Enhanced Formalization, Fun-Factor, and Field Testing for a Low-Cost Braille Writing Tutor

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Abstract

The reported work advances the state-of-the-art in assistive technology for the blind by enhancing a low-cost automated tutor designed to teach braille writing skills to visually impaired children. The relatively low cost of this tutor makes it relevant and accessible to blind communities in both the developed and the developing world. We build on our prior work to extend this tutor along three dimensions. First, we provide a roadmap to formalize the tutor design according to the Intelligent Tutoring System methodology. Second, we conduct preliminary field tests of different aspects of the tutor in three countries and report on our findings. Third, and finally, we improve the tutor's motivational factor by creating educational games that add to the fun of using the tutor. The outcome of this work is an enhanced low-cost tool that can help to promote braille literacy in blind communities around the world.

INTRODUCTION

BRAILLE is a widely-used language that is the only means of literacy for blind people. Each braille character is formed using 6 dots placed in a cell of two columns and three rows. A subset of these 6 dots is embossed to represent each character. Thus, a dot may be raised at any of the six positions to form sixty-four (2^6) unique combinations. The positions of the dots are universally numbered from 1 to 6 in a standardized manner.

Despite its significance and the accessibility it brings, learning to write braille still has a number of barriers. More than 90% of the world's visually-impaired people live in developing communities [2] and it is estimated that less than 10% of the blind children in these communities have access to formal education [3]. Unfortunately, poorer areas tend to have both a disproportionately high number of blind people and fewer resources for educating them [1]. Therefore, the need to improve literacy for the blind in affordable ways is paramount.

The traditional method of writing braille itself creates formidable challenges to literacy [1]. In developed countries, braille is usually embossed with a 6-key typewriter known as a Brailler. These devices are fast and easy to use but usually cost around US$650 each [4]. In developing countries, such devices are sometimes available in small quantities at schools but are prohibitively expensive and so braille is almost always written with a slate and stylus. Using these tools, braille is typically written from right to left so that the page can be read from left to right when it is removed from the slate and turned over. Learning to write braille in this manner can be difficult. First, children must learn mirror images of all letters, which doubles the alphabet and creates a disparity between the written and read forms of each letter. Second, feedback is delayed until the paper is removed and then flipped over and read. For young children, this delay can make braille conceptually challenging since the act of writing has no discernable, immediate effect. It also takes longer for both the student and the teacher to identify and correct mistakes, and this slows the learning process. Together, these challenges contribute to the problem of illiteracy among the blind; especially in developing communities. Even in developed countries, writing braille with a slate and stylus is still viewed as the simplest and most affordable and portable format for note taking. In fact, some efforts are being made in the USA to renew the interest and skills for writing braille using a slate and stylus. Thus, assistive braille writing technology relevant and accessible to blind communities could have significant impact on millions of lives.

Braille Writing Tutor

To address these needs, a group at Carnegie Mellon University developed a Braille Writing Tutor (BWT) that uses audio feedback to provide guided practice for young children learning to write braille [12].

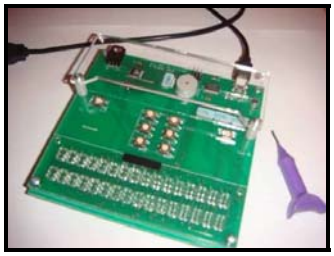

Figure 1: Automated Braille Writing Tutor

The BWT (shown in Figure 1) consists of an electronic slate (or E-slate) and a stylus, which monitors the student's writing and transmits data in real time to a computer for immediate audio feedback. The latest version of the BWT consists of two rows of 16 braille cells and 6 buttons placed over the top of the two rows to work as an input area on the E-slate. The stylus is a standard braille stylus that connects to the E-slate by its metal tip. Moreover, students can press on one of the two control buttons placed on the sides of the E-slate to perform a variety of mode changes. Further details of the BWT are discussed in prior publications by Kalra et al. ([1] and [5]). We built on this prior work with the BWT and enhanced it in several ways. These enhancements are the basis of the work reported in this paper.

Contributions

We identified three key areas for improvement in the BWT. First, we provide a roadmap for formalizing the BWT design according to the Intelligent Tutoring Systems (ITS) methodology. In this section we focus on mapping the key ITS components to relevant BWT elements, and briefly discuss the implementation of this roadmap. Second, we extend the field testing of the BWT beyond its initial deployment in India in the summer of 2006 [1]. We present feedback from three schools for the blind in three countries: India, Qatar, and Zambia. Finally, we focus on improving the BWT's fun-factor for generating enthusiasm for learning to write braille. To this end, we implemented several educational games that can be played using the BWT. The overall result of this work is a significantly enhanced tool for motivating and teaching braille literacy.

FORMALIZATION

We began our enhancements to the BWT by exploring how this work can benefit from the vast literature on Intelligent Tutoring Systems (ITS) [6] and designing a roadmap for formalizing the BWT design to benefit from this methodology. ITS are interactive learning environments based on instructions and guided practice assisted by computers. They offer the ability to present educational materials through a communication interface to the computer and respond intelligently and instructively to the student's performance. The intelligent response of the tutor is adapted to a particular student through collaborative work between the five core components of an ITS as illustrated below.

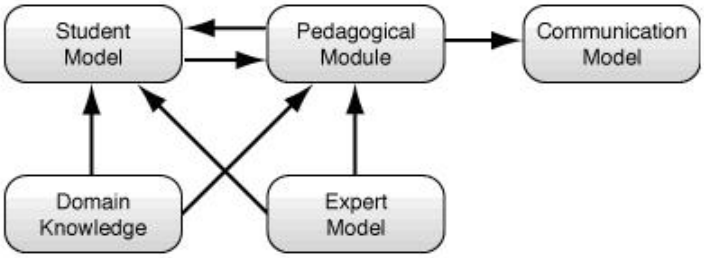

Figure 2: ITS components and their interactions [6]

Each of these components has a specific role. The Domain Knowledge contains the information being taught by the tutor. The Pedagogical Module captures the teaching process and makes decisions about how to guide the student. The Expert Model captures the skills of an expert of the knowledge stored in the Domain Knowledge and acts as a benchmark to evaluate the student performance. The Communication Model defines the interaction between the student and the system and addresses the question of how to present the material to the student in the most effective manner. Finally, the Student Model gathers and stores information specific to the current student, tracks the progress of the student based on the model, and provides useful data to the Pedagogical Module. Each of these five components needs to be customized for the BWT. Based on a survey of the relevant literature and based on our observations and interactions with the Al-Noor Institute for the visually impaired in Qatar, we mapped each of the core ITS components to relevant elements of the BWT. This roadmap is presented next.

Domain Knowledge

The domain knowledge component is designed to capture the domain knowledge in the tutor's area of expertise. For the purpose of the BWT this component contains information about braille character mappings from the alphabet of a given language to the correct combination of dots in the braille cell. It also includes basic knowledge on the numbering of the 6 dots. Note that this module is simple for basic braille since it only contains character maps for the various alphabets in different languages. However, for more advanced braille, this module will need to include rules for contractions and special symbols and operators for use in mathematics and some languages that include accents, etc. The current implementation of the BWT limits its domain knowledge component to the numbering of the 6 dots and the basic character maps for the specific languages being taught. The BWT can currently provide basic alphabet tutoring in English, Arabic, French, and Chinese braille.

Pedagogical Module

The pedagogical module is derived from the teacher's role in the classroom. The purpose of this ITS component is to capture the teaching process and make decisions about guiding students. This guidance is provided in the form of one-on-one interaction to maintain the individualized instructions that the ITS provides. Intelligent Tutoring Systems use two forms of the individualized instructions, meta-strategies and instructional strategies [7]. Meta-strategies refer to the overall picture of the teaching process while instructional strategies refer to the methods used to teach a particular concept. In a classroom setting at Al-Noor, the teachers tend to adopt the following strategies [8]:

- *Students' Trust*: the teaching process progresses smoothly once the teacher earns the students' trust.
- *Curriculum*: the curriculum for our target (Grade One) is teaching the English and Arabic braille alphabets and then moving to instructions on writing simple words.
- *Classroom Activities*: engaging students in the classroom through a mixture of lectures, discussions, hints and other forms of activities
- *Continuous Assessment*: evaluating the educational outcomes and the effectiveness of using the activities in the teaching process after a small number of activities.
- *Final Assessment*: measuring the overall level of understanding the entire curriculum for a grade level.

Next, we propose how these strategies might be included in a Pedagogical Module relevant to the BWT:

- *Students' Trust*: student trust in the tutor depends on the robustness of the tutoring mechanism, and effectiveness of the tutor's ability to teach. For the first aspect, we have employed a variety of strategies such as recording the teacher's voice for the audio feedback for young children and using other "happy sounds" to eliminate the student's fears of using a new device. We also improve the trust in the tutor's ability to teach by getting a respected person (such as a teacher) to endorse the tutor and introduce it to the student.
- *Curriculum*: writing braille is commonly based on a one-to-one mapping of characters to braille patterns. Thus, the tutor should deliver three types of information: Character mappings for relevant braille alphabets, the structure and the numbering of the 6 dots in the braille cell, and instructions on how to use the braille tutor. All of these are available in the current implementation of the BWT.
- *Classroom Activities*: these are the activities employed by the teacher to instruct the students on how to write braille. Braille writing is taught in a number of stages [7]: improving the sense of touch by exercising this sense to recognize very detailed objects; learning numbers before learning letters because each letter in braille is defined by a number of dots and each dot has a specific number assigned to it; learning the easy letters that have one, two, or three dots embossed in the left column; learning the less complex letters that have one dot in the left column and another in the right column; learning the tri-letters that have three embossed dots distributed in the two columns; learning letters with four embossed dots; learning the fully raised cell except one dot. While the BWT does not address the students' early activities of learning of numbers and the sense of touch, it provides 6 modes of instruction and exercises [5] that follow the basic curriculum strategies described above.
- *Continuous Assessment*: this could translate to giving the students short quizzes that cover different topics as they learn them. This is incorporated into the BWT in its instructional modes. For example, the tutor asks the student to emboss particular dots after teaching dot numbers, and asks the student to write specific letters after teaching dot patterns that correspond to letters.
- *Final Assessment*: final assessment measures the overall understanding of two main aspects of writing braille: (1) knowledge of the structure and the numbering of the 6 dots in the braille cell and (2) knowledge and speed of writing the braille alphabet. The BWT currently does not provide final assessment because its goal is to enhance the teachers' activities by providing guided practice.

Expert Model

The role of the expert model component of the ITS is to represent the knowledge and skills of an expert in the domain. It provides expert solutions to all the exercises and quizzes assigned to the student, thus providing a benchmark for comparison and evaluation of the student's solutions. Invariably this component will be implemented using a rule-based approach [6]. These rules are combined to solve different problems and exercises presented to the student. In the current version of the BWT, the solutions to the exercises only require knowledge of the dot numbering and patterns.

Communication Model

The communication model determines the interaction between the student and the tutor and addresses the question of how to present material to the student and receive feedback from the student in the most effective manner. A key difference in the communication model between most ITSs and the BWT is the use of graphical interfaces and visual cues. Visual feedback is inaccessible to blind students. Hence, the BWT must rely primarily on audio and tactile feedback to the student. The major drawback of audio feedback is that it prevents the use of the tutor by individuals who are both blind and deaf. Deciding what type of audio is best will depend upon the student's age, culture, and level of progress. One of the options we have for very young children is recording their teacher's voice to provide feedback to the student. A second option that older children find more exciting or "cool" is using a synthetic voice. It is also important to make sure that the audio feedback is relevant to the student's culture; that is, issues such as language, dialect, and accent need to be taken into consideration. The current BWT is customizable with locally recorded voices for audio feedback. The buttons and stylus on the tutor provide the students a tactile interface to the tutor. So the input to the tutor uses a tactile interface and the output from the tutor is in audio format.

Student Model

The student model is crucial to the ITS because it allows the tutor to provide adaptive customized feedback to each student. The current implementation of the BWT uses a simple knowledge tracing algorithm to track student progress and provide some level of adaptive feedback to the student [5]. This can be improved in several ways in the future. Because of the small number of different levels dealt with when teaching alphabet characters, and because of the small amount of feedback available to the tutor from the student, a stereotype approach [9] is one possibility for enhancing the student model in the future.

FIELD TESTING

The BWT has already been introduced in three different countries across the globe, and in each location we first built a partnership with a local institution. In Qatar, we partnered with the Al-Noor Institute, a school for the visually impaired, opened under the support of Her Highness Sheikha Mozah Bint Nasser Al Missned. The school offers many programs and facilities that serve the needs of visually impaired children in Qatar. The main goal of this field study at the Al-Noor Institute was to examine the relevance of the BWT to visually impaired individuals in Qatar and identify how we can enhance the BWT to better meet the needs of the visually impaired. We had several site visits and conducted a number of discussions with teachers at the Institute to identify several ways in which the BWT can be enhanced.

The field work in India was facilitated through a three-way partnership between Carnegie Mellon University (CMU), Microsoft Research India (MSRI), and the Mathru School for the Blind. Students from CMU, through a ten-week internship with MSRI, conducted a needs assessment and explored a variety of options for developing technology solutions to enhance education for the visually impaired. Furthermore, the students tested improvements and additions to the new version of the BWT by conducting field tests at the Mathru School, which was also the location where the first version of the BWT was tested.

The partnership with the Sefula School for the Visually Impaired in Mongu, Zambia was facilitated through the non-profit organization ProjectEducate. Over the space of two and a half weeks, a team of three researchers visited the Sefula School to setup the BWT, collect feedback and train the teachers to use the device, with the goal of launching a longer term research study that would be conducted by the teachers.

Preliminary Results and Observations

We had many discussions with teachers during the various site visits at each of the aforementioned blind schools, and many of the teachers were able to provide useful observations and feedback about their experience in using the BWT. Some of the feedback was specific to each location but some aspects were common to all locations. Most of the feedback we received was very positive and many of the teachers were excited about using the BWT at their schools.

However, the teachers also pointed out some areas for improvement. The lack of support for Arabic braille was seen as an obstacle for adopting the use of the BWT at the Al-Noor Institute in Qatar. This has since been remedied and the BWT now supports instruction in several languages including English, Arabic, Chinese, and French. Users from both the Al-Noor Institute and the Sefula School pointed out that the buttons on the BWT were too hard and uncomfortable to use for long durations. Some users suggested using buttons with a softer surface texture while others recommended elevating the buttons further from the circuit board. Teachers at all the schools mentioned that younger students had major problems in grasping the 6-dot braille concept and hence the 6 dot buttons on the BWT were very popular, but the teachers would like to see more cells represented as buttons in future versions of the BWT. Users in all three locations reported difficulties in using the stylus with some of the BWT devices. We found that these issues were related to specific devices due to bad alignment during assembly. We also discovered that particular types of stylus worked much better with the BWT than others. The teachers at the Sefula School pointed out that it might be difficult for students learning to write braille on the BWT device to transition to using a slate and stylus because, unlike the slate and stylus, the BWT has individual holes for each dot in a slate cell. We plan to make the slate-like cell components of the BWT more similar to the actual slates in future versions. Some of the sighted teachers at the Sefula School also requested more visual feedback to help them while instructing students. We are currently working on improving the visual feedback of the BWT for sighted teachers. Contacts in all three locations had some difficulty in understanding the accent of the synthesized voice used by default on the BWT so we had to customize the voice feedback with recorded teacher voices. Finally, many teachers were interested in additional modes for learning numbers and contractions. This feedback will be incorporated into future versions of the tutor.

To ascertain the effectiveness of the BWT in helping younger students to grasp the basic concept of the 6-dot braille cell, we conducted a field test on a group of 9 students from grades 1 and 2 at the Mathru School. A control group of 9 students was also set up and this group was not exposed to the BWT. The field test was conducted over the course of 5 weeks. Braille instruction was provided 3 times a week in blocks of 2 hour sessions. Prior to the field test, the teachers were trained on how to operate the BWT effectively. Initially each student was administered a pre-test to get an initial estimation of their knowledge of braille. The pre-test included 6 different elements where the student was asked to do the following (the student was only asked to move to the next step if they successfully completed the previous step):

1. Identify all 6 dots in a marble board in the shape of a braille cell.
2. Recite the dot patterns of all the letters.
3. Make each letter combination using the marble board.
4. Press all 6 dots in a braille cell using a stylus.
5. Make the letter combinations using a slate and stylus.
6. Write a set of 10 words based on Mathru's current spelling lesson of the week.

After the completion of 5 weeks of field testing all of the students were administered a post-test which was equivalent to the pre-test. Each of the 9 students in the test group showed noticeable improvement and understood the 6-dot concept. This is in contrast to the control group that had only 4 students with noticeable improvement. The teachers stated that they were able to identify the concepts that were troubling students in the test group, using the BWT, but were unable to identify problems with students in the control group. This shows the troubleshooting aspect of the BWT which can have a significant impact in learning because teachers can focus on specific skills for children. For example, one of the students was struggling with the 6-dot concept. Before using the BWT, the student was unable to identify all 6 dots consistently and the teachers did not know why the student was struggling. After working with the BWT, the teacher realized that the student did not know how to find dot 1. He would arbitrarily choose any of the dots and consider it to be dot 1. After troubleshooting and helping the student learn the concept of dot 1, the student was able to correctly identify dots 2 through 6.

Students preferred to use the BWT compared to the slate and stylus because it allowed them to write letters using the buttons, which is a lot easier than using the stylus. The teachers had to explain to the students that even while using the BWT, the students would eventually have to learn to use the stylus. Students enjoyed receiving the audio feedback from the BWT. The students claimed that they were comfortable with the American English accent but would often remember only the last thing that was said. For example, when the BWT prompted the student to press dots 1, 4, and 5, the student would press dot 5. After additional practice, the student learned to concentrate more and answer the question correctly. Also, students had memorized the dot patterns for the entire alphabet and could recite the whole patterns from A to Z. However, they would often encounter problems when asked for the pattern of a random letter. The BWT was able to identify this problem quickly.

Figure 3: Students and teachers at Mathru School (above) and teachers at Sefula School (below) using the BWT

Enhancements Based on Field Tests

Based on feedback from teachers at the Al-Noor Institute, we decided to enhance the BWT by adding support for basic Arabic braille characters, and improving the surface of the 6 buttons to allow long-duration use of the BWT. The addition of support for Arabic braille involved creating a new character set and modifying the tutoring code to handle the new character set. This has greatly increased the relevance of the BWT in Arabic speaking communities like Qatar. For the second enhancement we used a soft plastic sticker that is easily available in bookstores in Qatar at a very low cost (less than 1 Qatari riyal) to pad each button on the BWT. These stickers are flat at the bottom and rounded at the top and their texture is much softer and hence more comfortable compared to the current texture of the 6 buttons.

During the field tests conducted at the Mathru School, a hinged back plate was added to the BWT below the braille cells. This allowed students to insert paper into the BWT and get a hard copy of what was written, in addition to the audio response on the computer. They were then able to practice reading and writing simultaneously. The teachers welcomed the new feature as it provided them with a way to carry out combined reading and writing exercises. However, additional testing needs to be performed to see if this feature can help in learning to read braille. We also discovered that using a particular stylus already available at the Mathru School alleviated many of the difficulties that students had in using the BWT by making it easier to insert and remove the stylus in the braille cells. Additionally, a new feature was added to the software to read aloud the entered text when using the free spelling mode. The reading feature was essential when a student wanted to know what he/she had just written. We also added a feature to delete the last entered character, which was necessary to delete a character that was entered by mistake. Also, questions are now repeated when a student enters the wrong answer. All of these features help to enhance students' learning experience.

In all three locations, we were able to replace the synthesized voice with the recordings of the teachers at each school to provide a local accent that will be easier for the students to understand. At the Sefula School, since the teachers were also being introduced to computers for the first time, there was additional training required and there was some debugging necessary to get the sound working on all the computers. We also had one case where one of the teachers was having difficulty using the device because his fingers were reaching through the small slit in the plastic dust cover and touching the solder joints on the circuit board. This problem was easily addressed by placing tape over the slit.

Observations and Discussion

Each student who worked with the BWT at the Mathru School was given a series of statements that he/she had to agree or disagree with. These statements comprised of: (1) I want to continue with the BWT, (2) The BWT is like a game, and (3) I like using the regular slate and stylus better than the BWT. 22 students were tested on the BWT at the Mathru School and all of them agreed with (1) and disagreed with (3). 8 users agreed with (2). The answers were given by students but some of the questions and answers may have been lost in translation with the younger students. Also, many of these students often give answers they think the interviewer wants to hear. However, even if those biases exist, observations during the study showed that students enjoyed using the BWT. Students especially enjoyed the 6-button feature and the audio feedback. Future field tests will show if the increased enthusiasm for learning braille can be sustained after the novelty of using the BWT for the first time has passed.

Since the BWT needs to be connected to a computer to function, there were many additional roadblocks that we faced when introducing the device to the Sefula School in Mongu, Zambia. In addition to helping transport and setup the new computers at the school, we had to provide basic training on computer use and maintenance in order to make it possible for the school to continue to use the devices after our departure. Given that there is no direct interaction with the computer when using the device, this seems like unnecessary overhead, and we are now looking into options for making the BWT a standalone device. In the short time that we were in Mongu, and despite not interacting with any students directly, we were able to get a lot of useful feedback and many ideas for future improvements to the BWT. We hope that the data we gather from future work there will provide a clearer picture of the effectiveness of the BWT in this setting. Overall, we have received very positive initial feedback from all of our partners and we hope to continue to improve the BWT based on results of future field testing.

FUN-FACTOR

Educational computer games have been gaining rapid acclaim as motivational tools for children and youth [10]. They can assist people, expand concepts, and teach learners certain subjects as they play. Formally, one can think of games as a systematic study of the relationship between rules, choices and outcomes in competitive situations [11]. Despite the large number of existing educational computer games, we did not discover any such games that are catered to motivate blind and visually impaired individuals to learn or practice writing braille. Hence, we developed several educational computer games to fill this need.

We collected ideas from teachers at three partner schools to understand the process for learning braille and how it would impact the development of educational games for the BWT. For example, it was evident at one of the schools that many students struggled with writing braille, but even older students who understood the concepts of braille often made many mistakes and their speed of writing braille was very slow. Further observations revealed that many of the students lacked adequate practice and never became fully comfortable with braille writing.

Writing braille is essential for a blind student to take notes and participate in written exams. Textbooks in braille are not available for all subjects and are often much more expensive and inaccessible compared to typical printed books. Hence, in low-resource communities teachers dictate notes for most subjects and students have to take notes quickly and accurately. Students then use these notes as reference material to prepare for their exams. If a student does not have a solid foundation in braille writing it is hard for them to keep up with teachers and study for exams. Also in the higher standards, teacher's lessons are focused on getting students ready for state board exams and they do not have time to reinforce braille writing. Practicing writing braille is necessary to develop speed and accuracy. Adding educational games to the braille tutor would encourage students to learn and have fun simultaneously.

Before implementing any games we needed to observe and discuss the existing steps of how students learn to write braille. We learned that there were 3 significant steps involved in learning to write braille. First, a student needs to understand the 6-dot concept. Second, a student needs to learn the dot patterns for each braille symbol. Finally, the student has to gain comfort using the stylus and gain control and confidence while indenting the correct dots. The previous version of the BWT had curriculum to teach all of these steps to students but no educational games that would reinforce these steps with students.

Our primary motivation for incorporating games into the tutor was that games would provide extra incentive to practice braille writing. We were also interested in testing whether material from other subjects could be incorporated into games so multiple subjects could be reinforced at the same time. We also hoped that by incorporating other subjects, students in higher grades would be interested in playing games which would lead to an increase in braille writing practice. Sample educational games we have designed for the BWT are discussed below. We had the opportunity to test some prototype games with students at one of our partner schools.

Animal Game Developed in India

Teachers at our partner school in India informed us that many of the younger students enjoyed learning about animals. Based on that feedback we created a game that would make students identify and spell the name of an animal that made the distinct sound that they heard through the computer. The game was created to help improve spelling and braille writing. We also wanted to test whether we could expand the scope of the BWT to teach subjects beyond braille. The animal game was created only to identify animals, but if tests were successful other similar games could be incorporated such as identifying historical speeches. The game was created as a separate mode on the BWT. Using the knowledge tracer the game would identify the level of the student. Based on the level of the student the software would pick an animal name out of a set library of animal names categorized by the length of the animal name. By default the game would start with animals which have names that are 3 letters long. Once an animal sound was played, students were prompted to spell the name of the animal. A student was allowed 3 mistakes, with the sound replaying after each mistake, before the answer was revealed. Once the answer was revealed, students were asked to spell the name of the animal. The student's progress is tracked and the software can help the student to practice letter combinations if they make repeated mistakes on the same letter.

Hangman-Inspired Game Developed in India

Another goal when developing these games was to increase the number of older students using the BWT. To accomplish this goal we decided to create a hangman-inspired game [13] for the BWT. Not only would this game emphasize spelling but would also help students to remember patterns of individual letters and logically think about general trends found in English words. We also hoped that by playing hangman students would be introduced to new words and this would help them expand their vocabulary. The hangman game emulated the traditional word game where a student must guess letters in a word until they can figure out the complete word. The software was also linked to the knowledge tracer software and selected a word length based on a student's level. The software would inform the student of the number of letters and ask students to guess a letter. After each guess the word was revealed, with dashes and letters based on whether the students had guessed the letter or not. Following 7 mistakes the student was allowed one final guess to spell the entire word.

Feedback on Games in India

In India we had the opportunity to test the animal and hangman games with children at our partner school which provided us with valuable feedback. We tested 13 students from grades 4 through 10 on these 2 games. This age group was selected because the games assumed that the players had an intermediate level of vocabulary. Students were tested individually and were first taught the rules of the games. We then played a couple of game sets, explaining our reasoning as we progressed in the game so that the student would become familiar with the game. Then we allowed the student to play the game and provided help only if needed.

All of the students that were tested with the games reported that they enjoyed playing them. The games reinforced braille letter writing and helped students to think in English. They helped students to recall spelling and forced them to think of trends in vocabulary. The teachers wanted to play the games as well and 3 of them played both games. Preliminary tests showed that many students have an extremely slow pace of braille writing and games such as hangman can help them improve their writing speed. The students loved hearing the animal sounds and 10 out of 13 students preferred the animal game to hangman. The animal game showed that games can be used to incorporate tutoring of other subjects. The game had some unfamiliar animal sounds, such as those made by a hyena, which the students were able to reproduce after playing the game. Moreover, such games could expand the relevance of the tutor to older users.

Dominos-Inspired Game Developed in Qatar

The Arabic braille alphabet consists of 28 letters; each represented by a unique subset of the 6 dots embossed. The construction of domino tiles is very similar to the braille letters where letters are formed using 6 dots placed in a cell of two columns and three rows; the positions of the 6 dots are universally numbered from 1 to 6 and a subset of these 6 dots is embossed to represent each letter. Therefore, we structured a game inspired by the domino game's rules to motivate students learning the corresponding dot mapping for each character in Arabic braille. A key component in this game is entering braille letters that can match a single letter from both ends. That is, if a player is assigned the "left side" he/she must pick a letter where its corresponding dots in the 2nd column match the dots in the first column of the letter chosen by the computer. Using this concept can expand the student's ability to remember different characters in braille while enjoying the game. The computer has two forms of outputs to the players: graphics on the screen for debugging and demonstrating to sighted people, and sound. The player's input is accomplished through the input device of the braille writing tutor. The rules are as follows:

- *Number of players:* Two (taking turns using the BWT)
- *The deck:* the 28 letters of the Arabic braille alphabet
- *Game:* the computer randomly picks a letter from the deck and announces the letter verbally. The computer also announces whose turn it is (that is player 1 or player 2) and which side (left or right) should be attempted for matching the announced letter. The assigned player then tries to find the "heaviest" letter (the letter with the most embossed dots) to match the assigned side of the announced letter. In the next round, the second player is chosen to do the same activity to match the next announced letter on a side (left or right) randomly selected by the computer. Players are alternated sequentially. The challenge is competing against each other to match the heaviest letter within the constraints and the allotted time. There are 28 rounds, and after each round the program announces the sum of the total dots gained by each player from the rounds played. If the player enters an invalid character then he/she will get zero points. The winner is declared at the end based on the highest score.

This Dominos game was inspired by the popularity of the regular Dominos game among students in Qatar. The game has been implemented and is currently being evaluated in partnership with the Al-Noor Institute.

Initial Game Feedback from Zambia

During our meetings in Zambia, teachers at the Sefula School were enthusiastic about the BWT itself but were especially interested in incorporating games because they thought the students would respond well to them. They were particularly interested in games that would use music because there is a big emphasis on music at the Sefula School. The teachers allowed us to record some of them playing musical instruments and singing to be used in games developed for their use in the future. They suggested the students would respond positively to a song as a reward for their performance in a game and also suggested different musical tones could be used to indicate which dot in the braille cell the student pressed. There were also suggestions to provide a "score" that gave the student an idea of what their progress was as they used the device. The teachers' feedback gave us new ideas for games that could be developed in the future.

CONCLUSIONS AND FUTURE WORK

Braille literacy is an important skill that significantly enhances the opportunities for visually impaired individuals to play a meaningful role in modern society. Our research advances the state-of-the-art in assistive technology for the blind by enhancing a low-cost automated tutor designed to teach braille writing skills to children. The outcome of this work is an enhanced low-cost tool for increasing braille literacy in visually impaired communities around the world. Future work includes designing additional games and musical elements to the BWT, extending the field testing to different locations and for longer durations, adding other languages and mathematic capabilities, and making the BWT a stand-alone device that does not require connection to an external computer.

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