BrailleBuddy: A Tangible User Interface to Support Children with Visual Impairment in Learning Braille

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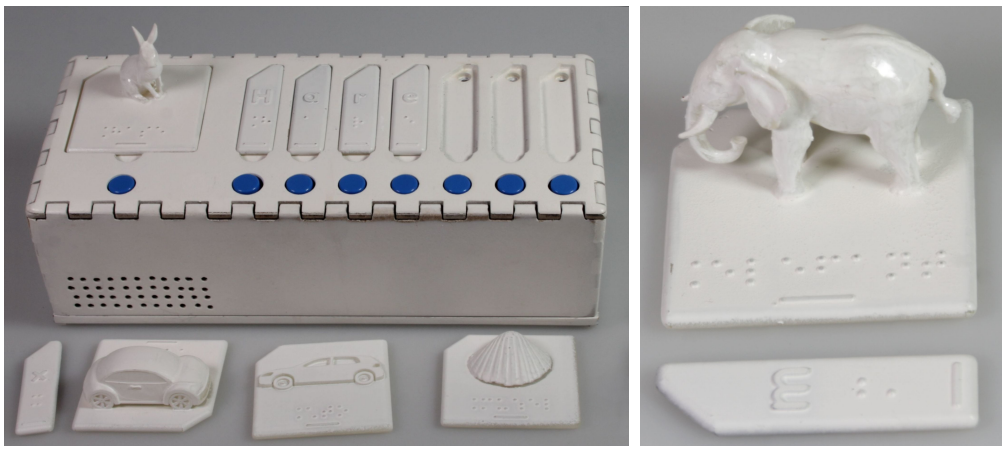

Figure 1: This figure shows two images. On the left, we see *BrailleBuddy*, a white wooden box with one large recessed area on its left and seven smaller recesses on its right upper surface. The user can place platelets, which we refer to as *cards*, into these recesses to trigger an action. The large recess, here occupied by a *word card*, i.e., a platelet with a 3D figurine of a hare, indicates that the user should spell the word "hare". To this end, the user places *letter cards*, i.e., platelets with single letters with Braille, into the other seven recesses. The image shows the correct solution—four *letter cards* occupy the first four recesses. The right image shows enlarged versions of the *letter card* for the letter "m" and another *word card*, depicting a 3D figurine of an elephant and the word "elephant" written in Braille.

ABSTRACT

Learning to read Braille is crucial to academic success for people with blindness or severe visual impairment. In our work, we investigate how we can support early learning of Braille with tangible computing. In a human-centered inclusive design process with interviews, six design iterations with prototypes, and feedback from experts, students, and teachers, we created *BrailleBuddy*. *BrailleBuddy* is a tangible user interface supporting children with visual impairments in learning Braille. We evaluated *BrailleBuddy* in a user study with children with blindness. Our results show that *BrailleBuddy* provides intrinsic motivation for learning Braille and can be used by children without supervision. *BrailleBuddy* complements the educational program as it allows children to play with and explore Braille characters at their own pace, thus lowering the challenge of learning to read Braille. In addition, an open-source toolkit is provided to enable educators and researchers to support individual requirements.

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CCS CONCEPTS

• **Human-centered computing → Haptic devices**; **Accessibility technologies**.

KEYWORDS

Braille, Learning, Children, Blind, Visual Impairment, Low Vision, Tangible User Interface

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1 INTRODUCTION

Written information is ubiquitous and access to it is taken for granted by many. While modern technology allows us to retrieve and create text using different modalities, such as speech input and audio feedback, a visual presentation of text remains the predominant option. This poses a challenge to people with moderate or severe visual impairment or who are blind, affecting an estimated 276 million persons worldwide [1].

One tried-and-tested solution for this problem is Braille, a tactile font that provides direct access to text without the assistance of other persons or mediating technology. Braille serves as an indispensable tool throughout all aspects of the life of a visually impaired person. It is the only non-digital system for reading and writing for personal use [41] and is also used for accessing digital data [9]. Braille is a crucial factor for academic success [35, 38] and is best taught at an early age [16]. There are no conclusive statistics on what proportion of children with visual impairment or blindness learn Braille [37], with some publications suggesting 10% [16, 35, 37]. For a fact, it is taught in many special education schools throughout the world.

Sighted children see printed language in many places throughout the day, such as on clothing, toys, street signs, or cereal boxes. They thus are provided many situations outside school where they can get accustomed to letters and practice reading them [24]. In contrast, blind children do not have a similarly rich environment for coincidental and extracurricular encounters with Braille letters, making learning to read and write Braille more challenging [24]. There exist methods of introducing such encounters, e.g., labeling everyday objects. Our work aims to provide additional opportunities to experience Braille outside a structured pedagogical context while supporting the learning of spelling and writing Braille.

Traditionally, school and special education teachers use non-digital materials to support the learning of Braille, such as tactile books [40], toys labeled with Braille [13], or self-made solutions [27]. Teachers or parents also increase their children's encounters with Braille by labeling everyday objects with Braille [24]. More recently, various digital learning aids in the form of tangible learning interfaces have been developed. They are used to learn abstract concepts and improve the tactile sense [2, 26, 33], learn Braille numbers [31], or Braille characters [3, 10, 11, 19]. In these works, the authors provide objects matching abstract concepts, e.g., geometric shapes or blocks labeled with enlarged Braille characters. The children then place these objects on a dedicated surface to receive feedback. The main advantages of these tangible interfaces are the possibility of manipulating real objects as an input for a digital device [17] and the natural kind of interaction they afford [4]. Such a digital device can provide versatile and individual feedback to the user. On the other hand, many digital learning aids are built to be operated under the supervision of a sighted teacher or parent. This restricts the child's interactions with the tangible information to times when an adult is available to provide help.

The goal of our work was to develop a digital tangible interactive device that a child can operate without assistance. Alleviating the need for supervision, the device could be used during breaks in school or at home, providing additional opportunities to experience Braille and individual audio feedback to support the users learning. We collaborated with special education teachers with and without visual impairment, a 9th grade student with visual impairment, and expert researchers specializing on working with children with visual impairment to investigate the design requirements for such a device. We find that, ideally, it should be entertaining to encourage its frequent use as well as be easy to set up and operate. Further, it should be robust against the unintentional moving of pieces, be fully operational using the tactile and auditory senses alone, and offer multiple difficulties or game modes to keep children engaged. In six iterations, we created and refined different prototypes, leading to *BrailleBuddy*, a self-contained tangible device in the form of a box with several recessed areas on the top surface into which the child can place various platelets to receive auditory feedback. Throughout the paper, we will refer to platelets as *cards*. The platelets contain either single letters in elevated Braille and elevated visual fonts ("*letter card*") or entire words written in elevated Braille combined with a 2D relief image or a 3D figurine ("*word card*"). Multiple game modes with several levels of difficulty make the use of the box engaging for children at all stages of learning.

In collaboration with a special education school, we evaluated *BrailleBuddy* with eleven first to third grade students with visual impairment, who are currently learning Braille, and their teacher. In this study, we collected qualitative feedback on three different game modes, each with a different difficulty level. Even without training, seven children were able to complete their first game on *BrailleBuddy* without any support regarding the interaction, showcasing that the device is generally usable in an unsupervised mode. Further, nine children enjoyed playing with the box, highlighting its intrinsically motivating nature to interact with Braille. Feedback from the special education teacher was positive, and the special education school voiced a strong interest in obtaining a final prototype of *BrailleBuddy*. The study also provided insights with regard to future adjustments to *BrailleBuddy*. Overall, our results show that *BrailleBuddy* has the potential to be successfully integrated into the learning of Braille, specifically by offering children an opportunity to play with and explore Braille in an extracurricular fashion.

Our contribution presented in this work is threefold: (1) an initial design of *BrailleBuddy* based on literature and six iterations of refinement with stakeholders, (2) an open-source repository for recreating or evolving *BrailleBuddy* on Github[1] [21] and mirrored on Zenodo[2] [22], and (3) a user study with 11 children currently learning Braille showing that children enjoy playing with *BrailleBuddy* and can do so in a self-directed manner.

2 RELATED WORK

Relevant related work for our paper comes from the area of Braille, Braille Learning, and tangible user interfaces for people with visual

[1]Github: https://github.com/FlorianLa/BrailleBuddy [21].
[2]Zenodo: https://doi.org/10.5281/zenodo.7606193 [22].

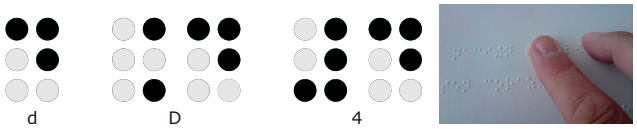

Figure 2: The left image shows a lowercase d on the left, consisting of one character. An uppercase D is depicted in the middle, followed by the number 4. They consist of the same character as the lowercase d, preceded by the capital and number characters, respectively. The right image shows a person reading a Braille book [5]. As in most books and documents, the book is printed using standard-size Braille characters.

impairments. Specifically, the overlap area—tangible interfaces for learning Braille—is relevant to our work. Following an introduction to Braille, we discuss these research fields below.

2.1 Braille

Braille is a tactile writing system invented in 1824 by Luis Braille. In Braille, each character consists of six dots, arranged in a rectangle layout consisting of three rows and two columns. Those dots are elevated from their surroundings and can be identified by moving the fingertips along the characters. Some letters consist of two characters, where the leading character indicates the interpretation of the second one, e.g., a number or an upper case letter, see Figure 2.

The encoding of the basic characters of the Alphabet is similar across languages, but special characters or abbreviations differ between countries, and modifications, e.g., systems using eight dots, exist [24]. In Braille, a word is not perceived as a series of single letters but rather as a tactile "Gestalt" [39]. Hence, when learning to read, one has to learn to perceive larger chunks of information, e.g., words, as well as how to "disassemble" these chunks into letters in order to spell. Further, a child learning Braille needs not only to practice reading, spelling, and writing but also to train their haptic perception and familiarize themselves with the understanding of written language [24]. Therefore, tactile materials are frequently used. These materials range from books with tactile elements [40] over store-bought solutions for enlarged Braille cells [6] or swing cells [7] to similar home-made devices [14, 27].

2.2 TUIs for Learning Braille

Tangible User Interfaces (TUIs) are one way to connect such tactile elements, the manipulation of physical objects, and the richness of real-world affordances with the possibilities of technology [17, 18]. TUIs provide a natural form of interaction [4] and can simplify abstract concepts, thus reducing the cognitive load [25, 42]. Therefore, they have a great potential to enhance a learning experience [4, 28]. There are various previous research reports on using TUIs to support children with visual impairments in learning. Here, objects representing abstract concepts like geometric forms are placed on a dedicated surface [2, 20, 26]. Adding Braille characters to such objects allows for supporting the learning of Braille. Najjar et al. provide mathematical symbols and numbers as enlarged Braille characters on blocks that can be placed on a table [31]. Then, Audio feedback guides users through solving math questions. Pires et al. built a system combining color- and shape-coded elements with Braille letters [32, 33]. This allows users without visual impairment to use the system as well. Also, users with visual impairment who have residual vision can benefit from the visual information, as the use of the visual sense, wherever possible, is preferred [23].

Often, blocks with front or upwards facing enlarged Braille characters are used to place characters next to each other [3, 10, 19], or to play collaboratively with sighted teachers or parents [11]. Information about the physical world is transferred to the digital space using either a webcam [10, 11] or near field communication [3, 19]. Other authors suggest using infrared emitting blocks with enlarged Braille characters [8] or alternative form factors, e.g., a cotton strip with bags [12].

These digital resources for learning Braille offer a wide variety of different game modes. Some works only provide audio feedback after an object is placed, detailing the geometric shape or the relation to other objects [2, 20]. Najjar et al. guides the children through stories, e.g., baking a cake, to improve their math skills [31]. Most works, however, focus on placing Braille characters representing text. Here, the different game modes entail placing a single character, which has been communicated through audio [3, 8, 19], spelling a word which is selected randomly [8, 10, 19] or by a sighted parent or teacher [11] and communicated through text to speech or through a related sound, placing random letters and then sorting them alphabetical [19], fixing a given word containing a spelling error [10], find a word by ordering a set of letters selected by a parent [11], or guessing the correct word by playing the game hangman [11], i.e., guessing random letters and receiving feedback if the letter is contained in the word.

In contrast to these related works, our portable prototype is easy to set up, uses standard-size Braille characters (not enlarged ones), offers an interaction design that is highly responsive, and allows for self-directed exploratory Braille reading and spelling for children.

3 ITERATIVE DESIGN PROCESS

Our initial concept was based on previous works. From there, we conducted six iterations with stakeholders to adapt and improve our idea and the design of our prototype. We illustrate these iterations in Figure 3 with a picture for each designed prototype or conceptual prototype we discussed in that iteration. In the first iteration, we created two conceptual prototypes based on related works. Here, our focus was on providing automated audio feedback to the user. The first concept, *BrailleEggs*, resembles an enlarged Braille character where single dots can be selected by placing egg shaped objects similar to store-bought [6] or home-made [27] devices. For the second concept, which resembles a *SwingCell* [7, 14], we build a prototype using clay and marbles. In the second iteration, we discussed the concept of *BrailleEggs* and the clay prototype with one sighted (E3) and one blind (E1) special education teacher for children with visual impairment and a blind digital accessibility consultant and braille expert (E2). We decided to not include children currently learning Braille in these early iterations, but to rely on the expert opinion of educational professionals. Following their feedback, especially the request to focus on standard-sized Braille characters as well as spelling words and not learning single characters, we designed an overall concept for *BrailleBuddy*.

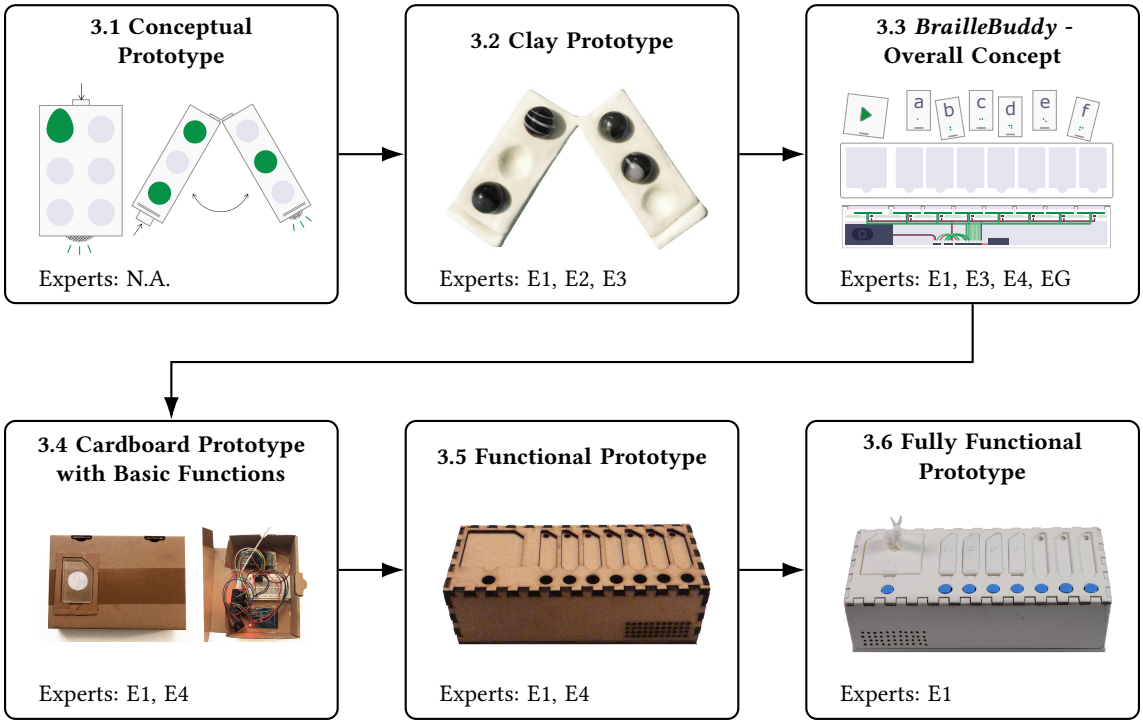

Figure 3: This figure depicts the six iterations of our design process and showcases the prototype used in each iteration. We listed the experts involved in that iteration below each picture. The images are ordered from left to right and from top to bottom. We started with a conceptual prototype based on our literature review and created a clay prototype to discuss with experts. Based on these discussions, we designed the overall concept for BrailleBuddy and built a cardboard prototype followed by a functional prototype. Lastly, we conducted a pilot study with the fully functional prototype used in the evaluation in Section 5.

We discussed this concept in the next iteration again with E1, E3 and a 9th grade student (E4) who recently learned Braille. Additionally, we consulted a research group (EG) from a different university who specialize in working with children with low vision (one of the participating researchers is also a Braille user with a visual impairment). In the next three iterations, we used the refined concept to construct a cardboard prototype with basic functions, a wooden functional prototype and a lacquered fully functional prototype. These prototypes were discussed with E1 and E4.

A detailed list of experts involved in the design process is shown in Table 1. The final version of *BrailleBuddy* is described in Section 4 and its evaluation in Section 5.

3.1 General Idea and First Concept

In the existing research, we identified a gap for a tangible user interface that (1) children can operate without adult or sighted supervision; (2) does not require a complex setting up process, such as having to mount a camera for input; (3) provides immediate and automated audio feedback; (4) offers different levels of difficulties or various game modes to keep Braille learners engaged over a long time. To the best of our knowledge there is no device that combines these four points. There exists a broad variety of Braille resources. However, easy to use [6, 7, 40] or self-made low-cost devices [14, 27] often lack audio feedback or the possibility of various game modes or increasing difficulty. More technical approaches often use a complex setup [11, 20] or are designed for supervised use [3, 11].

Since most research uses enlarged Braille characters [3, 8, 10, 11, 19, 31], we as well started with enlarged Braille characters. We designed two concepts for prototypes resembling one Braille character. Both have a speaker for audio feedback, a button to repeat that feedback and six dents representing the Braille dots where the user can place marbles or egg shaped objects to write a Braille character. Placing objects inside such a form is a common principle for Braille resources and research [7, 12, 24, 27].

The first concept, *BrailleEggs*, resembles a three-by-two egg carton, where each egg is one dot of the Braille character. Similar approaches, e.g., using ping-pong balls and an egg carton, are frequently created as a low-budget tool to support Braille learning [15, 27] or more sophisticated approaches of manipulable enlarged Braille characters can be bought [6]. For the second concept, *SwingCell*, we used a similar interaction principle with a button and a speaker, but used the form of a swing cell [7, 14, 24] to allow the user to unfold the Braille character into a six-by-one layout. For complex interactions, i.e., spelling a word, the user needs to input letters sequentially. A sketch of the concept of *BrailleEggs* and *SwingCell* is depicted in the top left image in Figure 3.

Table 1: Here, we list information on the four experts and the group of expert researchers and their involvement in our design process. Three of the four individual experts are blind from birth.

ID	Description	Gender	Diagnosis	Iteration
E1	Special education teacher	f	Blind from birth	2,3,4,5,6
E2	Digital accessibility consultant	m	Blind from birth	2
E3	Special education teacher	f	-	2,3
E4	9th grade student	m	Blind from birth	3,4,5
EG	Expert group of researchers	N.A.	N.A.	3

3.2 Requirement Interviews and Clay Prototype

We then conducted a phone interview with E3 to discuss our concept and also met with E1 and E2 to discuss our concept utilizing a clay prototype and marbles, see the top middle image in Figure 3. We combined these meetings with semi-structured interviews to confirm and supplement our literature research. Our idea was well received, and there is a clear desire for such a device. E1 and E2 highlighted that the box should be haptically but also visually appealing. Additionally, it was mentioned that the transition from a three-row to a one-row layout is usually not challenging to learn (E1, E3) and enlarged letters are usually not used for an extended period of time during learning (E1). Therefore, we were advised to focus less on a single letter but rather on spelling words using standard-sized Braille characters (E1, E2, E3). Even though, or rather *because* standard-sized characters are not common in other works, we decided to follow the experts' advice.

3.3 *BrailleBuddy* - Overall Concept

Based on the educational professionals' feedback in the last iteration, we designed a preliminary version of *BrailleBuddy*. A sketch of this concept is depicted in the top right image in Figure 3. *BrailleBuddy* consists of a box with several recessed areas on the top surface, into which the user can place *cards*. These *cards* are labeled with tactile symbols, Braille words, or Braille characters and have a tactile marker in the form of a horizontal line at the bottom to indicate the correct orientation. Upon placing a *card*, audio is played to the user, giving instructions or informing about the *card* placed. Pressing a *card* into the box triggers another replay of the audio feedback. To allow for collaborative play with sighted children, teachers or parents, we included printed but recessed or elevated text on the *cards*.

We discussed that design in parallel with different experts. Again, we consulted both the sighted and the blind special education teacher E1 and E3. Here, we provided a detailed description of our concept per email to confirm if we implemented their previous suggestions correctly. Additionally, E1 consulted one of her 9th grade students (E4) and integrated his feedback into her reply. To gain an additional point of view, we presented the idea to a group of expert researchers specializing in working with visually impaired children (one participating researcher is a Braille user with visual impairment). In an online meeting, we showcased our design and explained its functionality. All suggestions provided by EG were either also suggested by E1 or E3 in this iteration or confirmed to be valid improvements in later iterations.

The repeatable audio feedback was well received (EG). Additionally, due to their clearer affordance, E1 recommended switching to conventional buttons for audio feedback (instead of pressing the *cards*). The inclusion of printed but elevated or recessed text was judged to be helpful as such text is sometimes used in public places (E1). However, it was pointed out that children with residual vision trying to learn Braille might be able to circumvent reading Braille (E1). The tactile marker on each *card* to indicate the orientation was well received by all experts. Nevertheless, EG suggested also beveling one corner to make the correct orientation a mandatory prerequisite for the *card* to fit into the recess. They further suggested reducing the size of the *letter cards* as otherwise, the distance between Braille characters is too large to learn the connection between letters forming a word. EG and E1 also suggested some form of structured storage plate for the *letter cards* to reduce the workload on the children during the search process for a specific letter.

3.4 *BrailleBuddy* - Cardboard Prototype

We created a cardboard prototype with basic functions, providing one area for a *card* and no buttons, i.e., no repeatable audio feedback, see the bottom left image in Figure 3. Further, the audio feedback was limited and for demonstration only. We also 3D-printed various *cards* in different sizes and variations, i.e., elevated or recessed printed text, sharp or rounded edges, and lacquered or non-lacquered surfaces. In a meeting at a special education school, we presented these prototypes to E1 and E4. While all *cards* felt good when touching, E1 and E4 agreed that lacquered *cards* with round corners are more pleasant to touch than the other variants. Further, the narrower *cards* proved easier to grasp and E4 could locate the Braille character more easily. Still, E1 noted that the *card* should still be wide enough to place two characters next to each other, e.g., for numbers or capital letters. For the printed text, raised letters could be recognized more easily than recessed ones. Placing the *card* did not pose a challenge and the concept was grasped quickly by E1 and E4.

3.5 *BrailleBuddy* - Functional Prototype

We now created a prototype of *BrailleBuddy* in the planned dimensions as well as a series of games playable on the device (described in Section 4.3). The prototype had seven recessed areas for *letter cards*, of which four were functional. We used a wooden case as depicted in the bottom middle image in Figure 3, printed a larger

variety of *letter* and *word cards* in the previously determined dimensions and provided concrete audio feedback. For *word cards*, we printed different versions of each object—once a 2D relief image and once a 3D figurine.

We again discussed the device with E1 and E4. The beveled corner suggested by EG was very well received. Still, other materials used by the school always had the left upper corner beveled. Therefore, E1 suggested we also use the left corner instead of the right one. For the audio feedback, E1 asked to use the regular (non-phonetic) pronunciation of letters and make explanations not too text heavy. The interaction itself was perceived as intuitive and easy. E4 could recognize all *word cards* easily but showed more interest in and excitement for the 3D figurines.

3.6 *BrailleBuddy* - Fully Functional Prototype

The fully functional version of *BrailleBuddy* is depicted in the bottom right image in Figure 3. It has the beveled edge on the left side of the *cards* and is a wooden box with sanded edges and a lacquered surface. In this last design iteration, we tested the different game modes of *BrailleBuddy*, discussed the audio feedback, and went through the planned study procedure with E1. E1 suggested a small stand or case to place the selected characters during the game *Word Scramble*. Otherwise, only minor adjustments to *BrailleBuddy* were suggested. However, E1 encountered a problem with the light receptors. The shadow of her hand or outside light could lead to false detections regarding whether and where a *card* had been placed. We, therefore, adjusted the size of the holes in the lid of *BrailleBuddy*, which mitigated the issue. The final version of *BrailleBuddy* includes these adjustments and is described in Section 4.

4 *BRAILLEBUDDY*

The final prototype can be seen in Figure 1. It consists of a wooden box. Children can place one large and seven small *cards* into the recessed areas on the top. The first *card* is larger and sets the game mode for the box, i.e., the child can select their favorite type of game. We refer to such a *card* as *word card* or *game mode card*. In the other seven slots, the child needs to place *letter cards* with single letters to solve the selected game. Placing any *card* triggers audio feedback. The child can replay the audio by pressing a button beneath the *card*. We connected our prototype via a USB cable to a Notebook. This connection provided power to *BrailleBuddy*. In future versions, this could be replaced with a battery. During the study, we used that connection also to log the study data and regulate the volume of the built-in speaker.

Based on our design process, all *cards* are lacquered, have a notch on the left upper corner, rounded edges, and printed text is always elevated. *Letter cards* are as narrow as possible but wide enough for two Braille characters. The audio feedback uses non-phonetic pronunciation when reading letters and the explanatory feedback is concise. The distance between the recesses for *letter cards* is small. This supports the perception of a whole word when multiple *letter cards* are placed. The buttons to repeat the audio feedback are noticeable by touch and are placed underneath each recess for *cards*. We still provide 2D relief images and 3D figurines for the *word cards*, as no clear choice could be made beforehand.

4.1 DIY - Open Source

We provide all models, building instructions and code in an open-source repository [21, 22]. This repository also includes remarks about potential changes based on our final evaluation or tips about a more cost-effective construction. In general, *BrailleBuddy* can be built with little equipment and while a laser cutter is recommended, it is not crucial. Nevertheless, a 3D printer with sufficiently detailed printing to create Braille dots is required. With this, *BrailleBuddy* can be built, extended, and adjusted to country-specific requirements by researchers and educators worldwide.

4.2 Hardware

Case and Letter Card Storage Plate. The case of *BrailleBuddy* is 250mm wide, 105mm long and 80mm high and was cut from thin wood, which was layered wherever necessary, i.e., the top consists of two layers of wood glued together. Then, all edges were sanded and the box painted white to prevent injuries or splinters. The case can be opened and closed using a childproof clipping system. The areas for the *cards* have a notch in their left corner to identify the correct orientation of *cards* and another half-circle-shaped notch at the bottom to allow for removing a *card* from the box more easily. Using the same method, we also created a storage plate to hold the *letter cards* in four rows, allowing for quick tactile scanning through the *cards*.

3D Printed Cards. We created three different types of *cards*; *letter, word*, and *game mode cards*. *Letter cards* have the dimensions 59x16x4mm (height, width, thickness) and contain one letter consisting of up to two Braille characters, e.g., for upper case letters. Additionally, the letter is added in printed but elevated text above the Braille characters. *Word cards* are 59x59x4mm in size and contain a 2D relief image or a 3D figurine depicting an object. We expected the figurines to be motivating elements. Below the object, we provide the Braille word for that object, so that children can learn to perceive the word as a whole tactile entity in addition to feeling each individual letter. The words are selected from a list of words suggested by E1. *Game mode cards* are 59x59x6mm in size and are labeled in Braille with the name of the game mode triggered by placing the *card*. All *cards* have a recessed space on their backside, holding an RFID tag. Further, the *cards* have an elevated line on the bottom and the left upper corner is beveled to indicate the orientation of each *card*.

In total, we printed 99 *letter cards*, two *game mode cards*, 12 *word cards* with 3D figurine, and 33 *word cards* with 2D relief image, see Figure 4. The used Braille alphabet contains 38 letters, of which 35 were included once as upper case letter and all 38 once as lower case letter. Further, we included an additional lower case *letter card* for 13 letters, two additional ones for five letters and three additional *letter cards* for one letter. The letters contained multiple times were chosen based on the words depicted in the *word cards* and used in *Word Riddle* or *Word Scramble*, i.e., so that there are enough letters to build every possible word. Going forward, the frequency of letters in the used language can be used to determine how often letters should be contained. All words with 3D figurines also had a corresponding *card* with a 2D relief image. All *cards* were printed on a Formlabs Form 3, an additive raisin 3D printer. We used clear raisin and ensured that the supporting material was not connected

Figure 4: The left of the three images shows the two *game mode cards* and a selection of 10 fully lacquered *word cards* with 3D figurines. The fourth column in that picture shows three non-lacquered *word cards* with a 2D relief image with the RFID tag visible and one partially lacquered *word card* with a 3D figurine. The middle image shows a selection of 20 lacquered *word cards* with a 2D relief image. The right image shows all 99 *letter cards* inside their storage plate.

to the Braille dots or crucial parts of the relief images or figurines. Remains of the support material could otherwise negatively impact the touch experience. Additionally, all *cards* were lacquered with white paint to improve the experience of touching the *cards*.

Electronic Components. *BrailleBuddy* is controlled by an ESP32, a microcontroller with WIFI and Bluetooth. It includes five RFID readers, seven light sensors, and a speaker. The RFID readers recognize the corresponding tag in the placed *cards*, while the light sensors determine the exact location of a placed *letter card*. The sensors are connected to the ESP using a multiplexer and the speaker is connected using an mp3 module. We also integrated a memory *card* for storing sound files. Further, we integrated eight push buttons to allow repeating the audio feedback when a *card* is placed. A view of the electronic components as they are stored in *BrailleBuddy* and a schematic overview are depicted in Figure 5.

4.3 Interaction and Game Modes

BrailleBuddy offers two different forms of interaction. A child can either place or remove a *card* in one of the eight slots or press one of the eight buttons located below each slot. In each case, *BrailleBuddy* plays audio feedback to the user. The audio depends on the current state of *BrailleBuddy* and the area or button selected. We developed three different game modes; *Word Copy*, *Word Riddle*, and *Word Scramble*. We give a schematic overview in Figure 6. When powering *BrailleBuddy*, a short introduction is given. This repeats when pressing the left-most button. All other buttons initially indicate that the corresponding recess area is empty.

Word Copy. In this game, the user places a *word card* for an object in the first slot of *BrailleBuddy*. The box now instructs the user to spell that word by placing single letters to the right. A press on the left-most button repeats these instructions, while a button press below any other recess either indicates that it is empty or repeats the feedback from placing the *letter card*. The letter is read and marked as correct or incorrect in the latter case. If the word is completed and correctly spelled, it is read aloud by the device and a finishing sound is played.

Word Scramble. When placing the *game mode card* for *Word Scramble*, a word from a list of words is selected randomly. The user is instructed to place these letters in a randomly scrambled order on the box. Again, the left-most button repeats these instructions. In addition, the other buttons indicate which letter has to be placed in each particular recess if it is empty. If a *letter card* is already played, *BrailleBuddy* indicates if it is correct or not. After all letters are collected and placed on the box, *BrailleBuddy* instructs the user to bring the letters in the correct order. The left button now repeats the new instructions and the other buttons read the letter and then note it as correct or incorrect. If all letters are brought into the correct order, the word is read and a finishing sound is played.

Word Riddle. Similar to *Word Scramble*, the user has to reconstruct a word selected randomly by *BrailleBuddy*. However, here the letters are unknown and have to be guessed. Again, the left-most button repeats the instruction and the other buttons indicate that the recess above is empty or repeats the feedback from placing the *letter card*. When a *letter card* is placed, *BrailleBuddy* tells the user one of three messages, indicating if: (1) the letter is not contained in the word; (2) the word contains X of the placed letter, where X corresponds to the actual number, but the current position is wrong; (3) the word contains X of the placed letter and the current position is correct. Additionally, for uppercase letters *BrailleBuddy* adds the information that this letter is contained in uppercase when placing a lower case *letter card* and vice versa. If all letters are guessed and ordered correctly, the word is read aloud by the device and a finishing sound is played.

5 EVALUATION IN THE SCHOOL CONTEXT

To evaluate the functionality, usability, and learning experience of *BrailleBuddy*, we conducted a user study at a special education school. We focus on two research questions resulting from our main goals. **RQ1:** Can children interact with *BrailleBuddy* without support? **RQ2:** Do children enjoy playing with *BrailleBuddy*? Further, we collect feedback for further improvements or additions to *BrailleBuddy* and on the difference between 2D relief images and 3D figurines on *word cards*.

5.1 Participants

We recruited 11 participants in grades one, two, and three from a local school specializing on students with visual impairments. Second and third grade students attend school in a combined class. Ten participants were fully blind, one had residual vision. The ages of the participants ranged from eight to 12 years. The gender distribution was five male and six female students. The study was

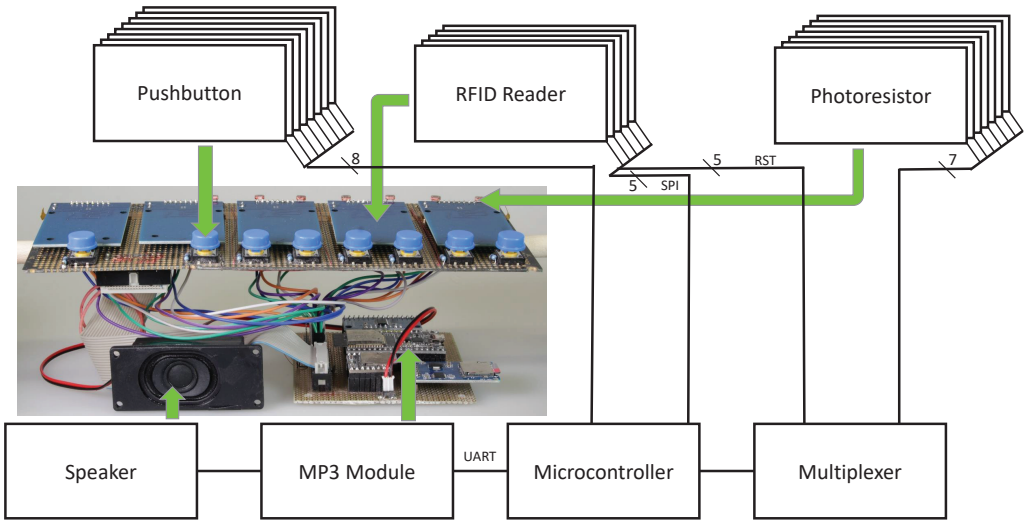

Figure 5: The image in the left center row shows a picture of the internal electronic components of *BrailleBuddy* in the same layout as they are stored inside the case. Around that image, we show schematics of the components and how they are connected.

conducted on the premises of the school and at least one teacher was present at all times to create a comfortable and known environment for the children. The participants were selected based on the teachers' assessment of their current ability to read Braille and spelling Braille characters, e.g., they are still in the process of learning but already have a basic understanding of the letters. Still, the group of children showed some diversity regarding their knowledge about Braille reading and spelling. In addition to their visual impairment, one participant has a hearing impairment, one Attention Deficit Hyperactivity Disorder (ADHD), and for two children the teacher reported a level of fine motor skills below their age group. The teachers advertised the study in advance and provided consent forms to the parents. Only children with signed consent forms were allowed to participate in the study. The Institutional Review Board of the authors' department approved the study.

5.2 Setup

In Figure 7, we depict the study setup. *BrailleBuddy* and the storage plate with all *letter cards* were placed in front of the children. They could adjust the object's position to their preference. The cardboard box containing the *word* and *game mode cards* was placed outside the child's reach. When necessary, one of the experimenters held the box closer so that the child could reach in. At the beginning of each study, the *letter cards* were sorted so that all upper case letters are contained in the upper two rows of the storage plate. The video camera used to record the study was positioned above the table in a way that did not capture the children's faces, following ethical considerations.

5.3 Methodology and Procedure

We limited the study to a duration of 30 minutes per participant. This duration was also suggested by the group of expert researchers from design iteration 3.3 (EG) and related work [36] and allowed the children to have enough time to explore the functions and to experience the prototype at their own pace. It also takes the attention span of children in this age group into account, which is usually below 40 minutes [29, 30]. These 30 minutes included arriving in the room and sitting down as well as an introduction. During the whole session, one teacher and two experimenters were present. Due to the diverse development levels and less predictable actions of the participants compared to adults [34], we employed a semi-structured approach with three different phases.

First, we guided the participant to their place and introduced ourselves. Here, we also mentioned the goal of the study and encouraged critical feedback. Secondly, we explained the different elements of *BrailleBuddy* to the participant. They could explore *BrailleBuddy* and the *letter* and *word cards* with their hands and try placing them in the correct spaces. Lastly, we proceeded with an evaluation of the different game modes. We asked children to pick their favorite *word card* and place it in the leftmost space on top of the box. *BrailleBuddy* then guided the participant through the game *Word Copy*. Here, the participant had to recreate the word placed on the box using the provided *letter cards*. The experimenters provided little support, as one of the goals of this work was to create a device that can be operated in a self-directed manner by children. Depending on how fast the participant progressed, we asked them to place the *game mode card* for *Word Scramble* and later *Word Riddle* on the box. In both cases, participants were supported mainly by the feedback from *BrailleBuddy* to gather the required letters and bring them in the correct order or to guess a word by placing letters randomly, respectively.

During the study and at the end, we asked participants what they liked and disliked and what we could improve. To supplement these answers, we recorded video (working area only) and audio data to review later. In addition, the experimenters wrote down their observations to document the behavior of the participant and the teacher was interviewed after each participant about their impression of the children's behavior. Further, we recorded every

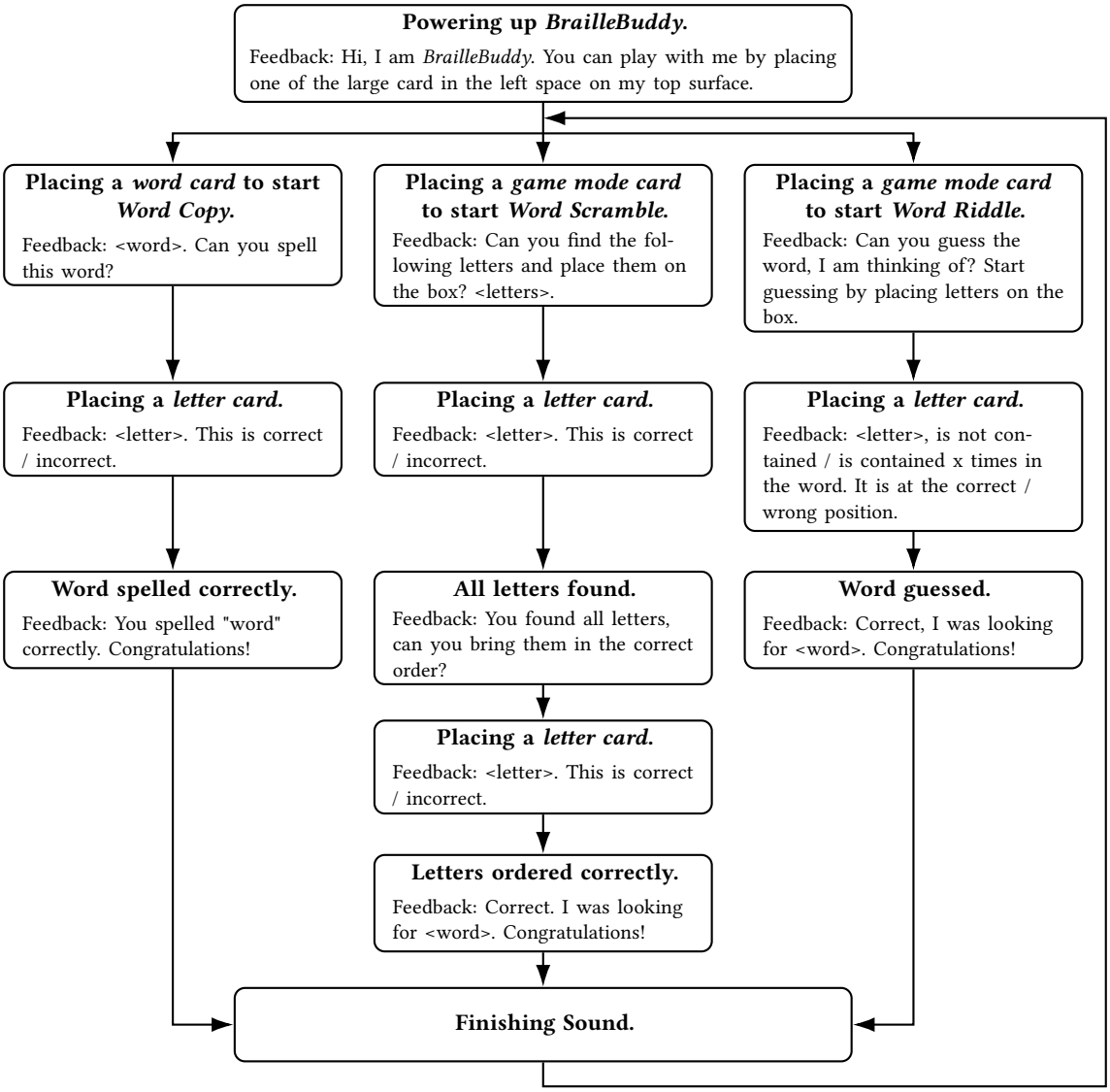

Figure 6: This chart showcases the application flow of *BrailleBuddy*. Each element first describes the users' action in bold text, followed by the shortened and simplified audio feedback given by *BrailleBuddy*.

interaction with *BrailleBuddy*, i.e., card placed, card removed, and button pressed, with the time, the digital state of *BrailleBuddy*, and current game values.

The experimenters provided assistance whenever children were not able to progress with the game on their own. We categorize this support into three types. First, support finding the correct *letter card*, e.g., "capital letters are in the top rows", "you already passed over the letter", or physical support such as presenting a smaller set of selected letters. Second, tips for solving the game, such as "Can the upper case letter stand in the middle of the word?", "The word you are looking for is a small animal", or "Which letter do you write often?". Lastly, help in interacting with *BrailleBuddy*. This can entail physical help in placing a card on the box, rotating a card, or verbal support like "You need to rotate the card by 180 degrees", "You placed the letter in a recess too far to the right", or "you need to place it in the front, where you had placed the hare before". To analyze this support, the videos were watched again. Every interaction with the box after a game was started was marked if verbal or physical help was provided prior to the interaction and then coded independently by two authors into the three categories. Out of 107 situations, the initial coding disagreed in 10 instances, which were subsequently discussed and a common coding was agreed upon.

6 RESULTS

Overall, our evaluation showed that *BrailleBuddy* (1) motivates children to interact with braille characters of standard size, (2) can be operated in a self-directed manner, and (3) provides an enjoyable

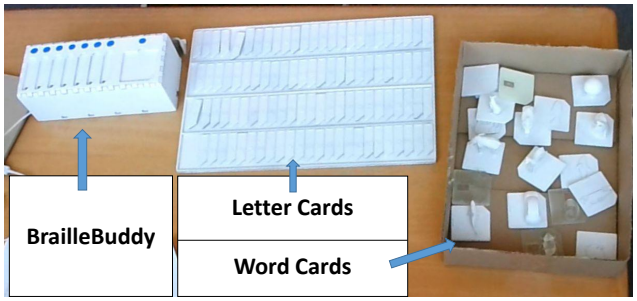

Figure 7: This image shows the study setup. *BrailleBuddy* and the storage plate with the *letter cards* were placed at the table's edge. The child was sitting in a chair and could move both the box and the storage plate freely (top left and center of the image). We observed bi-manual interaction throughout the study. The right part of the image shows the box containing the *word cards*.

learning tool for children to practice spelling and reading Braille. We report on the detailed results focusing on handling *word* and *letter cards*, interacting with *BrailleBuddy*, and the enjoyment and motivation of the children. In total, the children played 14 rounds of *Word Copy*, eight rounds of *Word Scramble* and five rounds of *Word Riddle*. All children played at least one round of *Word Copy*. Depending on how fast the child progressed through the game, they played another round of *Word Copy* or a round of *Word Scramble* and if time allowed a round of *Word Riddle*.

To compare the provided support for finding letters, solving the game, or interacting with the box, the amount of wrongly placed cards, and the time required to place each card over the course of the game, we divided each game in half based on the progress to solve the game. Here, the given support and the wrongly played cards (errors) are given as the ratio to the number of letters in the word to account for different word lengths. We did not compare performance across the different game modes for two reasons: first, the number of players and hence the average level of competency for each mode differs, and second, the game modes require different strategies, which necessarily result in different quantitative metrics, e.g., the error ratio will be significantly higher by design for the game *Word Riddle*.

For the first game played by each of the eleven participants, the mean and standard error of the five performance measures is shown in Figure 8. In the second half of the game, participants made fewer errors, required less support and were faster in playing the game. We conducted further statistical analyses on these data. The distribution of the time per correct card did not deviate from normality. Hence, we conducted a one-tailed t test for the directional hypothesis that the time improves in the second half. The decrease is significant ($t(10)=2.82$, $p<0.01$), i.e., the time improves significantly. The other measures were not normally distributed. Therefore, we conducted Wilcoxon signed-rank tests, again with a directional hypothesis. None of the four measures decreased significantly (error: $Z=1.51$, $p=0.09$; letter support: $Z=0.44$, $p=0.38$; game support: $Z=1.99$, $p=0.06$; interaction support: $Z=1.73$, $p=0.13$). In conclusion, the descriptive and inferential statistical analysis provides some evidence indicative of an improvement.

6.1 Finding the Correct *Letter Cards* and Identifying *Word Cards*

We presented all *letter cards* in a storage plate with four rows providing a more structured solution for searching *letter cards*. Seven participants (P1, P3, P4, P5, P6, P7, P8) were able to scan the *letter cards* independently and find the correct letters. However, to stay within the study duration, four (P3, P5, P7, P8) received three or fewer verbal hints throughout the study, e.g., when they moved over a letter multiple times without recognizing it. The other participants (P2, P9, P10, P11) needed more direct support, i.e., presenting a selection of letters. For example, P7 and P8 often jumped between rows while scanning and therefore scanned some *letter cards* multiple times and missed others. P2, P9, and P10 picked up *letter cards* to identify them, often rotating them in the process and therefore misidentifying letters. P9 and P10 did not put much effort into placing *letter cards* back into the storage plate and P10 even turned or moved other *letter cards* when picking one up. This led to a chaotic and jumbled search area, see Figure 9, greatly increasing the difficulty of finding letters. None of the children indicated or displayed to be distracted by the elevated printed text on the *letter cards* or randomly placed them on *BrailleBuddy* to avoid reading the Braille character by using audio feedback.

However, the average ratio of wrongly placed letters (mean 0.43 to 0.18; SE 0.13 to 0.13), the time needed to place each letter (mean 113s to 72s; SE 23 to 16), and the ratio of times support was given to find a letter (mean 0.53 to 0.45; SE 0.14 to 0.14) decreased from the first to the second half of the first game, see Figure 8. In some cases, children were guided by the teacher recommending scanning the full row from left to right and adapted this strategy for other letters. P4 demonstrated from the beginning that such a clear strategy and scanning of the whole search area proves quite beneficial. With their clear strategy and overview of the *letter cards*, P4 found the correct letters fast. Only P11 regularly placed an unidentified *letter card* on *BrailleBuddy* to receive audio feedback, even though we reminded participants of that possibility.

The *word cards* for the game mode *Word Copy* either depict 3D figurines of the object in question or 2D relief images. Out of the 14 rounds of *Word Copy* played, a *word card* with a relief was only picked twice, showing a strong preference for the 3D figurines. While P5 and P7 could not identify any figurines, the other participants recognized their chosen figurines or at least some key features, e.g., P8 recognized the wheels on the 2D car and P4 and P9 pointed out the key features of the 3D elephant. However, there were some false identifications resulting from similar shapes: a hare was identified as a rabbit and a shark was identified as a dolphin. This problem is mitigated by the audio feedback when the *word card* is placed on *BrailleBuddy*.

6.2 Handling *BrailleBuddy*

During their first game, 4 out of 11 children were given support in interacting with *BrailleBuddy*. In the second half of that game, support was only given to two children. The other seven children did not need any help. On average, the ratio of times support was

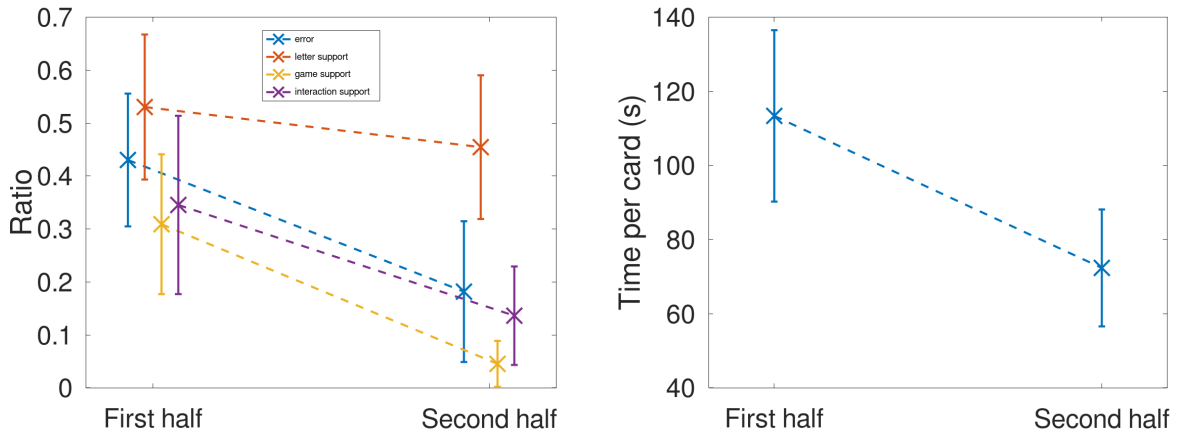

Figure 8: Here, we show two graphs. Both graphs display the average data over the 11 participants' first game. We split the game in its first and second half and plot the mean over all participants as an x and the standard error as vertical lines. The left graph shows the ratio between wrongly placed cards and the different types of support in relation to the word length. The right graph shows the average time required to place a correct card. For all measurements, the value decreases in the second half, i.e., performance improves.

Figure 9: Here, two pictures display the state of the storage plate for *letter cards* after one round of *Word Copy*, right when starting *Word Scramble*. The left image is from P5 and shows an orderly area, which benefits her strategic search approach. In contrast, for P10, shown on the right, the *letter cards* are jumbled and partly turned around.

given to the number of letters in the word dropped from 0.35 (SE 0.17) in the first half of the game to 0.14 (SE 0.09) in the second half; see Figure 8.

When interviewing the teacher afterward, she noted that in her opinion six participants could interact with the device independently, while P2, P9, and P10 could not. For the remaining two children, the teacher was uncertain. She noted that P11's attention span might not be sufficient to interact with *BrailleBuddy* continuously when unsupervised and P7 is not a mother-tongue speaker of the used language; therefore, the audio feedback from *BrailleBuddy* might not suffice.

The buttons were used infrequently. However, in some cases (P1, P2), buttons were pressed multiple times to trigger the audio feedback, as that was found enjoyable. P1 even guessed correctly that a button press repeats the audio feedback after questioning what the buttons do. For *Word Scramble*, eight participants used the buttons to check what letters they needed to find. Three of these eight only did so after being reminded of that option multiple times. P4 even pressed the button again before placing a *letter card* to ensure that they place it in the correct spot and P6 pressed all buttons once after starting the game and then placed the *letter cards* by memory.

6.3 Difficulty, Enjoyment and Motivation

During their first game, four children received support on how to solve the game a total of seven times during the first half and once during the second half. However, seven children did not receive any hints. Here, the average ratio decreased from 0.31 to 0.05 (SE 0.13 to 0.04); see Figure 8.

All participants were interested in *BrailleBuddy* throughout their session. Yet, this might be partly attributed to a novelty effect and an exciting interruption of the normal school day. Nevertheless, all children played for the whole study duration, did not lose interest and showed motivation in interacting with the device. According to the experimenters' observation, nine children vividly expressed their enjoyment of the game or indicated that they want to play again. P1, P2, P3, P4, P5, P9, and P11 laughed, P11 even clapped her hands on successful completions, and P9 started jumping when

getting positive feedback from *BrailleBuddy*. P7 and P11 stated, without being asked, that they would like to have *BrailleBuddy* at home and P10 asked to play again when their session ended. When asked, 10 participants would like to play with the box again, and only P2 was unsure about it. Except for P9, all participants stated that they would use the box in their free time and at home.

After the study, the teacher noted that she felt two participants were not really enjoying the study and was unsure for two others, but confirmed that the other seven were clearly enjoying playing with *BrailleBuddy*. In general, some participants showed great interest in the box, e.g., P2 asked, "Does it make music, too?" and P7 inquired about where the speaker is located and how *BrailleBuddy* recognizes what *card* is placed on the box.

7 DISCUSSION

Our results show that *BrailleBuddy* is usable by children and that they actually enjoy playing with the device. Still, they also revealed limitations or issues that make the interaction with *BrailleBuddy* challenging for some individuals. In the following, we will highlight the well-received parts and give recommendations to improve the device, integrating the study results and concrete recommendations by the participants or the supervising teachers.

Limitations. Without any training and only a brief explanation of the box, seven participants could interact alone with *BrailleBuddy* during their first game. Two more did not need support during the second half of their first game. Nevertheless, there are improvements or alternative variants of *BrailleBuddy* that may allow more children to interact with the box without adult supervision. For example, two children found it troublesome to rotate cards correctly and subsequently to place them in one of the recessed areas on top of *BrailleBuddy*. While they completed this task at the end of the study, i.e., after half an hour of training, a version of *BrailleBuddy* could use differently shaped *cards*, e.g., triangles or adding a handle to the cards. Alternatively, replacing the seven separate recessed areas with one wider area, where cards can be slid from right to left, might help not to place a correct letter in a wrong slot. Additionally, *BrailleBuddy* could not sustain the attention of one child with ADHD. Instead of finding and placing the correct cards, they rather played with the buttons on *BrailleBuddy* and enjoyed the presented audio feedback. Adding more versatile feedback, e.g., instructing the next task or giving hints after a button is pressed multiple times, could draw more attention and motivate children to follow the game. Similarly, most of the support given by the experimenters or teachers could be replaced by automated feedback if the box could detect when children are taking more time to complete the next step or when a correct character is placed in the wrong recess.

Audio Feedback does Support Users. The audio feedback was perceived well. Especially, the winning sound effects and congratulations at the end of a game were liked by the children. All but two participants understood the instructions and grasped the concept of the interaction quickly. Yet, some required additional help or explanations throughout their study. For example, in one instance the pronunciation of one letter was misunderstood. Here, more detailed feedback or a tutorial would support the child in starting a game with the device independently of adult support and without prior training. Further, the device could support multilingual output. For P7, who is still learning the provided language, a different language for the introduction and explanations would have improved the user experience. Participants also suggested using sounds other than text for feedback, i.e., playing the sound an animal makes instead of or in addition to reading its name. One of the teachers mentioned that connecting headphones to *BrailleBuddy* would be very useful if the device is used in a quiet environment or by children with hearing impairment. For the same reason, they suggested a volume control at *BrailleBuddy*. For our prototype, we can only control the volume using the attached computer.

Cards are Correctly Sized. The experimenters perceived the *cards*' size and thickness as fitting and good to handle by nine children. *Cards* with reduced thickness or height are technically possible but increase the required motor skills and pose a swallowing hazard. The width is already minimal due to the requirement of two Braille characters fitting on one *letter card*. It is essential to use standard-size Braille characters, which should not be surrounded by too much margin. Therefore, wider *letter cards* are also not feasible.

Storing Letter Cards in Multiple Cases. While the storage plate could be scanned easily and letters found quickly when the right strategy was employed, children are not always orderly and act strategically. While some children systematically scanned all available *letter cards*, others picked some randomly and put them back. Therefore, splitting the large search area into smaller, sorted fractions, e.g., upper and lowercase letters or consonants and vowels, might support some children in finding the desired letter faster. Further, the teachers suggest reducing the set of available letters based on the abilities and current knowledge of the child and providing a separate case for *word cards* to keep them orderly. During the study, the majority of support in finding a letter was given in the form of reducing the search area, either by specifying a region or presenting a selection of cards, simulating such separate cases.

Playing with BrailleBuddy is Enjoyable and Created Motivation. While enjoyment is not necessarily required for a learning tool, *BrailleBuddy* aims to complement traditional teaching materials. Therefore, the main contribution lies in unsupervised usage by children in their free time. Continuous engagement and enjoyment are key factors in creating intrinsic motivation. According to the present teacher, seven out of 11 children clearly enjoyed playing with *BrailleBuddy*. Most evidently, some children suggested new game modes or activities, e.g., spelling their name with the box (P1), showing a great interest in *BrailleBuddy*.

8 CONCLUSION AND OUTLOOK

Through an extensive, inclusive design process, we condensed multiple requirements and properties desired by stakeholders into a tactile user interface designed to support children in learning Braille. Integrating these, we built *BrailleBuddy*. This tangible device is designed to complement the schools' materials and lessons for children learning Braille. The engaging and different game modes of *BrailleBuddy* require children to read Braille letters and spell words. Our evaluation in a special education school for children with visual impairments shows that *BrailleBuddy* can be operated bi-manually

and in a self-directed manner with no or little training and is enjoyable for most children. Therefore, *BrailleBuddy* can motivate children to playfully deepen or extend their Braille reading skills.

Besides the small technical suggestions previously made, *BrailleBuddy* can be extended in many ways to improve the experience for users. More challenging games for experienced users can be created to increase the long-term engagement with *BrailleBuddy*. Additionally, multiple *BrailleBuddy*s could be connected to implement collaborative or competitive multiplayer games. To further increase the possible games of *BrailleBuddy*, the figurines on the *word cards* could be designed and used to learn and recognize the shape of objects, as E1 pointed out. We have published the source code, building instructions, references to the used 3D figurines, and models for other researchers, practitioners, and schools to use, adapt, and extend *BrailleBuddy* [21, 22].

We outlined an inclusive and human-centered design process for a novel tangible learning device for blind and visually impaired children. Reading and spelling are vital aspects of academic success; hence, our work focuses on motivating children to engage with Braille. Lowering the initial hurdle to experience learning progress is essential for many children to stay motivated. Our research indicates that it is possible to reduce that hurdle with a tangible device and keep children engaged with Braille reading and spelling over a considerable time.

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