IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 23 October 2022, accepted 22 November 2022, date of publication 12 December 2022,
date of current version 21 December 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3228455

RESEARCH ARTICLE

Tac-Trace: A Tangible User Interface-Based Solution for Teaching Shape Concepts to Visually Impaired Children

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This research project was supported by a grant from the "Research Center of the Female Scientific and Medical Colleges", Deanship of Scientific Research, King Saud University.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Department of Information Technology, College of Computer and Information Sciences, King Saud University, Saudi Arabia.

ABSTRACT A novel, low-cost, Arabic language tangible user interface (TUI)-based solution for teaching and reinforcing the concepts of planar shapes and their relationships to visually impaired (VI) children is presented. The solution employs a computer vision-based system to track tagged 3D-printed objects which children can manipulate to receive audio instructions and feedback in the context of various activities for learning progressively difficult shape concepts in a systematic manner. A graphical user interface (GUI) is also provided for the teachers to create and manage student accounts, track their students' individual progress and download and print the templates and models of the tangible tokens along with their barcodes. The aim is to provide an engaging, accessible solution that would mitigate the demands on the time, efforts and financial resources of the teachers while allowing children to autonomously learn and review shape concepts at their own pace. By utilizing off-the-shelf components for setting up the TUI and providing templates and CAD models for generating the tangible tokens, we have endeavored to make the system affordable and easily reproducible. The system has been developed in consultation with teachers for VI children to ensure its compliance with current teaching and classroom practices. Initial evaluations of the system with VI children and their teachers have validated its potential and yielded valuable design recommendations which would not only inform the design of future iterations of our system but also benefit other researchers seeking to build similar systems.

INDEX TERMS 3-D printing, assistive technologies, blindness, children, education, geometry, shape perception, tangible user interfaces, teachers, visual impairment.

I. INTRODUCTION

According to the World Health Organization, 2.2 billion people suffer from vision impairments globally with low- and middle-income regions having a higher prevalence of such impairments than higher-income ones [1]. This indicates a critical need to develop low-cost solutions that utilize non-visual modalities to assist visually impaired (VI) people in learning about various concepts, not only to enhance their knowledge but also to facilitate their carrying out their daily living activities. This need is even more pronounced for VI children whose first exposure to several abstract notions is constrained to be primarily via non-visual means.

Learning the characteristic properties of geometrical shapes is essential for VI children since these form the basis of higher levels of cognition, allow the construction of mental space representation vital for everyday tasks and provide background for understanding many

The associate editor coordinating the review of this manuscript and approving it for publication was Eunil Park.

topics in higher mathematics which require spatial thinking [2], [3], [4].

Previous research has shown that verbal descriptions alone are not sufficient to convey visual concepts, especially those of mathematics, to VI children [5] who gain an understanding of the structure and properties of various two-dimensional (2D) and three-dimensional (3D) shapes only through prolonged tactual exploration of physical objects with their hands accompanied by continual feedback in the form of physical and verbal cues from an instructor [4], [6], [7], [8], [9]. This process may have to be repeated several times before an adequate mental representation of the object is formed and reinforced [4]. Once the child learns to tactually recognize various shapes, more advanced concepts are gradually introduced using the same methodology [4].

Despite the proven effectiveness of the above teaching approach, an often-encountered lack of financial resources to purchase or custom-create non-visual educational supplies in classrooms for VI children, along with a scarcity of adequately trained educators [10], makes it difficult to provide the materials and one-on-one interaction required for this mode of instruction. Instructors for VI students generally utilize commercially available sets of geometric shapes (such as flat plastic [11] or wooden shapes [12]) against the backdrop of a plain surface as a staging area for teaching shape concepts – for children with low vision, the objects may be brightly colored for easier distinction [13]. However, since such sets do not usually include irregular shapes (e.g., to teach the concept of a quadrilateral shape, several closed shapes with four sides of various lengths are required), teachers have to custom produce such shapes themselves by cutting them from firm materials (such as cardboard or hard foam) or by pasting textured paper on cardboard [4], [6], thus, rendering the production of such non-visual learning aids time-consuming, labor-intensive and imprecise. Furthermore, the static nature of such manipulatives necessitates constant intervention and validation from the instructor during their use [14]. Many countries, such as the United States, have dealt with the dearth of special education teachers by mainstreaming VI children into public schools [15]. However, teachers in these schools face similar challenges in terms of having neither sufficient time to expend on individual instruction nor adequate funds to acquire or create non-visual aids to teach their VI pupils the above-mentioned concepts [4].

Tangible user interfaces (TUIs) [16], which couple physical objects to digital representations, offer a viable solution for alleviating the demands on the teacher's time and efforts. TUIs have been shown to enhance learning for children by enriching their experience, play and development [17], [18]. Interaction with tangibles encourages engagement, excitement and collaboration [19], promotes discovery and participation [20], improves comprehension [21], makes computation immediate and more accessible [22], and offers a resource for action in addition to an alternative form of data representation [23]. As pointed out in several studies (e.g., [24], [25]), these interfaces appear particularly suitable for learning in abstract problem domains by relating abstract concepts to physical experiences or concrete examples. Since graphical user interfaces (GUIs) traditionally used in educational computer-based solutions have limited or no utility for VI children who mainly rely on touch and hearing for learning geometry concepts [9], TUIs are especially pertinent to their needs as these afford tactual exploration of physical objects while also allowing the interaction to be augmented with other non-visual digital modalities such as audio or haptics.

Despite the benefits of TUIs for VI children's education, the physical interface required for such systems presents a hindrance in disseminating them - even if the software is made available for free, the targeted users may not be motivated to make use of these systems because of the cost and effort required for setting up the hardware components for the tangible interface [4]. However, the advent of increasingly affordable rapid prototyping technologies, such as 3D printing, has made it viable to custom create tangible objects for the TUI conveniently and inexpensively. These objects (which can be customized in terms of shape, size, color, texture and embossed with Braille markers and letters) cost a fraction of the expenses incurred to purchase and/or the time required to manually create equivalent geometric solids with similar customizations in numbers in high proportion to the number of students [4]. Moreover, if an object gets lost or broken, it can be easily replaced by 3D printing it out again [4].

Only a handful of TUI-based solutions for teaching shape and geometry concepts to VI children have been introduced so far. Even though 3D printing has been extensively utilized in recent years to create static manipulatives for teaching VI students about various STEM topics (see [26] for a detailed review), most existing TUI-based systems [27], [28], [29] for teaching shape and geometry concepts to the VI do not appear to have availed of this option for creating TUI components; the few that have done so (e.g., [30] and [31]) do not offer users the facility of downloading CAD models to 3D print the tangible objects themselves. Also, most of these solutions are prototypes for exploratory studies which simply introduce basic concepts but do not allow the child to advance to increasingly complex notions in a systematic manner via tutorials, practice and tests. Furthermore, they do not permit teachers and caregivers to record and track the children's progress; a requirement that is especially important for teachers who are dealing with multiple VI children at any given time. Moreover, none of them offer support for Arabic language essentially precluding their use for VI individuals who primarily rely on Arabic for communication.

We have, therefore, developed a novel, low-cost and accessible Arabic language TUI-based system to teach the concepts of various planar shapes and their relationships to VI children. Our solution employs a computer vision-based system to track the position and orientation of 3D-printed objects with affixed visual tags (barcodes) placed on a transparent surface; children can feel these objects, put them on the surface and receive audio instructions and feedback in the context of various engaging learning activities. Shape concepts are introduced in a progressive manner with increasing levels of difficulty in compliance with current classroom practices; children are allowed to advance to a higher level only after completing lessons, doing hands-on training and passing a test for the current level. The system also provides a GUI for the teachers to create and manage student accounts, track their students' individual progress and download and print the templates and models of the tangible tokens along with their barcodes. Our solution aims to mitigate the demands on the time and efforts of the teachers by enabling VI children to learn and review shape concepts autonomously at their own pace while still allowing teachers to monitor their progress. By utilizing off-the-shelf components for setting up the TUI and providing templates and models for generating the tangible tokens, we have endeavored to make the system affordable and easily reproducible.

It should be noted that we previously conducted an exploratory study for examining the potential of TUIs for teaching tactual shape perception and spatial awareness sub-concepts in small-scale space to VI children [4], [32]. Only a rudimentary prototype was developed for that study which simply exhibited the tangible interaction and asked a few questions to teach tactual shape perception; it was further limited in that it supported only English and did not provide any interface or functions for teachers. The prototype was demoed to teachers for VI children in the USA who received the idea positively and expressed enthusiasm for utilizing such a system in their classrooms. We have now incorporated the invaluable insights and design recommendations generated from that study into our current work; not only have several usability issues observed with the initial prototype been addressed but the rudimentary version has been expanded into a complete educational application that provides functions for both VI children and their teachers as outlined above. Continuing to follow a user-centered approach, we have also gathered further requirements via semi-structured interviews with teachers at local inclusive schools for the VI to ensure that the solution is compliant with current teaching practices in the local context. Whereas in the exploratory study, not only did the nascent nature of the prototype preclude any systematic evaluation with the teachers of VI children but the prototype was also not demoed to or tested with any VI children; however, in the current study, evaluation sessions were conducted at a local school for the blind to test the system with both VI children and their teachers. These initial evaluations have yielded highly favorable results, thus, confirming the system's potential for future research and development.

The rest of the paper is organized as follows: Section 2 provides an overview of existing TUI-based solutions for teaching shape and geometry concepts to VI children highlighting their challenges and limitations. Section 3 expounds upon the requirements collection study conducted with teachers for VI children. Section 4 describes the system design and architecture. Section 5 explains the methodology used to evaluate the system's usability with VI children and their teachers, reports the results of the evaluations and discusses some findings and ensuing design implications for TUI-based systems for VI children. Section 6 concludes the paper and identifies some directions for future work.

II. RELATED WORK

The potential of TUIs has recently begun to be exploited for the VI with some solutions being developed for various contexts and tasks such as creating and playing music [33], [34], enhancing access to museum exhibits [35], desktop access [36], exploring geographic maps [37], [38], [39] and navigation [40].

In recent years, the effectiveness of TUIs for learning abstract concepts, especially for children, coupled with the importance of touch as a sensory substitution modality for the VI, has particularly sparked interest in investigating the use of TUIs for the education of VI children. Consequently, several TUI-based solutions have been proposed for teaching various concepts to VI children, such as Braille letters and words [29], [41], [42], [43], [44], Braille numbers and mathematical operations [45], [46], [47], [48], [49], [50], computational thinking [51] and programming skills [52], [53], [54], [55].

Though some prototype TUI-based applications have been developed to allow VI users to access graphs and charts (e.g., Riedenklau et al. [56] combine Tangible Interactive Objects (TAOs) [57] with interactive sonification [58] to enable users to explore scatter plots; the Tangible Graph Builder [59], a tabletop TUI system, allows users to browse and construct both line and bar graphs; Tac-tiles [60] utilizes a graphics tablet augmented with a tangible overlay tile to guide user exploration of graphs), however, research on employing tangible interaction for teaching shape and geometry concepts to the VI still appears to be at a nascent stage with only a few applications having been introduced so far. For example, Manshad et al. [27] present Trackable Interactive Multimodal Manipulatives (TIMMs), programmable objects embedded with various sensors and motors and with markers underneath them, that can be moved on an interactive tabletop with their positions, proximity and orientation tracked via an infrared camera and other associated hardware and can provide tactile feedback to the user via embedded vibration motors; the platform allows students to create graphical representations including outlines of geometric shapes on a multitouch tabletop which they can subsequently modify and interact with. Rühmann et al. [30] introduce an Android tablet application along with a deformable physical appcessory composed of ball-and-spoke components that can be manipulated to construct geometric shapes; when placed on the tablet, the appcessory's shape is detected and visually displayed by the application and appropriate auditory and vibrotactile feedback is provided when exploring the shape via touch. Adusei and Lee [31] present a construction kit of simple geometric primitives that snap together to produce more complex forms such as lines, angles and polygons; when placed on a tablet, the geometry of these objects is sensed (via the capacitive touch screen and electrodes embedded in the objects) and audio feedback is provided; learning is accomplished via quiz questions with various modes of difficulty (i.e., size identification and shape making, shape modification and problem solving). Jafri et al. [4], [32] utilize a computer vision-based system to track tagged 3D printed geometric shapes that can be manipulated by the child to receive audio feedback regarding shape and spatial relationships in the context of various learning activities. Lozano et al. [28] teach about shapes, textures, and numbers using physical objects with embedded NFC tags that when placed on a surface are recognized by an application running on a mobile phone with an NFC reader located beneath that surface; the child is asked to put specific objects on the surface and appropriate auditory feedback is provided. Baqai et al. [29] use infra-red (IR) tag-embedded blocks with embossed motifs representing numbers, alphabets, shapes and mathematical operators to teach about words, shapes and mathematical concepts via quiz-based games with appropriate auditory feedback; to keep the cost down, rather than using a mainstream desktop or mobile computing device, the system utilizes low-cost hardware components - a battery, optical detectors and a microcontroller - for the detection and processing of the IR patterns.

Initial evaluations of the above systems with VI users have yielded positive results validating the potential of using TUI-based solutions for teaching shape and geometry concepts to the VI. However, most of these systems (such as [27], [31] and [29]) require specialized hardware components which the teachers and caregivers of VI children may find hard to acquire and put together themselves. Also, solutions like Rühmann et al.'s [30], Lozano et al.'s [28] and Baqai et al.'s [29] are still at a preliminary stage teaching only simple shape identification and need to be developed further to teach more advanced concepts such as similarity and congruence and relationships among various shapes. Moreover, systems like Baqai et al.'s [29] that employ embossed motifs of shapes at fixed orientations neither afford shapes to be reoriented and explored from all angles (which is deemed to be important for shape recognition by blind individuals [6]) nor do these allow different shapes to be placed next to each other to gain a deeper understanding of how certain shapes can be combined to make other shapes. Furthermore, none of these systems provide teachers/caregivers with options for downloading models and producing the tangible components themselves or allow them to track the children's progress. Last, but not least, none of these systems support Arabic language precluding or limiting their use for Arabic speaking populations.

III. REQUIREMENTS COLLECTION

As mentioned, we previously conducted an exploratory study [4] to examine the potential of TUIs for teaching tactual shape perception and spatial awareness sub-concepts in small-scale space to VI children in which semi-structured interviews were conducted with three teachers from two well-known schools for the VI in the USA and a rudimentary version of the TUI was demoed to them; the study yielded invaluable insights into strategies used by instructors to teach shape and spatial relationship concepts to VI children as well as several practical suggestions for the proposed tangible interface and interaction which we have strived to incorporate into the development of our current system.

However, since our current system supports Arabic and is targeted towards schools in Arabic speaking countries, hence, to ensure that the proposed solution would also comply with teaching practices in the local context, we decided to conduct further semi-structured interviews with three teachers who teach VI children in elementary grades at two inclusive schools in Riyadh, Saudi Arabia. Similar to our previous study [4], the interviews were structured around the following topics: current methods and the use of tangibles for teaching shape concepts, computer-based technologies being employed for this purpose, feedback about the utility of the proposed system and suggestions to better adapt it to the users' needs.

The results of the interviews revealed that the local and the US teachers concur on several essential points: both introduce shape concepts by using physical objects representing the shapes; the objects are initially fairly large (1''-2'') and are usually made of wood, heavy-duty foam or plastic to ensure that the edges and corners are well-defined and are thus, easier to tactually perceive – different sizes and less rigid materials (such as sponge) are gradually introduced as learning progresses; basic 2D shapes – i.e., circle, triangle, square and rectangle – are presented first, one at a time, before progressing to more complex planar and 3D shapes; hints about the number of sides and corners are provided to help the children distinguish among the shapes (e.g., ''this shape has three sides and three corners, so it is a triangle''); shape concepts are reinforced by starting with simple tasks such as asking the child to find a particular shape among several different ones and progressing to more advanced tasks for inferring relationships among different shapes such as asking a child to put two identical shapes together to form another shape (e.g., two squares can be combined to make a rectangle). Teachers from both countries indicated that neither do they currently use computer-based technologies for teaching shapes nor are they aware of any such tools for VI children. They all unequivocally expressed enthusiasm for using the proposed system in their classrooms citing the independence that it offers VI children for reinforcing previously learned concepts without requiring constant intervention by a teacher/caregiver as its most attractive characteristic. The system was deemed most suitable for children in the age range of 5-11 years by four of the teachers but the remaining two (one from Saudi Arabia and the other from USA) thought that children younger than eight years who have had no previous experience with computers may find it confusing to receive audio instructions and feedback from a device rather than a human instructor. The US teachers particularly welcomed the option of 3D printing the shapes because of the customization possibilities that would open up; as one teacher remarked: "This would help a lot so you can have different textures, multiple sizes, braille numbers printed on the sides ...". Suggestions for system features included having separate accounts for children and allowing teachers to track their progress, providing several 2D and 3D shapes to accommodate different age and skill levels, and providing simple games to reinforce shape concepts (such as combining shapes to form new shapes).

All the above teaching practices and suggestions have informed the final design of our system as explained in the next section. Furthermore, some recommendations by the US teachers - to whom the rudimentary version of the TUI was demoed - for increasing the robustness of the tangible setup and adding a tactile border to make it easier for children to locate the interaction area on the TUI were also incorporated into the TUI design as described in section IV.A.1.

Some of the teachers also recommended adding activities for teaching more challenging concepts such as shapes with more than four sides, three-dimensional shapes and dividing shapes into fractional parts (e.g., halves, quarters). They also suggested letting the child draw the shape and allowing teachers to not only select among existing shapes and activities but also to add their own shapes and tasks. These suggestions would be incorporated in future iterations of the system.

IV. SYSTEM DESIGN AND ARCHITECTURE

We have developed Tac-Trace, a standalone TUI-based system that assists in teaching concepts of planar shapes and their relationships to VI children and also allows special education teachers to track their students' progress. The solution is targeted towards VI children in early elementary grades aged between 5–11 years with some basic knowledge of Braille and has been designed to closely conform to the practices currently being employed to teach these notions in order to facilitate its integration into special education classrooms. VI children can interact with the system via a tangible interface by placing physical objects on a horizontal surface and can receive audio instructions and feedback while their teachers can access the system via a GUI. The GUI and audio output as well as Braille text on the tangible objects is in Arabic to support its use by students and teachers in local schools. The system introduces increasingly complex shape concepts to children via a series of interactive activities. The system design and architecture as well as implementation details are described below.

A. SYSTEM DESIGN

The system is comprised of three main components: a tangible tracking system, 3D printed tangible objects, and a spatial application connected to the tracking system that provides the activities for the child as well as the functions for the teacher. A detailed description of these components is given below.

FIGURE 1. Trackmate barcode [61], [62].

1) TANGIBLE TRACKING SYSTEM

For tracking the objects, we have utilized Trackmate [61], [62], an open-source, do-it-yourself computer vision-based tangible tracking system introduced by the MIT Media Lab's Tangible Media Group. The Trackmate system operates as follows: Objects of interest are tagged with specially designed circular barcodes (Fig. 1), where each barcode contains a six-byte unique ID. The objects can be placed on a transparent surface with a webcam connected to a personal computer (PC) underneath it. A Tracker module on the PC reads the object's tags by processing images from the webcam and sends information about the object's identity, its position, its rotation and its color to a spatial application on the PC via LusidOSC [63] (a protocol layer for unique spatial input devices which enables any LusidOSC-based application to work with the system).

The physical components for the Trackmate system can be configured in several different ways [62]. We had selected the Portable Plexi Cliffhanger setup [64] for our initial demonstration for the US teachers; however, they pointed out that the exposed edges of the plexiglass sheet may pose a safety hazard for the children and that the webcam perched on a tripod may be probed out of curiosity or accidentally kicked by the children; also, the setup required the lighting in the room to be carefully adjusted (e.g., the ceiling lights had to be turned off) for the tracking system to function correctly which would not be practical in a real-world classroom [4]. We, therefore, decided to switch over to the Hardwood Curio setup [65] which resolves all the above issues. For this configuration, a high-definition Logitech webcam was placed, along with a light source, in a wooden box (12" × 12" × 12") with the webcam directed upwards at an angle perpendicular to the base of the box as shown in Fig. 2(b). A 12" × 12" plexiglass sheet was inserted into a groove running along the upper edge of the box to form a transparent horizontal surface. This setup is more robust to lighting conditions, protects the webcam, and covers the plexiglass edges. Though the setup description [65] calls for a glass sheet, we chose to use plexiglass since it is lighter, stronger, better at reducing glare and more shatter-resistant as compared to glass [66] making it a sturdier and safer option for a tool targeted towards children. Since the objects need to be placed within a certain area in the center of the plexiglass sheet to be detected by the webcam, following the US teachers' suggestions, a tactile border was created around that area using strips of wide duct tape to facilitate the VI children's tactual localization of that area. The setup of the TUI is shown in Fig. 2.

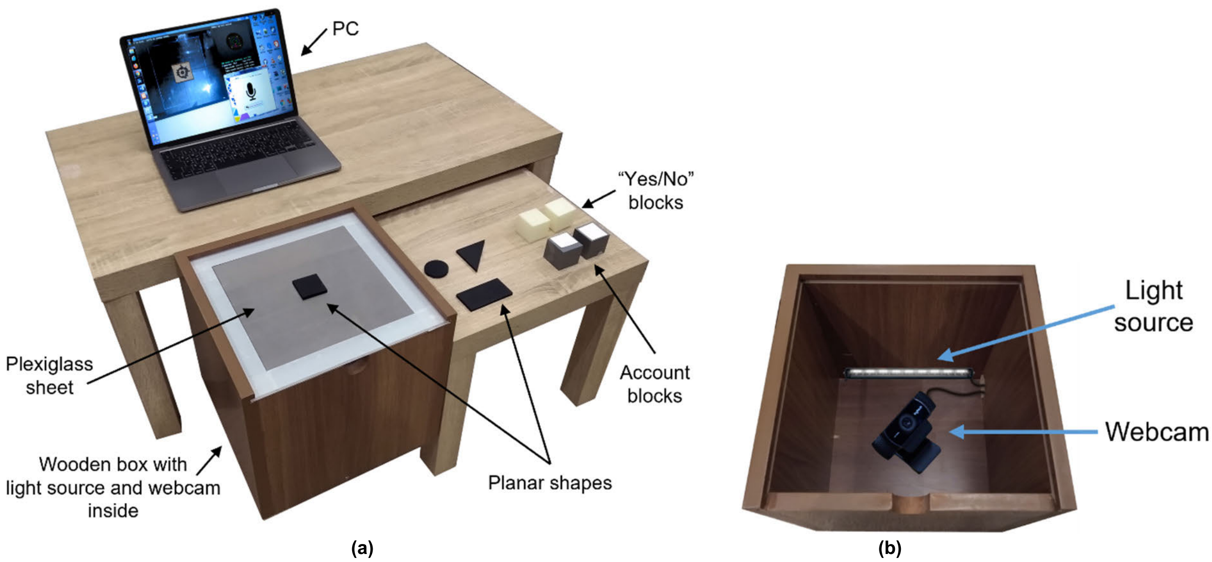


FIGURE 2. **(a) Hardware setup for the tangible interface; (b) Internal view of the wooden box showing the light source and webcam.**

2) TANGIBLE OBJECTS

Three types of tangible objects are used in our system as shown in Fig. 3: (1) account blocks: grey cubes with a child's name embossed in Arabic Braille attached on top. The child can read his/her name in Braille to identify his/her block and then put the block on the plexiglass to log in to the system; he/she is then asked to remove the block and can place it again on the plexiglass when he/she wants to log out (the idea of the account cube has been adopted from [50]). (2) a "yes/no" block: a beige cube, with the word "yes" on one face and the word "no" on the adjacent face in Arabic Braille, that can be used by the child to answer a question posed by the system that requires a "yes" or "no" response (e.g., "Do you want to continue practicing?"). (3) a set of planar shapes: circles, squares, rectangles and triangles (two larger-sized white and two smaller-sized black instances of each) that the child can use in the learning activities.

Different colors were used for the different object types to make it easier for children with some residual vision to distinguish among them; also, a Braille dot was placed on the larger shapes to facilitate differentiating them from smaller ones. All objects were generated by creating CAD models for them using the Tinkercad program [67] and then 3D printing them on a Makerbot Replicator 2× printer [68]. Unique barcodes (tags) measuring about 1"by 1" were produced for all objects utilizing the Tagger software provided by the Trackmate system and were then printed and attached to the bases of the corresponding 3D printed objects (it should be noted that for the account blocks, the barcodes are generated by the system when the teacher creates an account for the child as described in section IV.A.3 b).

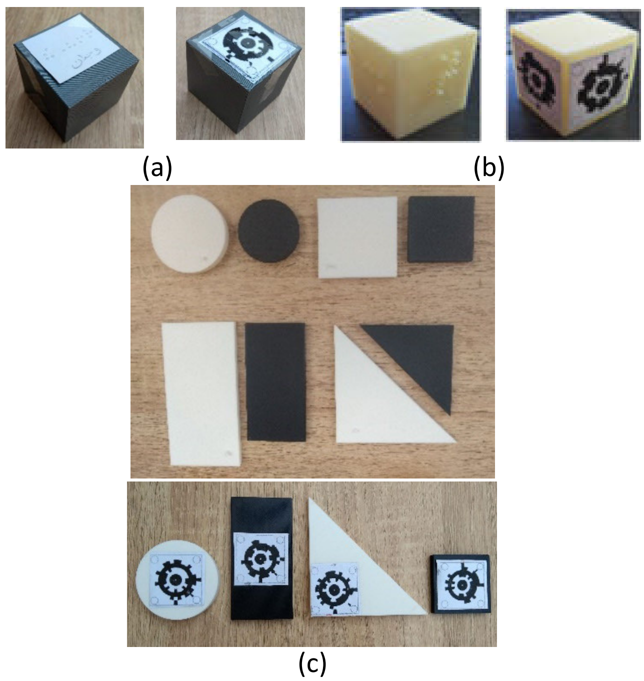


FIGURE 3. **(a) Account block (b) "Yes/no" block (c) Planar shapes (two larger-sized white and two smaller-sized black instances of each are provided); circular barcodes are attached to the bases of all objects.**

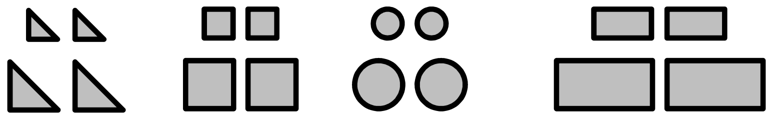
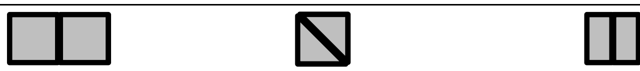
3) SPATIAL APPLICATION

A spatial application has been developed that runs on a PC and is connected to the tangible interface via the tracking system. The application provides activities for the child to learn about shapes and their relationships by manipulating the tangible objects and also provides functions for the teachers that they can access via a GUI.

a: ACTIVITIES FOR CHILD

Once a child logs into the system using his account block (as described in section IV.A.2), he/she is presented with activities for teaching him/her about different planar shapes

TABLE 1. Sets of tangible shapes provided for each level.

Level	Tangible shapes provided
1	 One instance of each shape (circle, triangle, rectangle and square)
2	 Two large and two small instances of each shape (circle, triangle, rectangle and square)
3	 Two instances (both large or both small) of a triangle, rectangle and square

and their relationships. These activities are divided into three levels presenting progressively complex concepts: level 1 (L1) introduces basic planar shapes (i.e., circle, triangle, rectangle and square); level 2 (L2) teaches the concepts of similarity and congruence among planar shapes; level 3 (L3) presents the relationships among different shapes by showing how two identical shapes can be combined to form a different shape (e.g., a square can be created by putting two congruent right-angled triangles together).

The child is provided with a specific set of physical shape tokens for each level as shown in Table 1: one instance of each basic planar shape for L1, four instances (two large and two small) of each shape for L2, and two congruent instances of each shape, except the circle, for L3.

Each level consists of three stages: lesson, practice and test.

1) Lesson: When a level is started, an interactive lesson is given first to introduce the concepts. In a L1 lesson, the child selects each shape by placing it on the plexiglass and the system provides some information about it (such as name, number of sides, number of corners); in L2, the child selects two instances of each shape and the system explains if they are similar or congruent; in L3, the child selects pairs of congruent shapes and the system guides him/her as to how to put them together to form another shape.
2) Practice: After the lesson, a practice session ensues in which the child is asked five questions to reinforce the concepts taught in the lesson. If the child cannot answer at least four questions correctly, he/she returns to the lesson stage; otherwise, he/she qualifies to advance to the test stage. At this juncture, the system asks the child if he/she wants to continue practicing; if the child answers "yes" (using the "yes/no" block), another practice question is given; the process is repeated until the child answers "no" upon which he/she progresses to the test stage.
3) Test: A quiz consisting of five questions is administered to evaluate the child's grasp of the concepts taught. If the child cannot answer at least four questions correctly, he/she is given the option to return to either the lesson or the practice stage; otherwise, he/she progresses to the next level. If the child fails the quiz three times, this is a clear indication that he/she is struggling with the concepts being taught at that level; a notification is, therefore, automatically sent to his/her teacher's account to alert her that additional intervention may be needed.

The system keeps track of which level and stage the child is at so that the child can stop and log out at any time and then log in later to resume from where he/she left off. It also records information about each child's progress so that it can be viewed by the teacher.

Appropriate audio feedback and instructions are provided at each level. The audio content has been designed to appeal to children so as to retain their interest and motivate them to continue. Instead of using synthetic voices, all instructions have been recorded using real female human voices conveying warmth and friendliness; a conversational tone has been adopted to make the children feel more at ease and the shapes have been anthropomorphized to engage the children's attention and enhance their enjoyment. For example, in L1, the system greets the child when he/she logs in and informs him/her that the shapes are excited about meeting him/her; each shape then introduces itself when the child places it on the surface ("Hello! My name is Square!"). Correct answers are rewarded by positive remarks while incorrect answers prompt helpful cues to support the child's conceptual understanding. An initial erroneous response triggers an informative hint (e.g., "Remember: a square has four equal sides."); a subsequent incorrect answer generates another detailed hint while a third mistake causes the answer to be finally marked as wrong and prompts the system to move on to the next question.

The shape concepts and their progression in terms of complexity, the activities selected to convey these concepts, the audio hints and the division of each level into three stages is based on the feedback from the teachers we interviewed and by consulting some elementary math textbooks referred by them.

b: FUNCTIONS FOR TEACHER

The teacher interacts with the system via a GUI displayed on the computer monitor. She can register and log in to the system and do the following: (1) Manage her students and track their progress: She can add a student to the system by entering the student's name, age, gender, and grade – a unique barcode is generated for the child which the teacher can print out and place on the base of a 3D-printed cube and she can put the child's name in Braille on top of the cube to create an account block for the child. She can also view all her registered students, edit their personal profiles, delete their accounts and furthermore, view their progress information including which level and stage they are at as well as their scores and number of passed and failed quiz attempts at each level. Moreover, she can receive alerts if a student has failed a quiz three or more times. (2) Print the tangible objects and their barcodes: To allow the teacher to replace any tangible object in case it gets damaged or lost, an option to download its CAD model and 3D print it is provided; in case a 3D printer is not available at a school, an alternative of printing the object's outline and using it as a template for creating a cardboard cut-out is also given. The teacher can also print out the corresponding barcode of any object.

B. SYSTEM ARCHITECTURE AND IMPLEMENTATION DETAILS

The overall architecture of the system is shown in Fig. 4. We chose the Model-View-Controller (MVC) architecture [69] since this divides the application into three main logical components thus, supporting parallel development and code reuse; moreover, it allows the data to be displayed in multiple ways. As shown in Fig. 4, the model consists of the database containing the data for the tangible objects and the users' accounts, the view includes the GUI for the teacher and the TUI and audio output for the child while the controller is comprised of the Trackmate tangible tracking system and the spatial application that implements the system's programming logic for the child and teacher parts.

The system has been developed for Microsoft Windows [70] PCs. The spatial application's software has been written in the Java programming language and connects with the Trackmate system via the LusidOSC protocol [63]. The database was implemented using MySQL [71] and managed using phpMyAdmin [72]. The audio files are played using the built-in sun.audio library in the Java API.

V. SYSTEM EVALUATION

The system was evaluated at a local elementary school for VI girls to identify any usability issues and to get some feedback from the target users about its usefulness, functionalities and interaction design in order to better adapt it to their needs.

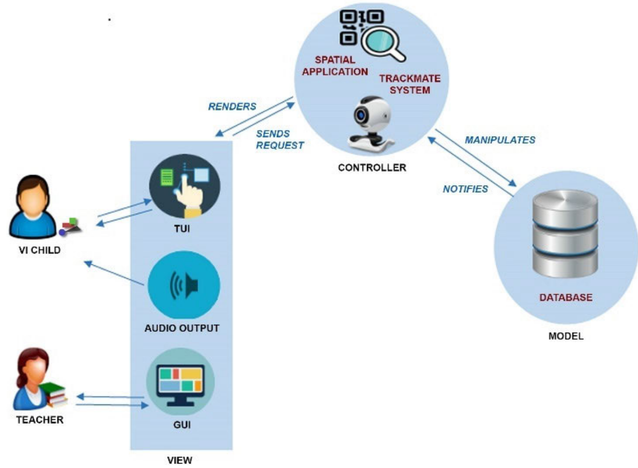


FIGURE 4. System architecture.

A. PROCEDURE

Informed consent was obtained from the school to test the system with its teachers and students and a preliminary evaluation session was arranged in a classroom at the school itself, as recommended by previous studies [73], to minimize any inconvenience to the participants and to provide them with a familiar environment where they would feel at ease and would be more likely to frankly express their thoughts and opinions. First, an exploratory usability testing session was conducted with one of the teachers to evaluate the teacher's interface; the system was briefly explained to the teacher and she was then asked to use each function at the interface. The time per task was recorded and any difficulties or errors observed were noted down. The teacher was also asked to observe the testing of the child's part (described next) and a brief post-test interview was conducted to get her feedback and suggestions about the entire system. Next, the child's interface was evaluated with eight VI students (three 10-, four 12- and one 15-year-old) (due to some miscommunication with the school, some of the children were older than the targeted age range of 5-11 years). To gather their initial impressions about the system, we described the child's part to them and then had them take brief turns doing the activities in levels 1 and 2. A think-aloud protocol was applied, observation notes were taken and a short post-session group interview was conducted. The Director of the school and another teacher were also present during the evaluation of the child's part and their impressions were also sought and recorded.

Since most of the children who participated in the study were older than the target age range, hence, a second evaluation session was arranged at the school to test the child's part with children who were within the target age range. Three female children – a 9-year-old blind first-grader, a 6-year-old blind first-grader and an 11-year-old low vision (with some light perception) fourth-grader – were recruited; these will be referred to as C1, C2 and C3, respectively from this point forth. The children were asked about their previous experience and challenges using electronic devices and their familiarity with planar shapes. The system was then briefly described to them and they were allowed to explore the tangible objects and the plexiglass surface. Levels 1, 2, and 3 were then tested with C1, C2 and C3, respectively. Each child was asked to log in to the system using her account block (an account block for each child was created beforehand) and to follow the instructions given by the system. The time per task was recorded and any difficulties or errors observed were noted down. A brief post-test interview was conducted to determine the child's opinion of various aspects of the system.

The data collected from the observations and the interviews from both evaluation sessions was analysed and some findings and recommendations were developed to inform the design of the system.

VI. RESULTS

A. EVALUATION OF TEACHER'S PART

The teacher was able to complete all tasks provided at the teacher's interface in a reasonable amount of time with no major issues except for the task of generating an account barcode for a newly added student; since the Tagger software generates only an image of a new barcode without its associated ASCII value, the barcode has to be printed and placed on the plexiglass by the teacher; it is then read by the tangible tracking system to acquire its ASCII value which is stored in the system for future use. Though relevant buttons had been provided on the interface to guide the teacher, she had difficulty understanding what she was required to do and we had to verbally instruct the teacher to print and place the barcode. To resolve this issue, we will investigate if it is possible to modify the Trackmate code to automatically generate and store the barcode without explicitly requiring the teacher to take actions to perform the sub-steps involved. The teacher's overall feedback about the interface was very positive and her comments indicated that she found the interface easy to understand and use in general. She recommended extending the system so that it would allow the teacher to add more shapes and activities of her own choosing to the system.

B. EVALUATION OF CHILD'S PART

1) FIRST EVALUATION

All the children were able to follow the audio instructions easily and figured out how to use the system quickly. Several of them mentioned that they liked the "friendly" tone infused in the audio content. Their comments indicated that they liked the idea of learning by themselves without the teacher, felt comfortable using the system on their own, were satisfied with the system in general and enjoyed using it. The evaluation also revealed a few concerns: one child had some issues with her nerves which impaired her ability to feel intricate textures; consequently, she had trouble discerning the braille text on the "yes/no" and account blocks. This indicates a need to provide alternative input modalities such as speech. Several of the children also got confused by the "yes/no" block since it was not clear that the same block had different texts on two of its faces. To make it consistent with the rest of the tangible objects (where each object represents a single thing or word), they suggested that there should be separate blocks for "yes" and "no". Since most of the children were a bit older than our target age group and were, thus, already well acquainted with planar shapes, several of them asked us to provide 3D shapes in the system rather than planar ones to make the tasks more challenging and better adapted to their skill levels.

The teachers who observed the children using the system gave their approbation of the concepts and activities provided at each level and asserted that it would prove very useful for VI children for the self-learning of as well as the reinforcement of shape concepts. They requested us to provide the system to them once it took its final form so that they could integrate it into their classrooms. For future work, they also echoed the children's suggestions of providing 3D shapes in addition to planar shapes proclaiming that these are more difficult for VI children to learn.

2) SECOND EVALUATION

The pre-test interview revealed that all the children had previously used computers, mainly for playing games, while C3 had also utilized it for studying and memorizing the Quran. All of them were also familiar with the basic planar shapes included in the system. The children's age, gender, level of visual impairment, grade as well as the game levels tested by them and the average times taken per task are given in Table 2.

The following observations were made:

1. All the children were able to understand quickly how to use the system and, with the exception of C1, were able to answer all the questions correctly (even C1 made only one mistake in the testing phase when she put a triangle instead of a rectangle). For the tangible interaction, all the children spent most of the time on searching for the shape; once it was found, they were able to place it fairly quickly on the target area.
2. It should be noted that the questions in L1 of the game required placing only one shape while those in L2 and L3 required placing two shapes; hence, as expected, C1 took less time than both C2 and C3 for both the lesson and training questions; however, for the testing, C1 took less time than C2 but more than C3 - this seems to be because C3 was older, in a higher grade and had some residual vision that she could utilize and having learned the system thoroughly in the first two stages, was able to place the shapes at a faster pace in the testing stage.
3. In L2, the lesson explained that similar shapes are of the same kind but can have different sizes while congruent shapes are of the same kind and of the same size. However, C2 appeared to have trouble understanding this and had to be prompted with hints like "both shapes should be small(big)" for congruent and "one shape should be small (big) and the other should be big (small)" for similar but not congruent.
4. In light of the remarks concerning the "yes/no" block in the first evaluation, for the 2nd evaluation, the "yes"

TABLE 2. Children's demographic information and average times for tasks.

ID	Age (years)	Gender	Level of visual impairment	Grade	Game level tested**	Average time (in seconds) spent in searching for and placing:				
						account block	planar shape(s)*			"yes/no" block
							Lesson	Training	Testing	
C1	9	Female	Blind	1	L1	30	24.25	11	20.5	46
C2	6	Female	Blind	1	L2	38	60	78.25	77	56
C3	11	Female	Low Vision	4	L3	16	32.66	16	8.33	11

*Average time per question

**Each question in L1 required placing only one shape while each question in L2 and L3 required placing two shapes

and ''no'' blocks were separated; this seemed to resolve the issue of confusion arising from text appearing on two sides of the same block.

5. Though the account blocks, the ''yes'' and ''no'' blocks and the shapes were placed in three separate groups on the table in front of the children, it was observed that the children immediately mixed the different type of objects when exploring them; we had to eventually give them only the kind of objects required for the stage that they were at: account blocks at log in and log out times, ''yes'' and ''no'' blocks when a question requiring a ''yes/no'' response was asked, and shapes when doing the lessons, training and testing
6. A braille dot was placed on top of the bigger shapes to aid the children in distinguishing the larger shapes from the smaller ones. However, none of the children appeared to exploit this feature.
7. A technical issue encountered was that the maximum volume of the audio output on the PC being used was not very loud. Especially when testing with C3, even though the classroom door was closed, noise from a school event commencing in the immediate vicinity permeated into the room causing C3 to complain that she could not hear the audio feedback clearly. Since the system is meant to be used in a regular classroom where ambient noises are likely to occur, this issue can readily be addressed by providing the audio output via speakers or earphones.
8. Using the box setup did succeed in making the system more robust; though the children jostled the box quite a bit while searching for the shapes or when locating the target area, this did not displace/dislodge the camera and the lights. Also, even though the classroom was well lit and had quite a bit of ambient light, enclosing the camera and lights within the box made them much less sensitive to the illumination conditions in the room as compared to the cliffhanger setup.

Some differences were observed between the two blind (BL) children, C1 and C2, and the low vision (LV) child, C3:

- Both C1 and C2 took longer to find the correct shapes as compared to C3. They also frequently placed the shapes on the plexiglass so that the shape was not entirely in the target area and furthermore, put the shapes with the tag side up several times – C3 made these errors only a few times and quickly corrected them in most cases. Based on our observations, the disparity in level of visual impairment was a major factor contributing to these differences since the BL children were relying entirely on touch (by moving their fingers over the shape and the plexiglass) while the LV child was utilizing not only touch but also her partial vision (by bringing some shapes close to her eyes or directing her gaze to the objects or plexiglass surface) to achieve these tasks. It should be noted that factors such as age and the amount of previous exposure to shape concepts could also have contributed to these variations and warrant further investigation.
- For levels 2 and 3, since a relatively large number of shapes were put out, some of these were directly in front of the children while others were a bit on the right. It was observed that C1 and C2 kept searching for the shapes only in the area directly in front of them while C3 searched through all the shapes including the shapes on the right. Two factors were observed to contribute to this difference: 1) the level of visual impairment: since C1 and C2 were blind, they could not visually perceive the shapes towards the right and thus, just kept searching via touch in front of them; 2) the age and physical reach: C3 was a bit older and her immediate reach naturally included the area on the right.
- C1 and C2 seemed to struggle reading the Braille text on the account blocks and the ''yes'' and ''no'' blocks while C3 was able to read the text easily and quickly. This could be attributed to C3 being more adept at Braille since she was older and in a higher grade academically.

The post-test interview results indicated that, despite the issues outlined above, all the children enjoyed interacting with the system, thought that it was easy to understand and use and indicated their preference for using such a system as compared to traditional methods for teaching shape concepts.

C. DISCUSSION

The evaluation sessions validated several of our design decisions (such as using conversational real human voices for engagement, the box setup for robustness, hints for scaffolding and quiz questions and progressive stages for motivation). The results also revealed some key usability issues and provided several valuable insights into design considerations for TUI-based systems for VI children which would be taken into account in future iterations of our system and will also benefit other researchers creating similar systems for the VI.

Some design implications for TUI-based systems for VI children in general and our system in particular that have emerged based on our observations and the feedback from the teachers and the students during the interviews and the hands-on interaction are as follows:

- It is important to take the differences in age and the level of visual impairment into account when designing tangible systems for VI children; older children with partial vision can be provided with a larger number of tangible tokens since they would still be able to identify a desired token quite efficiently; they may be able to handle a larger target area and more complex instructions regarding the tangible tokens (e.g., putting the tag side down). For younger and totally BL users: 1) The tangible objects should be limited to a relatively small number to facilitate rapid exploration. 2) The size of the objects should be smaller (as also suggested in [50]) so that even if there are more objects, they would fit in a small area directly in front of the user.
- Different types of tangible objects (e.g., in our system, the account blocks, ''yes'' and ''no'' blocks and planar shapes) should be placed in separate containers to prevent the children from accidentally mixing them while exploring.
- Since tactile sensory impairments and unfamiliarity with Braille would render Braille embossed blocks inappropriate as an input medium for some users, alternative input modalities such as speech, should also be provided.
- Tags had been placed only on the bottoms of the tangible objects in accordance with the instructions given for the Trackmate system. However, the observation results imply that when using a tracking system that utilizes visual tags, the tags should be placed on all the available faces of the tangible objects to remove the additional cognitive tasks of determining which side the tag is on and having to make sure that that side is on the bottom when placing the object.
- Based on observation 3, more consultation with teachers and learning resources may be required in order to improve the lesson contents to convey the concepts being taught more clearly.
- The tangible setup should be robust enough to withstand some rough handling by the children and changes in environmental factors and also be safe for the children to use. In our case, enclosing and fixing the camera inside a box put it out of their reach, made it relatively resilient to changes in illumination conditions, and made the tangible setup safer for them to handle (especially since the plexiglass edges were no longer exposed).
- If the system is being used in a classroom setting, earphones or headphones should be provided to avoid ambient sounds interfering with the audio output.

Though the evaluation studies yielded promising results, some limitations should be noted: The system was evaluated with a small number of students, all of whom were female and from the same school in Riyadh, Saudi Arabia. To ensure that the results can be generalized to a broader population, in the future, it should be evaluated with a larger sample of participants which is more diverse in terms of gender, educational institutions and geographic locations.

Though the children expressed a preference for the Tac-Trace system over traditional teaching methods, this preference may have been propelled by the novelty of using a new medium for learning familiar concepts. In order to determine if Tac-Trace promotes better understanding and faster learning and retention of shape concepts, a systematic study would need to be conducted that compares a control group which learns shape concepts using traditional methods with a group that uses Tac-Trace to learn the same concepts.

VII. CONCLUSION AND FUTURE WORK

A novel Arabic language TUI-based system that teaches the concepts of planar shapes and their relationships to VI children and also allows teachers to track their students' progress has been presented in this paper. We have aimed to make the solution affordable, accessible and easy for teachers to set up themselves by employing off-the-shelf components for constructing the TUI and providing templates for 3D printing the tangible tokens. The system has been developed in consultation with experienced teachers for VI children to ensure that it is compliant with current teaching practices and can be readily integrated into VI classroom routines. Initial evaluations with teachers and children at a local school for the VI have yielded positive results with teachers approving of the design and activities and children finding the system easy to use and more enjoyable than traditional learning methods. The requirements collection and evaluation studies have also yielded several valuable suggestions for improving the usability of the system as well as design recommendations for enhancing the tangible interface and interaction and ideas for additional features which will not only inform the design of future iterations of our system but would be instrumental in guiding other researchers developing similar TUI-based solutions for the VI. We hope that our system will practically benefit VI children and their teachers enabling the children to learn and reinforce shape concepts independently at their own pace in an engaging manner using familiar classroom teaching patterns and physical learning aids amenable to touch and allowing teachers to monitor their progress while reducing the demands on their time and efforts and financial resources.

In the future, we plan to resolve the usability issues revealed in the evaluation studies and extend the system to incorporate the teachers' suggestions for teaching more advanced concepts such as shapes with more than four sides, 3D shapes and fractional parts. As per the teachers' request, we also intend to add customization options that would allow them to tailor the system according to their students' age and skill levels by selecting a subset of the existing shapes and activities and creating and adding their own shapes and tasks. Other future work directions include extending the system to other languages and platforms to accommodate a broader range of users, introducing activities for collaborative learning that would allow multiple children to use the system simultaneously, providing alternative input options such as speech and adding more ludic elements such as themes and objectives [74] to make the learning experience more engaging and enjoyable.

ACKNOWLEDGMENT

The authors would like to extend their sincere thanks to the teachers from the two inclusive schools in Riyadh, Saudi Arabia, who participated in the requirements collection study for their invaluable insights into how the concepts of geometric shapes and their relationships are taught to VI children. They would also like to express their gratitude to the teachers and students from the Noor Institute for the Blind, Riyadh, who participated in the evaluation studies for helping them to test the usability of their system and for providing them with feedback and suggestions for improving it further.

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