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Usability Engineering of a Tangible User Interface Application for Visually Impaired Children

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Abstract

Educational applications provide engaging learning experiences particularly for children, but their visual nature limits their usefulness and accessibility for the visually impaired (VI). By utilizing physical objects in the interactions, tangible user interfaces (TUIs) could make educational applications more accessible for VI children. Fully understanding the specific needs of users and involving them in the system design and testing are necessary for developing usability and accessibility guidelines to improve the overall user experience for such applications. This paper reports on the user-centered design process for an innovative, engaging TUI-based educational application for VI children, wherein several gamification elements were included to enhance the user experience and increase engagement. An evaluation was also conducted over two iterations to assess the TUI application's usability quantitatively and qualitatively. The results of the evaluation sessions generated several design recommendations and guidelines to enhance educational TUI-based applications for VI children.

Keywords

Tangible User Interface, Visual Impairment, User-Centered Design, Education, Assistive Technologies

1. Introduction

According to recent estimates by the World Health Organization [1], 2.2 billion people worldwide suffer from vision impairments. In Saudi Arabia, about 1 million people are visually impaired (VI). Therefore, providing adequate education facilities for the VI is a major concern. While there are a few schools exclusively focused on VI children, similar to other countries, the current trend in Saudi Arabia has been to mainstream VI students into regular schools where they receive special education classes with dedicated teachers [2]. Nonetheless, VI children require learning to be adapted to their unique needs; for example, teaching VI children usually requires the teacher to pay continuous attention and give regular feedback, which takes time and effort.

While many fun and engaging educational applications have been developed to reinforce the concepts

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learned in class for sighted students, their visual nature limits their usefulness for VI children as VI learners rely on touch and manipulation of objects to develop conceptual understanding. This particular learning requirement could be addressed using tangible user interfaces (TUI), which allow users to manipulate physical objects mapped to computer systems, thereby overcoming any graphical user interface (GUI) deficiencies. Consequently, there have been several TUI-based educational applications developed for the VI for different purposes and ages [3–6] in recent years, most of which have been found to be effective in enhancing learning.

This research proposes a TUI-based application for VI children as well as design recommendations and usability guidelines to enhance educational interactive system user experiences for VI children. First, a local needs assessment was conducted [7] by observing the educational environments and interviewing special education teachers to identify the VI challenges when using educational tools and applications. A TUI-based application for VI children was then developed by employing well-known practices of designing for children with special needs to meet the identified requirements. The usability of the system was then evaluated in two iterations, with the first prototype evaluated by a special education teacher and the second prototype assessed by VI students at a local school to investigate efficiency, effectiveness, and user satisfaction. Learnability as captured by a learning curve revealed usability improvements after repeated trials.

The rest of this paper is organized as follows: Section 2 gives an overview of the related work; Section 3 details the design of the educational TUI-based application; Section 4 presents the evaluation process and results; Section 5 discusses the results and derives design decisions, limitations, and possible future work directions; Section 6 presents the conclusion.

2. Related Work

This section first presents a review of the existing TUI-based educational applications for VI children, and then reviews some usability evaluation methods involving children.

2.1 TUI-based Educational Applications for VI Children

2.1.1 Applications to learn Braille

Jafri [8] proposed a low-cost software solution for the teaching of Braille to VI children, which required the manipulation of near-field communication tag-embedded blocks with embossed Braille letters on their side and audio feedback. The blocks were found to have made the learning effortless and encouraged collaborative activities. Bintaleb and Al Saaed [9] designed an interactive tactile Braille keypad to help blind children learn Arabic Braille letters and numbers, with the pilot usability evaluation on three blind children indicating learning improvements. Recently, Gadiraju et al. [5] introduced BrailleBlocks, a system that included a set of interactive games to help VI children learn and practice Braille together with a sighted person. Using the system, the VI children assemble Braille letters and words and receive audio and multimedia feedback. Sighted parents and teachers can also use a GUI to play with and learn Braille together with VI children.

2.1.2 Applications to learn geometry and shapes

Manshad et al. [10] introduced trackable interactive multimodal manipulatives, which are marked programmable objects that can be moved by users on an interactive tabletop, to enable VI children to learn geometry concepts independently. To teach VI children tactual shape perception and spatial awareness concepts, Jafri et al. [3] presented a TUI-based spatial application that utilized tagged 3D-printed custom geometric shapes and provided audio instructions and feedback. The evaluation of the system with teachers of VI children validated its potential and provided valuable insights into design considerations for such systems. Adusei and Lee [11] developed Clicks, a digital manipulative to simplify the learning of geometric concepts and. It consisted of a construction kit with basic geometric shapes that snapped together to produce more complex shapes. These objects were then placed on a tablet to identify their shape and provide audio feedback. Lozano et al. [6] designed “Touch&Learn,” a TUI-based system to teach basic concepts such as Braille numbers, shapes, and textures to VI children, wherein the system interactions were based on speech recognition, touch, and sound.

2.1.3 Applications to learn mathematics and arithmetic operations

Breiter et al. [12] evaluated the usability of the AutOMathic Blocks System, which allowed VI students to solve arithmetic problems using blocks embossed with Braille numbers and operators with barcodes. The selected block was identified using a barcode reader, and the student placed the block on a touch-sensitive tablet. The system was evaluated with both sighted and blind students, and both groups were found to have preferred two-dimensional math problem representations rather than linear presentations. Avila-Soto et al. [13] proposed the TanMath system for teaching VI students basic math operations utilizing tangible numbers; computer vision techniques were employed to identify the numbers while providing auditory feedback. To identify the TanMath requirements, interviews were conducted with VI educators, with a Wizard-of-Oz evaluation technique employed with one VI student. Pires et al. [4] conducted participatory sessions with VI children and their educators as a preliminary step to developing a TUI system that used tangible blocks of different sizes and colors for the numbers 1 to 5 and gave auditory feedback, which allowed VI children to solve addition or subtraction problems and interact with the system.

2.2 Usability Evaluations with VI Children

Brule et al. [14] reviewed a corpus of 178 papers on quantitative empirical VI technology evaluations and found that the design and conduct of such evaluations remain a challenge especially for VI children. Based on experience in working with VI children for several years, Raisamo et al. [15] assessed the usability of multimodal applications with VI children using questionnaires, interviews, exploratory usability testing, child tutoring of the parent about the system, and various observation methods that had been refined to suit the VI children; they found that conducting evaluations in familiar environments for the children, such as school, elicited more comments and suggestions. Darin et al. [16] sought to identify the most suitable usability evaluation methods (UEMs) for discovering interface usability design problems for a blind audience by conducting evaluation sessions using different UEMs; it was found that observation through video recording could identify majority of the usability problems, and that the questionnaire was the least useful method.

Xu [17] investigated the problems with the existing TUI evaluation methods for non-VI children and sought to identify the most suitable methods for non-VI children using an RFID puzzle game prototype on the life of the Romans. The author found that the think aloud (TA) method was a little difficult to apply as it required prompting the children to talk, that peer tutoring (PT) was easily understood—requiring little evaluator intervention—that the drawing intervention (DI) method revealed information about the TUIs not acquired from the traditional methods but further validation was needed, and that observation methods (videotaping and note taking) were important. Like Raisamo et al. [15], Xu [17] found that children felt more comfortable and focused in a school environment compared to a lab.

2.3 Summary and Discussion

Table 1 summarizes some of the existing TUI-based educational applications for VI children. Previous studies found that there are several challenges in designing attractive and usable TUI-based applications for VI children. For example, software designers are required to design both physical and interrelated digital operations instead of only the digital found in traditional GUI-based applications, and they also need to consider the special needs of the target users (VI children). To achieve this, a user-centered design (UCD) approach is needed with the VI children as design partners.

Table 1. TUI-based educational applications for VI children

Study	Year	Learning objective	Proposed system
Breiter et al. [12]	2012	Arithmetic problems	AutOMathic; blocks embossed with Braille numbers and operators with barcodes attached to them
Manshad et al. [10]	2012	Geometry concepts	Trackable Interactive Multimodal Manipulatives (TIMMs); marked programmable objects on an interactive tabletop
Jafri [8]	2014	Braille letters	NFC tag-embedded blocks with audio feedback
Jafri et al. [3]	2017	Tactual shape perception and spatial awareness concepts	Application based on tagged custom 3D-printed geometric shapes with audio instructions and feedback
Adusei and Lee [11]	2017	Geometry concepts	Clicks; a construction kit with basic geometric shapes that snap together to produce more complex geometrical shapes, placed on a tablet
Avila-Soto et al. [13]	2017	Basic math operations	TanMath; a concept of a system utilizing tangible numbers and computer vision techniques to identify numbers
Lozano et al [6]	2018	Braille numbers, different shapes and textures	TUI-based system based on speech recognition, touch, and sound
Pires et al. [4]	2019	Simple math problems and additive composition tasks	Tangible blocks of different sizes and colors representing numbers 1 to 5 and giving auditory feedback
Bintaleb and Al Saeed [9]	2020	Arabic Braille letters and numbers	Interactive tactile Braille keypad using an Arduino connected to a website
Gadiraju et al. [5]	2020	Braille letters and words	BrailleBlocks; a set of interactive games with audio and multimedia feedback

Evaluating the developed software with potential users is important in determining their perceptions of the system and the possible usability issues. Nevertheless, TUI-based application usability evaluations are difficult for several reasons, particularly with VI children. First, the unique and distinct TUI-based application interface requires adjustments to the current evaluation methods to ensure proper evaluation of the application properties. Second, evaluation methods for children are different from those for adults as they need to focus more on observation to capture signs of engagement. Third, the evaluation methods must be compatible with the capabilities of the VI children evaluating the TUI-based application. The studies discussed in Section 2.2 identified some of the most appropriate evaluation methods and processes for assessing certain applications with children, with almost all previous studies emphasizing the importance of an iterative system evaluation approach to reveal the usability issues and acquiring valuable input from the actual system users.

3. User-Centered Design of the TUI Application

In this study, a UCD approach involving VI children throughout the system development lifecycle, as detailed in the following sections, was adopted:

3.1 Context and Requirements

The Saudi Arabian education system generally encourages VI students to be mainstreamed in regular schools with sighted students and to receive special education programs from dedicated teachers. This paper extends the requirements elicitation study reported in [7], with the additional user requirements identified through field observations at a local inclusive Saudi Arabian elementary school offering special education classes for VI students. Three sessions for teaching reading, writing, and mathematics to four VI first grade students (one blind and three with some residual vision) were observed, followed by semi-structured interviews with three special education teachers for grades one to three at the same school. The interviews focused on the needs of the VI students, the challenges faced by the teachers and them, and the design recommendations particular to a TUI educational system. The study revealed the extensive use of tangible materials to support the learning process; although the interviewed teachers realized the value of educational computer-based software for improving the learning environment, the study revealed the absence of any computer-based assistive technologies in the class. Mathematics was found to be the most appropriate subject area for a TUI-based application for VI students to use individually and/or collaboratively in class. Based on the observed materials and the teachers' feedback, several tangible object characteristics, such as the materials, shapes, sizes, and colors of the objects, were identified. Furthermore, the importance of games and teamwork to keep the students engaged and competitive and the need for repetition to allow them to grasp and memorize the concepts were established.

Based on these requirements, a TUI-based application called Practice Math with Braille Blocks (PMBB) was designed for elementary school VI students to practice mathematical concepts.

3.2 System Overview

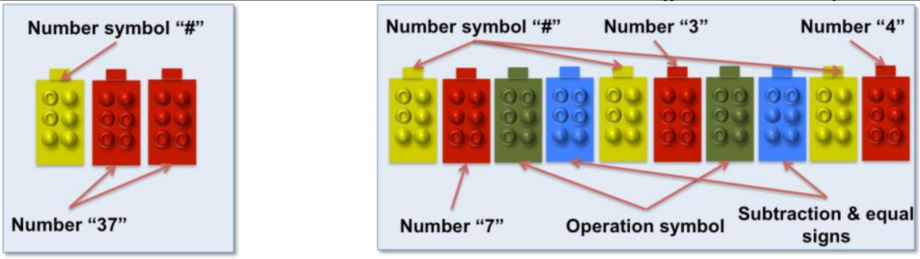
PMBB is a TUI-based educational application to practice mathematical operations such as addition, subtraction, multiplication, and division designed for VI children from 4 to 12 years old (preschool to 6th grade) who know the Braille number system and understand spoken Arabic. The application design includes gamification elements such as themes, collaboration, levels, and points to motivate and engage the students. Two game themes were developed, wherein the students achieve progress by correctly solving math problems: (1) baking a cake, which requires the student to gather cake ingredients and (2) getting ready for bed, which requires students to help a virtual character perform the steps to get ready for bed. The PMBB has two play modes wherein different types of points can be gained: (1) a single mode for a single player to earn individual "performance points" and (2) a collaborative mode wherein players can log in together and earn "collaborative points."

The student interacts with the system by placing blocks on a transparent plexiglass tabletop that identifies each block from a tag affixed to its base. The system provides audio instructions and feedback as follows. The student logs in to his/her account by placing the account block with his/her name on it on the tabletop. He/she selects a theme by placing a theme block, the system asks some questions based on the difficulty level assigned to the student. Currently, two levels are supported: a beginner level, wherein the student has to represent numbers (Fig. 1(a)); and an advanced level, wherein he/she has to do addition, subtraction, multiplication, and division problems (Fig. 1(b)).

The system validates the placed objects, gives audio feedback, and calculates the earned points. Upon successfully completing a level, students access to the next one. The student can log out of the system at any time by placing an account block on the tabletop. The PMBB keeps a record of the name, the assigned difficulty level and the "performance" and "collaborative" points of each student.

The instructions and feedback were designed to motivate the children to continue, for which a real female child's voice was used rather than a synthetic voice. Placing a block on the tabletop triggers different sound effects that indicate correct or incorrect input. As the system was to be tested with students in local schools, the speech output was in Arabic.

The system also has a visual screen-based interface for the teachers to interact with using a keyboard and a mouse, through which the teacher can add, modify, or delete a student account, assign difficulty levels, and retrieve performance reports for each student for any given period or for any specific difficulty level.

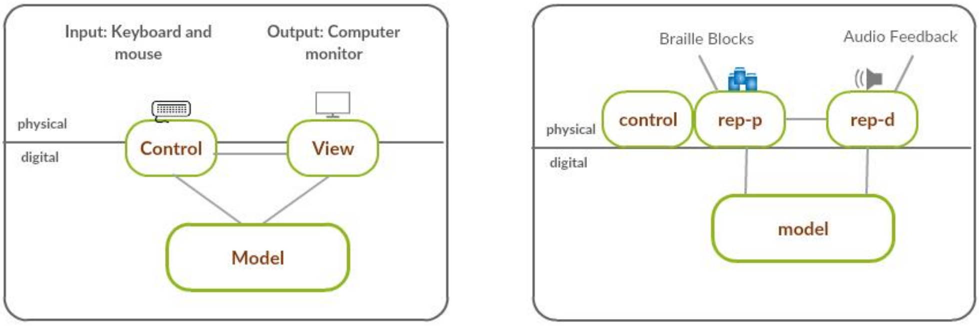


(a) (b)

Fig. 1. Representations using Braille blocks: (a) number "37" and (b) representation of the equation "7 – 3 = 4."

3.3 Interaction Design

As the application has two different interfaces, two different interaction models are used to represent the interactions: (1) a model-view-control (MVC) architecture that implements the application for the teacher, as shown in Fig. 2(a) and (2) a model-control-representation (physical and digital) (MCRpd) introduced in [18] and used as the interaction model for the TUI-based subsystem as shown in Fig. 2(b). Derived from the MVC model, this preserves the model and control components but divides the view component into two representation components: (i) a physical representation (rep-p), which is the tangible representation of information and (ii) a digital representation (rep-d) such as video or sound. In Fig. 2, rep-p is integrated with the control, which shows the direct effect of manipulating the physical representation on the control element, and is also coupled with the rep-d and the model.



(a) (b)

Fig. 2. PMBB Interaction models: (a) MVC architecture for the Teacher app and (b) MCRpd architecture for the Student TUI.

The hardware components are as follows:

1. An 11.8 × 22.4-inch plexiglass top attached to a table using C clamps.
2. A Logitech webcam connected to the computer using USB cable to capture live video stream from underneath the plexiglass top and send it to the computer; the distance between the webcam lens and the plexiglass is 18 inches to capture the full plexiglass space.
3. Tangible blocks with identifying tags attached to their bases; a detailed description of these blocks is given in Section 3.4.

The following software components were also considered:

1. ReacTIVision [19]: An open source, cross-platform software providing up to 216 different tags that can be attached to tangible objects; when the objects are placed tag side down on the plexiglass top, the system identifies the tags and determines their positions and orientations from the input

video stream of the webcam placed beneath the top. This data is then sent to the controller (client application) through the TUIO protocol [19].

2. Controller: The client application receives and processes the tangible object data to provide the appropriate feedback.

3.4 Tangible Object Design

Four tangible object types were designed based on the requirements identified in the previous study [7]. (1) Braille blocks are brightly colored rectangular cork blocks with Braille numbers, arithmetic operators, and symbols embossed on the top, with a rectangular marker on the upper lateral edge indicating the upward position of the block. Blocks of the same kind are similarly colored to aid students with residual vision in distinguishing them. (2) Account blocks are beige-colored wooden cubes with the students' names embossed in Braille on the top. (3) Theme blocks are plastic blocks with toy bed and toy cupcake affixed to the top. (4) Confirm and cancel blocks are plastic blocks with foam cancel and confirm cutouts symbols affixed on the top. The different tangible object types were made with different materials to make it easier to distinguish them tactually. The tangible objects are shown along with their characteristics in Table 2.

Table 2. Description of tangible objects

Material	Colors	Represented data	Pictures
Cork	Yellow, red, blue and green	Braille numbers, operations, and symbols	 
Wood	Beige	User names	
Plastic	White, pink and beige	Game themes: "Get ready for bed" and "Bake a cake"	 
Plastic	Red and orange	Confirm and cancel options	 

4. Usability Evaluation of the Proposed System

4.1 Usability Evaluation Model

The ISO 9241-11 standard identifies efficiency, effectiveness, and satisfaction as the major usability attributes. Some studies have proposed usability models that include learnability as an important factor; nonetheless, [20] argued that the new draft (ISO 9241-11:2018) made it clear that usability, as defined in terms of effectiveness, efficiency, and satisfaction, applies to all aspects of use including learnability.

In this study, the evaluation process involved going through the system while assessing the conformance of its design to these usability factors. Table 3 summarizes the evaluation framework. The evaluation was guided by a set of predefined heuristics based on Nielsen's 10 heuristics, which have been widely used for user interface design. Usually, these heuristics are applied to usability inspection methods by expert reviewers at the early design stages, which means that the results can be influenced by the experts' judgments. In this study, however, Nielsen's heuristics were used to guide the usability evaluator who was also the facilitator during the user testing, examine the usability problems, and judge the compliance of the system based on the usability factors. Therefore, to assess the fulfillment of each factor, each heuristic was mapped to the appropriate usability factor and the metrics. The heuristics along with the usability factors and metrics are shown in Table 3. This model was used in the usability evaluations of the two functional prototypes of the PMBB system as detailed in the following sections.

Table 3. Usability evaluation framework for TUI with VI users

Heuristics	Usability factors	Metrics
H1. Visibility of system status: Clarity of instructions for providing user guidance	Effectiveness	Error rates due to misunderstanding audio instructions Requests for help
H2. Match between the system and the real world: Ease of identifying each tangible object and distinguishing among the different objects	Effectiveness	Error rates due to placement of the wrong type of object Requests for help
H3. User control and freedom: Freedom to place the tangible object anywhere on the table and have it recognized	Effectiveness	Error rates due to incorrect recognition of an object
H4. Consistency and standards: Arrangement of the objects in correct order with respect to Braille conventions in writing mathematical equations	Effectiveness	Error rates due to incorrect arrangements
H5. Error prevention: Prevention of a problem from occurring or delaying task completion	Effectiveness	Types of errors preventing task completion Types of errors delaying task completion User responses and comments
H6. Recognition rather than recall: Ease of quickly finding the correct object and placing it correctly	Efficiency	Time elapsed between starting searching for an object and locating it Time spent to place an object correctly
H7. Flexibility and efficiency of use: Efficiency for both inexperienced and experienced users	Efficiency	Time spent to complete each task correctly in different levels
H8. Help users recognize, diagnose, and recover from errors: Responsiveness and clarity of feedback associated with the correct/wrong input of different objects	Effectiveness	Error rates due to misunderstanding audio feedback Requests for help
H9. Aesthetic and minimalist design: (i) Aesthetic and minimalist design of tangible blocks as well as the table. (ii) Non-annoying feedback given during the interaction, shall not contain irrelevant or rarely needed information	Satisfaction	Facial expressions after hearing the feedback User responses and comments
H10. Help and documentation: Continuous assistance and help	Effectiveness	Facial expressions after hearing the feedback Requests for help

4.2 First Prototype Evaluation

An exploratory usability test was conducted with a teacher of VI students, who had also participated in the requirement-gathering interview described in [7]. The teacher had some residual vision and 9 years' work experience teaching first grade students.

4.2.1 Procedure

The session began by briefing the participant on the purpose of the evaluation and the functionalities in the student mode of the system. The participant was then asked to perform the following six principal tasks in student mode: (1) examining the tangible objects before using the system; (2) logging in to the system; (3) selecting a game theme; (4) playing the beginner level; (5) playing the advanced level; and (6) logging out of the system. As the TA protocol was employed, the participants were asked to say their thoughts aloud as they performed the tasks and explain any issues or difficulties they encountered. The data were gathered from the participant's audio recording and automatically logged to keep track of the time spent on each task and the input errors. Observation notes were made on a data collection form to record the information related to the number and type of errors, number and type of assistance requested, and comments for each task in the session.

4.2.2 Results

Tasks 1, 2, 3, and 6 were completed within 2–5 minutes, which was reasonable according to the teacher. Nonetheless, tasks 4 and 5 (completing the beginner and advanced levels) required 20–30 minutes, which the teacher felt was too long. Based on the teacher's comments and our observations, such slow progress was attributed to the usability problems (P) outlined in Table 4, which also includes the corresponding Nielsen's heuristics (H) and the required system modifications (R). The additional requirements and design improvements were implemented to develop the second prototype, which was again evaluated with VI students and is discussed in the subsequent section.

Table 4. Usability problems identified in the pilot usability testing

Usability problems (P)	Heuristics	Design recommendations (R)
P1: Inadequacy of the system feedback, as some errors occurred due to minimal system feedback and imprecise response to errors	**H1:** Visibility of system status	**R1.1:** The system shall repeat the presented math problem in case of no activity for 10 seconds. **R1.2:** The system shall provide verbal instructions as hints to the user when a mistake is made. **R1.3:** The system shall provide more guidance (instructions about the next step) to the user while solving a math problem.
P2: The large number of math problems presented in a theme contributed to the lengthy time spent on the task.	**H7:** Flexibility and efficiency of use	**R2:** The system shall present 5 (instead of 10) math problems to complete a theme for the beginner's level and the advanced level.
P3: Searching through the many number blocks to locate a particular number block took a considerable amount of time, causing the participant to forget the presented problem.	**H6:** Recognition rather than recall	**R3:** To simplify the search for a required block, the tangible blocks shall be grouped and categorized based on how numbers and operations are taught in class.
P4: In an attempt to offer flexibility, the design of the plexiglass top did not include specific placements for the blocks. This approach caused confusion as when to leave a block on the table and when to remove it.	**H5:** Error prevention	**R4:** Specific placements for the account and theme selection blocks should be fixed, so that users are not required to remove them from the table until they have finished playing.

4.3 Second Prototype Evaluation

To evaluate the usability of the tangible interaction of the student mode of the PMBB system, an assessment usability test on the second prototype was conducted with seven female VI students from a public inclusive school in Riyadh. All participants have had experience with mobile devices such as smartphones and IPads, with one participant having had experience using a computer with a Braille keyboard. The types of games they had played on the IPad were coloring games and puzzles; on the computer, the students reported that they had played an educational game that presented questions and for which they had to input answers using the keyboard. Their visual impairment was roughly assessed through their ability to differentiate similar colors (such as green and blue) and identify shapes without touching them. Participants with "good residual vision" are able to identify block shapes and differentiate similarly colored blocks visually. A "poor residual vision" assessment suggested that the participant was unable to separate similarly colored blocks or to recognize the block shape without a tactual examination. Table 5 summarizes the participant demographics.

Table 5. VI participants' demographics

ID	Age	Grade	Impairment level	Electronic devices	Games
7A	7	2nd	High residual vision	iPad	Coloring games
7B	7	2nd	Blind	Mobile	Coloring games
8A	8	3rd	High residual vision	iPad	Coloring games
10A	10	3rd	High residual vision	Mobile & PC	General knowledge games
10B	10	4th	High residual vision	None	None
11A	11	5th	High residual vision	iPad	Coloring games
12A	12	6th	High residual vision	iPad	Coloring games

4.3.1 Procedure

The system was set up inside a school classroom (Fig. 3), and tangible objects were organized based on the teacher's recommendations in the previous evaluation. The webcam was fixed inside the plexiglass table, and a video recorder was placed on a tripod next to the computer monitor to capture the participants' interactions with the system. Individual sessions with each student were conducted in the classroom and were about 45–60 minutes long. A special education teacher was present during the sessions to provide some encouragement to the participants and help answer any questions.

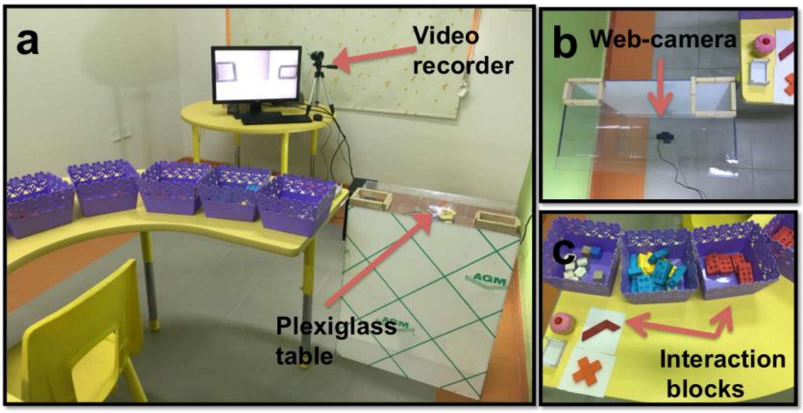


Fig. 3. PMBB system setup in the classroom.

Before starting the session, the evaluation purpose and procedure were explained to and approved by the participating student's parents. The session was then conducted as follows. In the first 10 minutes, the system was explained to the participants, and a brief background interview was conducted to learn about their experiences with technology, the types of educational games they had played, and the difficulties, if any, that they had experienced. The participants were then given 10 minutes to explore the tangible objects and the table space, and they had 30 minutes to perform the tasks. Finally, a post-test interview was conducted in the last 10 minutes to gather information about their preferences, likes and dislikes and to follow up on any problems that may have come up during the session.

The testing involved six main tasks that were individually performed by each participant in the same order: (1) examining the tangible objects and identifying their purpose; (2) logging in to the student account; (3) selecting the game theme; (4) playing the beginner level (which required representing five numbers with the Braille blocks); (5) playing the advanced level (which required representing and solving five math problems); and (6) logging out of the system.

The tasks were designed to assess the usability factors based on the usability evaluation model shown in Table 3. The data were collected through: (1) forms for recording the information related to the number and types of errors, number and types of assistance requests, and comments for each participant for each task in a session; (2) video recordings for capturing the participant's facial expressions; and (3) automatic logger to keep track of the time spent on each task.

4.3.2 Results

The evaluation was conducted using the model presented in Table 3 to map the usability factors and metrics. The results were then organized based on the efficiency, effectiveness, and satisfaction usability factors, and learnability was also assessed to identify the usability enhancement over time.

Efficiency

To assess system efficiency, the completion time of each task was recorded. All participants performed the login, theme selection, and logout tasks in less than a minute. The beginner level task was completed by all participants within the expected time limit of 10 minutes (median = 9 minutes; SD = 0.82 minutes). For the advanced level, two participants required the teacher's assistance to complete the task; for the other five participants, significant variations in completion times were observed based on their age, with the older students (4th–6th grade levels) and the younger students (2nd and 3rd grade levels) taking a mean time of 15 minutes and 29 minutes, respectively, to complete the tasks.

Effectiveness

To measure the effectiveness, the errors that occurred while performing the tasks were recorded along with the system's response. The number and types of errors for both beginner and advanced levels are shown in Table 6. Forgetting to place the preceding "#" block and "code" block before the respective operands and arithmetic operators (as required in the Braille system) was the most common error (50% of the errors in the beginner level, 40.38% of the errors in the advanced level). Confusing numbers and operators was also a common error on both levels.

Additional errors were specific to the advanced level, such as forgetting to place the operator block between the operands. In addition, while solving the math problem during the advanced level, one participant gathered and placed the blocks on the table all at once, causing multiple errors. In this case, the system failed to detect the problem, and the teacher's intervention was required to explain to the participant what had happened and how to avoid it. In the beginner level, the participants were able to recover from the errors by following the instructions provided by the system and to complete the level with fewer errors. In the advanced level, five of the seven participants completed the level by following the system instructions. Nonetheless, participants 8A and 11A required the assistance of the teacher to complete the tasks; this suggests that the sound effects feedback and instructions needed to be revised to better capture the user's attention.

During the evaluation session with the blind participant (7B), the participant placed a block at the edge of the table, and it fell off. This error was not detected by the system as it had already detected the presence and position of the block before it fell off. Therefore, it was decided that a border around the table would prevent such problems from occurring.

The system audio feedback and response to the user inputs were able to guide majority of the participants in completing the tasks independently, with most participants making fewer errors as they progressed through the task.

Table 6. Number and type of errors

ID	Beginner level		Advanced level					
	Forgetting "#" or "code" signs	Confusing number/ operator blocks	Forgetting "#" or "code" signs	Confusing number/ operator blocks	Forgetting operands	Forgetting operators	Wrong calculation	Wrong order of the blocks
7A	1	0	2	2	1	2	1	0
7B	1	0	1	1	0	1	0	0
8A	1	3	3	2	0	2	0	5
10A	1	1	4	2	0	0	0	0
10B	1	1	3	1	0	1	0	0
11A	1	2	4	4	0	0	4	0
12A	1	0	4	1	0	1	0	0

User Satisfaction

After performing the tasks, the sessions ended with an interview to assess the participants' satisfaction. The interview questions covered different aspects of the PMBB system, such as audio feedback (sound effects and instructions) and use context. The user responses were categorized into positive and negative feedback, with the positive feedback being responses that indicated satisfaction (such as like, nice, fun, etc.) and negative feedback being responses that suggested dissatisfaction with an aspect of the PMBB software (such as annoying, confusing, hard, etc.).

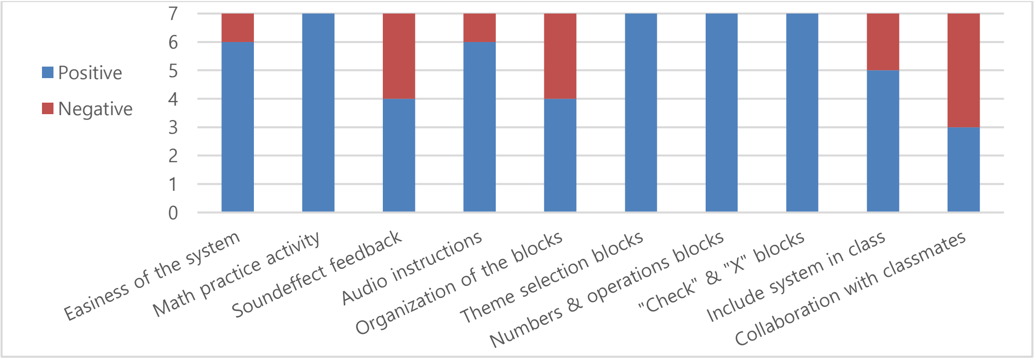


Fig. 4. Number of positive and negative feedback provided by the participants.

Fig. 4 shows that 80% of the responses were positive and 20% were negative. The design of the interaction objects was found to be satisfactory by all participants. Similarly, the responses regarding the math practice activities were all positive, indicating that they had enjoyed the activity. Majority of the participants found the system easy to use and the audio instructions clear and adequate, with five of the seven participants voting in favor of using the system as part of their daily classroom activities. Majority of the negative responses were related to the sound effects, block organization, and use of the system in collaboration with their classmates. Three of the participants described the "incorrect" sound effect as being annoying and startling, one participant thought the audio instructions were unnecessary and indicated that a sound effect would be sufficient feedback, three participants found searching for the desired block among the group of blocks to be difficult, and four students expressed preference to play alone rather than with others or even at home rather than at school.

Learnability

Learnability was examined by studying the learning curve to identify the usability improvements after repeated trials. Both high and low grade participants had good learning curves since they made fewer errors as they progressed through the levels. In the beginner level, the number of errors per trial decreased to zero from the second trial, implying that they had quickly grasped the interaction process. As shown in Fig. 5, however, the decrease in the number of errors was more gradual in the advanced level, indicating that the interaction process was more complex than the beginner level.

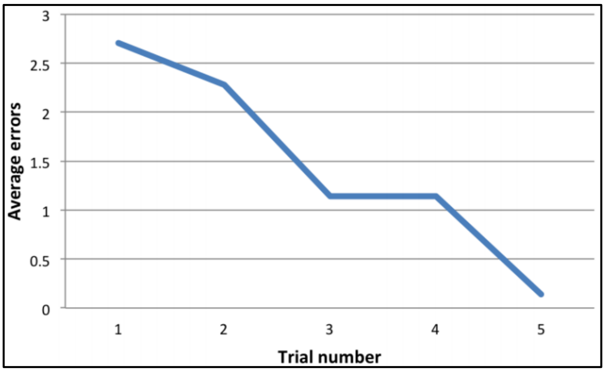


Fig. 5. Average number of errors per trial in the advanced level.

Participants 8A and 11A made the same number of mistakes throughout the task but were able to complete the fifth trial (final math problem presented in the task) following the teacher's instructions. Some participants (7A, 10A, 10B, and 12A) gradually reduced their number of errors per trial, whereas participant 7B was able to reduce the number of errors to zero from the 2nd trial. Nevertheless, they spent 7–10 minutes more to complete the task compared to the other participants. These results reflected the ease of learning and understanding how to use the system for majority of the participants despite the relatively small number of trials.

5. Findings and Discussion

The results of evaluating the PMBB system showed that it was capable of detecting most of the mistakes in representing and solving math problems using Braille blocks. The audio sound effects and instructions allowed the users to represent and solve the given problem correctly. Most participants had good learning curves as they progressed through the levels; thus indicating that learning to use the system was relatively easy. The object design received positive feedback, and there was good user satisfaction overall. Despite the positive evaluation results, which demonstrated that the system was capable of efficiently and effectively providing the required functionalities, further design improvements could enhance the system effectiveness and users' experience.

5.1 Design Recommendations

Further design recommendations were drawn from the gathered data, specifically from the common user errors and negative system feedback. The suggested improvements are detailed in the following paragraphs, and then summarized and mapped to the corresponding Nielsen's heuristics in Table 7.

Table 7. Summary of design recommendations

	Current system design	User feedback	Heuristics	Design recommendations
Feedback	Harsh error sound effect	Startling and annoying	**H9:** Aesthetic and minimalist design	Use a soft sound effect for wrong input
	Audio instructions to correct a wrong input	Noisy, not required		Present the audio instructions only upon user request
Interaction blocks and	4 cm×6 cm rectangular blocks; every two number blocks in one	Difficult and time-consuming to find the	**H6:** Recognition rather than	Design smaller blocks (2 cm×3 cm) and place each block type in one

table	basket and the operator blocks in one basket	desired blocks	recall	basket
	The bottom corners are dedicated for Account and Theme blocks, while the remaining area used for organizing other blocks	When placing the blocks all together,, they are detected by the system before being organized	**H5:** Error prevention	Form a grid on the tabletop for solving math problems and dismiss any block placement outside the dedicated grid
	Plexiglass tabletop without borders	When placed at the edge, the blocks might fall after being detected		Place borders around the plexiglass tabletop to prevent blocks from falling
Game design	The beginner level includes writing Braille numbers of single digit and more	Some similar number and operator blocks were confusing	**H2:** Match between the system and the real world	The beginner level should be divided into several levels focusing on the typically confusing blocks
	Audio feedback is played through speakers	Avoid noise distraction in class		Use headset instead of speakers

5.1.1 System feedback

The quantitative results indicated that the current system's feedback and instructions were effective in guiding the participants in completing the tasks successfully. Still, the qualitative results revealed some dissatisfaction with the audio sound effects and instructions. A few participants found the sound effect that was used for an incorrect input to be annoying and upsetting; therefore, a softer error sound effect could reduce this discomfort. One participant commented that the audio instructions were not needed; this was also observed in the video recordings when some participants realized that they had made mistakes as soon as an error sound effect was played but before listening to the correction instructions. Therefore, to avoid excessive instructions, users could be provided with minimum feedback when they make errors (only the sound effect); if needed, they could request additional instructions using an object (shaped as a question mark) that functions as a "help" option.

5.1.2 Interaction blocks and table

In the sessions, the blocks were organized in baskets wherein every two numbers were placed in one basket (two blocks of each number) and the operation blocks were in another basket (also two blocks of each operation type). Three participants found the search for the needed block to be difficult. Therefore, placing each type of block in a separate basket could simplify the search process; as this would require a larger table space, however, this could be resolved by designing smaller-sized blocks and using smaller containers. When one of the participants gathered the required blocks and placed them all on the plexiglass table at the same time, the system registered multiple errors because it detected the tags and identified the blocks as soon as they were placed on the plexiglass table and before they were organized correctly. To prevent these types of errors, there should be a specific interaction area with borders so that only the blocks placed inside the interaction area are detected. Fig. 6(a) and 6(b) below illustrate the current system tabletop and the recommended redesigned tabletop. This interaction table design enhancement was also recommended in a recently published study on a TUI educational system for VI children [3]. In addition, adding a border around the plexiglass tabletop would prevent the placed blocks from falling off the edge of the table as experienced by the blind participant.

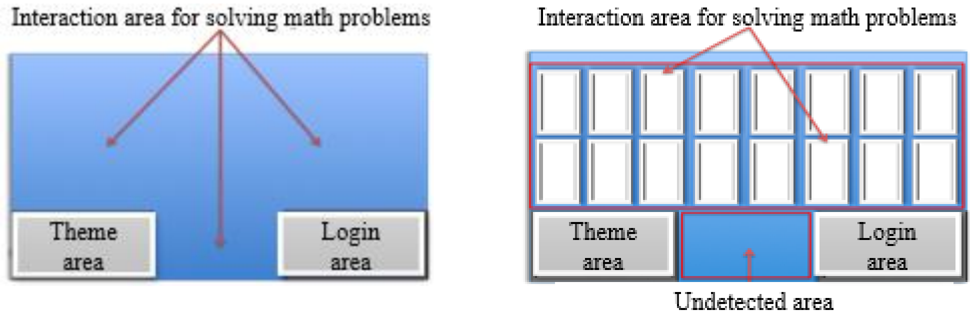


Fig. 6. Tabletop layout: (a) the current system tabletop and (b) the recommended redesigned tabletop.

5.1.3 Game design

As shown in Tables 5 and 6, the second most common mistake in both levels was confusing similar numbers and operation types. To avoid this problem, additional levels that provide practice with similar Braille numbers and arithmetic operators should be added to the game levels. Some participants also preferred using the system at home rather than in the classroom to reduce the distractions in class. Providing a headset with the system could resolve this issue, though.

5.2 Limitations and Future Work

The needs assessment and usability evaluation in this study were conducted in only one inclusive school. Therefore, conducting field observation in more schools and with more VI students could mean more precise specifications that better represent the local VI educational environment. This study also involved only female VI students; therefore, future work should also include inclusive schools for boys to allow for the identification of any gender-specific differences in the system requirements.

The system configuration used to track and identify the physical objects was somewhat complex because of the required settings on the reacTIVision system, such as camera calibration, focus adjustments for the classroom system setup that required the carrying of a heavy plexiglass table, and need to control the classroom illumination to achieve the correct tag identification. Therefore, future exploration of different tracking systems is necessary to compare tracking techniques, configuration complexity, identification and tracking capabilities, and setup expenses.

Despite the positive results of the usability evaluation, additional system enhancements and functionalities are still needed to improve the user experience further. First, the design recommendations elicited from the usability evaluation are to be implemented to reduce user errors and provide greater user control over the system feedback. Second, additional features could be added to the system to increase interactivity and engagement, such as providing rewards for advancing to the more difficult levels and offering a greater number of story themes. Third, applications for other disciplines such as reading and writing in Braille could be designed to expand the educational benefits of the system. Finally, full implementation and evaluation of the functionalities provided for the teacher are important to incorporate the system as an efficient tool for assessing student progress in class. Furthermore, implementing additional features, such as assigning tasks to a particular student or adding difficulty levels other than the predefined levels, could enhance system productivity.

6. Conclusion

This research followed a UCD process to propose, develop, and evaluate a TUI-based system for VI children to practice mathematical problem solving. The component-based system architecture facilitates its future reuse by TUI-based application designers; for example, the reacTIVision system could be conveniently replaced by some other tracking system.

The usability evaluation of the designed TUI-based system revealed the following: (1) the usability evaluation procedure suited the needs and capabilities of VI children and (2) further design modifications were necessary for this kind of applications. These design recommendations are of value to the TUI-based educational application development research field as they could generally be applicable to the design of any interactive applications oriented toward VI children.

This study advances the design and development of TUI-based applications for the education of VI children and contributes to their emancipation and integration into society.

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Author's Contributions

Conceptualization, AA. Investigation and methodology, AA. Project administration, BA, JR. All authors read this paper and approved the submission.

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Competing Interests

The authors declare that they have no competing interests.

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