluation show that combining tangible blocks and interactive audio games can bring children and parents together to practice and play with Braille.

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