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A tangible user interface-based application utilizing 3D-printed manipulatives for teaching tactual shape perception and spatial awareness sub-concepts to visually impaired children

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ABSTRACT

A novel tangible user interface (TUI) based solution for teaching and reinforcing tactual shape perception and spatial awareness sub-concepts in small-scale space to visually impaired (VI) children is presented. The solution utilizes a computer vision-based system to track tagged 3D printed geometric shapes which can be manipulated by the child and provides feedback via an audio interface. The aim is to create an engaging, accessible system which mitigates the demands on the time, efforts and financial resources of the teacher/caregiver and allows a child to learn and review these concepts autonomously at his/her own pace. 3D printing has been utilized for generating the tangible tokens and off-the-shelf components have been used for setting up the TUI in order to make the system low-cost, customizable, easily reproducible and do-it-yourself. The evaluation of the system with teachers of VI children has not only validated its potential and affirmed the need for and the willingness of the teachers to adopt such assistive solutions but has also provided some invaluable insights which would be a useful resource for other researchers interested in building similar applications. The system would be extended in the future to allow teachers/caregivers to create custom shapes and to teach other essential concepts such as object sequencing and texture recognition.

1. Introduction

Learning the characteristic properties of geometric shapes and spatial relationships among objects is essential for visually impaired (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 topics in higher mathematics which require spatial thinking [1,2].

Previous studies have shown that verbal descriptions alone are not sufficient to convey visual concepts, especially those of mathematics, to VI children [3]. VI children gain an understanding of the structure and properties of various two-dimensional (2D) and three-dimensional (3D) shapes, especially in complex forms, 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]. This process may have to be repeated several times before an adequate mental representation of the object is formed and reinforced. Similar guidance is required to teach positional and spatial concepts in small scale space (i.e., space that neither surrounds one nor requires one to move about to comprehend its total spatial layout [7]), such as beside, inside, outside, on-the-right-of, on-the-left-of, above, below, right-side-up, upside down, moving objects towards and away from each other [8,9]. Furthermore, since commercially available sets of geometric shapes 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 (such as sandpaper) on cardboard [4].

Unfortunately, a scarcity of special education teachers [10], along with an often-encountered lack of financial resources to purchase or custom-create non-visual educational supplies in

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classrooms for VI children essentially precludes the one-on-one interaction and materials required for this mode of instruction (the problem is even more severe in developing countries, where 90% of the VI population resides [11]). In many countries, such as the United States, the dearth of special education teachers has been dealt with by mainstreaming VI children into public schools [12]. 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.

A software application utilizing 3D objects which allows a VI child to review and reinforce the tactual shape recognition and spatial relationship concepts taught by the teacher may assist in alleviating both these problems: First, it would mitigate the demands on the teacher's time and allow the students to learn at their own pace autonomously. Secondly, by 3D printing sets of various geometric objects and coupling them with the application, a relatively inexpensive and easily reproducible tangible user interface (TUI) for tactual exploration and interaction can be provided. Given the rapidly decreasing costs of 3D printers and associated materials [13,14], these 3D printed objects (which can be customized in terms of shape, size, color, texture and embossed with Braille markers and letters) would 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. Moreover, if a shape gets lost or broken, it can be conveniently and inexpensively replaced by 3D printing it out again.

We have, therefore, developed a prototype version of a novel low-cost do-it-yourself TUI-based application to teach tactual shape perception and spatial awareness sub-concepts in small-scale space to VI children. Our solution expands upon Trackmate [15,16], an open-source computer vision-based tangible tracking system developed by the MIT Media Lab's Tangible Media Group for recognizing tagged objects (and their corresponding position, rotation and color information) when placed on a surface. To use our system, geometric objects, such as cubes, pyramids, etc., are 3D printed and tagged on multiple sides. Children can then feel these objects, place them on the surface and receive audio feedback regarding shape and spatial relationships in the context of various learning activities. The software would eventually be made available online at no cost to the user.

The initial idea of the system was introduced in a concept paper [17]. A prototype version of the system has now been implemented and is described in this paper. Adopting a user-centered approach, we have conducted semi-structured interviews with three teachers for VI children at two different schools for the blind in the US, demonstrated the prototype to them and, for the co-located teachers, allowed them to use the system themselves in order to better understand how these concepts are taught at school as well as to receive feedback about how our system can be adapted to meet the target users' needs. The valuable insights gained from the interviews and the results of the hands-on evaluation are also reported in this paper.

The research contributions of our work are threefold: The development of a novel TUI-based application, designed specifically for VI children, for teaching and reinforcing tactual shape perception and spatial awareness concepts in small-scale space; an innovative use of 3D printing for creating the tangible tokens (shapes), thus, exploiting and demonstrating the potential of this technology for customization, reproducibility and cost-effectiveness for assistive TUI-based educational software applications; the invaluable insights into current practices for teaching these concepts and detailed feedback about design considerations for TUI-based systems for this purpose from instructors of VI children, which not only validated some of our current design choices and will inform the design and development of future iterations of our system but would also be a valuable resource for researchers interested in building similar applications for this user group.

The rest of the paper is organized as follows: Section 2 presents an overview of previous work done on utilizing TUIs for educational applications for children in general and for teaching mathematical concepts to VI children in particular. It also outlines the use of 3D printing for the education of the VI. Section 3 describes the design and architecture of our system. Section 4 explains the methodology used to evaluate the system with teachers for VI children and reports the results of the evaluations. Section 5 discusses the findings and the improvements being made to the system based on the teachers' feedback. Section 6 highlights some directions for future work. Section 7 concludes the paper.

2. Related work

Instructors for VI students generally teach shapes and spatial relationships among objects in small-scale space by utilizing manipulatives [6] (i.e., tangible objects for hands on learning) such as 3D geometric solids (cubes, pyramids, spheres, etc.) against the backdrop of a plain surface as a staging area—for children with low vision, the objects may be brightly colored for easier distinction [8]. Some products for this purpose, specifically designed for VI students, include Geometro sets [18] (flat plastic shapes – triangles, squares, pentagons, and hexagons – that can be readily joined to form three-dimensional solids) and Rotograph [19] (a set of wooden plates with cut-out shapes for helping the child understand the concept of rotation). However, the static nature of such manipulatives necessitates constant intervention and validation from the instructor [20].

Tangible user interfaces (TUIs) [21], which couple physical objects to digital representations, appear to offer a better alternative. TUIs have been shown to enhance learning for children by enriching their experience, play and development [22,23]. Studies on this topic have reported that interaction with tangibles encourages engagement, excitement and collaboration [24], promotes discovery and participation [25], makes computation immediate and more accessible [26], and offers a resource for action in addition to an alternative form of data representation [27]. As pointed out in several studies (e.g., [28,29]), these interfaces appear particularly suitable for learning in abstract problem domains by relating abstract concepts to physical experiences or concrete examples.

The benefits offered by TUIs for learning have fueled research in this domain with several TUI-based educational applications being developed for sighted children in recent years [30–34]. However, research on exploiting this form of interaction for VI children is still in its infancy with just a handful of systems being introduced so far (e.g., for collaborative music creation [35] and teaching Braille letter recognition [36]). Though some prototype TUI-based applications have been developed to allow VI users to access graphs and charts (e.g., Riedenklau et al. [37] combine Tangible Interactive Objects (TAOs) [38] with interactive sonification [39] to enable users to explore scatter plots; the Tangible Graph Builder [40], a tabletop TUI system, allows users to browse and construct both line and bar graphs; Tac-tiles [41] utilizes a graphics tablet augmented with a tangible overlay tile to guide user exploration of graphs), however, our search yielded only a couple of such applications specifically designed to teach mathematical and geometrical concepts to VI children. One such product is AutOMathic [42], a system for teaching arithmetic and beginning algebra using Braille-embossed blocks with barcodes affixed to their bases. The child can pick up a block, pass it over a barcode scanner attached to a computer and then place it within a grid on