Exploring Projection Based Mixed Reality with Tangibles for Nonsymbolic Preschool Math Education



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TEI '19, March 17–20, 2019, Tempe, AZ, USA
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ACM ISBN 978-1-4503-6196-5/19/03.
https://doi.org/10.1145/3294109.3300981.
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Abstract
A child's early math development can stem from interactions with the physical world. Accordingly, current tangible interaction studies focus on preschool children's *formal (symbolic) mathematics*, i.e. number knowledge. However, recent developmental studies stress the importance of *nonsymbolic number representation* in math learning, i.e. understanding quantity relations without counting(more/less). To our knowledge, there are no tangible systems based on this math concept. We developed an initial tangible based mixed-reality(MR) setup with a small tabletop projector and depth camera. Our goal was observing children's interaction with the setup to guide our further design process towards developing nonsymbolic math trainings. In this paper we present our observations from sessions with four 3-to-5 year old children and discuss their meaning for future work. Initial clues show that our MR setup leads to exploratory and mindful interactions, which might be generalizable to other tangible MR systems for child education and could inspire interaction design studies.

Author Keywords
Tangible interaction; Embodied learning; Nonsymbolic math; Mixed reality; Tangible interaction for children

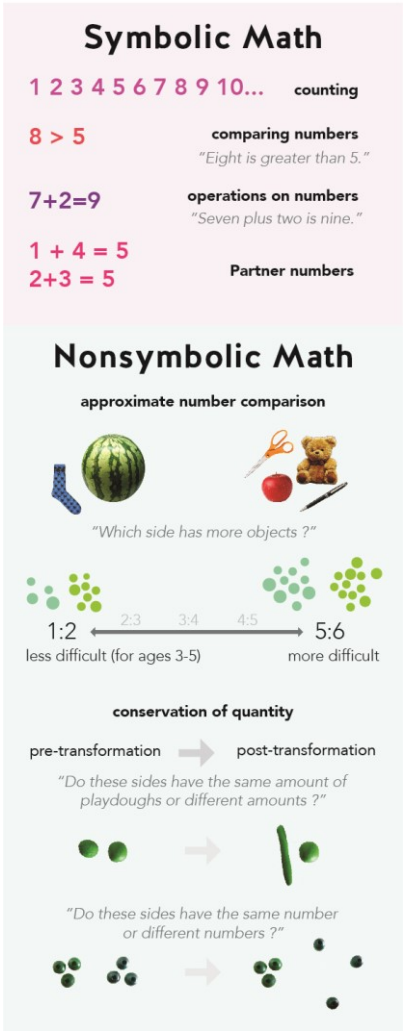


Figure 1: Symbolic and Nonsymbolic math

CSS Concepts
• Human-centered computing~Mixed / augmented reality • Human-centered computing~User interface design • Social and professional topics~Children

Introduction

Early math ability is essential for day to day life activities. Math development is also related to a child's later academic achievements and occupation in STEAM (science, technology, engineering, arts, and math) fields[10,15]. Several theories propose that humans' cognitive structures and understanding of abstract concepts, such as mathematics, are formulated through bodily interactions[1,5,8,13,14] which makes tangibles promising for education.

A new set of cognitive developmental studies [21,24] propose that one of the important foundation for mathematical understanding is *nonsymbolic number representation*, such as the ability to decide between two different quantities as more/less (Figure 1). This ability can be affected by several physical cues (shape, volume etc.) [20]. We believe that, tangibles, naturally having perceptual cues, can foster this understanding. To our knowledge, there is no tangible based systems that target nonsymbolic math.

Projection based mixed reality (MR) technologies with tangibles offer several potentials for our investigation efforts. To begin with, there are diverging views on perceptual details of tangibles might affect learning[6]. One view is that objects resembling everyday items (cars) help linking abstract concepts with the real world[16]. Another view is that detailed objects hinder learning by drawing too much attention to themselves, and limit generalizability of concepts by priming children to a certain representation[18]. We speculate that projecting perceptual details onto an object during training could attract the attention to the task, more than the object itself. Also, overlaying different visuals onto objects enables representation of various entities[22], which might contribute to the generalizability and relatability of the taught concepts.

Based on these findings and assumptions, we developed an initial projection based mixed-reality (MR) game with tangibles. Our goal was observing children's interaction with this system to guide our further design processes towards developing nonsymbolic math trainings. In our game, children's physical actions have effects on both the digital interface and the appearance of physicals via projection. The portable setup requires no installation and tracks objects and gestures. The training follows a narrative in which the child helps a virtual character by placing tangibles onto a surface and answers questions with pointing gestures.

In this paper we focus on our observations from sessions with four 3-to-5-year-old children. We discuss their meaning for the development of our work. Initial clues show that our MR setup leads to exploratory and mindful interactions, which could inspire both interaction design and education-oriented studies.

Background and Related Work

Symbolic Math

Symbolic math is an umbrella term based on written symbols and precise representations, such as writing or verbalizing 2+2=4 (Figure 2)[21].The current interactive tangible applications for early math focus on symbolic math, like number knowledge, via digital tangibles or table top studies[2,9].

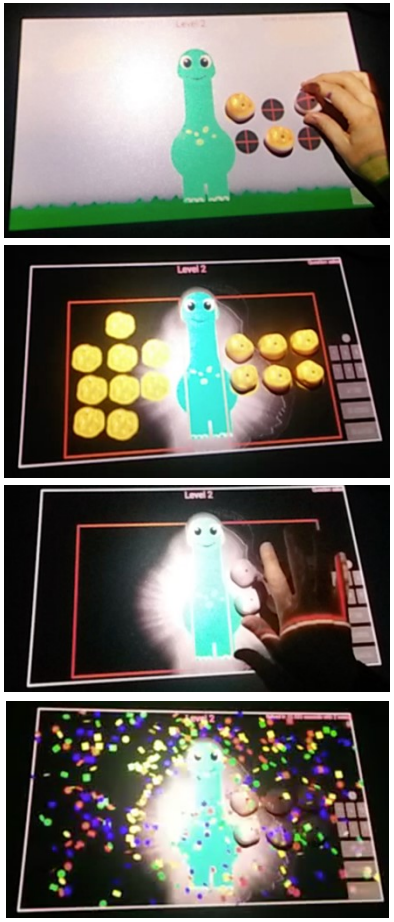


Figure 3: An example trial from the game. a) (top) Object placement and resulting 'powers' b) Projected ratio c) Answering "Which side has less stones?" with gestures d) Positive feedback audio + visuals

Nonsymbolic Math

It is asserted that nonsymbolic math ability reflects onto the symbolic math skills[4].This form of math covers a conceptual knowledge of and judgement between quantities, i.e. more/less comparisons without counting. In that respect, several screen-based trainings that focus on approximate number training emerged. In these applications the child sees different ratios of quantities on two sides of the screen that are presented for a short amount of time to prevent counting. After seeing both quantities, the child taps at the side that responds to the question: "Which box has more/less objects?".

Additionally, quantity can feature sensory magnitudes such as area and volume [20]. Piaget and many other scholars show how children's perception of quantity is affected by these [11]. In the conservation of quantity tasks, children between 2 and 6 years of age are presented the same amount of marbles in different arrangements. Upon these 'transformations', children most likely think that the quantities have changed.

Projection Based MR Systems

There are studies that use MR for math education via HMDs (head mounted displays) [17] but the user interacts with virtual objects. In one paper [23], handheld devices are used, but holding the device restrains the tangible interaction. In this point 3D projection mapping has a great potential. It lays a real time virtual image on top of a physical object , and any tangible can become an interface [7]. SMALLabs[25] uses a similar room scale technology with a fixed projective system. In contrary, we use a tabletop system that enables to focus on tangible interaction, which is needed for understanding nonsymbolic math.

Design Components

Tangible Objects

For the physical objects, we designed 3D printed amorphous white tangibles with smooth surfaces. This was to minimize the attention drawn their physical properties, and to enable clear projection of textures on (Figure 2). The rough diameter and height are 30mm,



Figure 2: Tangible objects with projected information.

appropriate for the age groups hand grip.

User Interface & Storyline

Before building the system, we deduced the essence of what we wanted the children to do in our trial. These were 1) training with tangibles to support the sensory magnitudes of quantity, 2) comparing these to other ratios for nonsymbolic math development and 3) experiencing objects with different appearances to support generalizability. Thereafter, we designed a narrative character and its storyline. "Dima" is a dinosaur inspired by children's fascination. It is drawn in front of a simple background and has minimal visual details. The projections on the objects have different colors/textures in each trial.

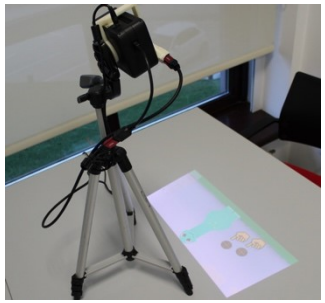


Figure 4: Overall setup.

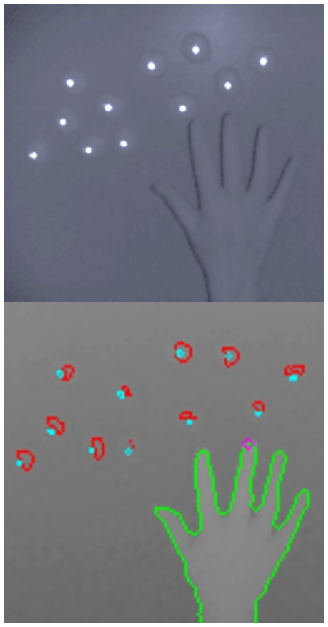


Figure 5: An example of a) infrared image, b) depth image with detected contours. (Blue: retroreflective markers, green: hand contour, pink: finger-tip, red: discarded contours.)

The children are asked to help Dima on a 'magical stone' quest. To that end, the child places objects at the shown spots, which makes the stones gain magical powers, (Figure 3a). Their power trigger another set of stones to appear (Figure 3b). All objects disappear after a while to prevent counting [12]. To gather both of their powers, the child gestures to the side that has more/less quantity, depending on the question. After gesturing at the correct response, Dima gives a congratulatory audio feedback, and the surface shows an effect (Figure 3d). For incorrect responses, Dima says "Reconsider your answer."

Training Module

By drawing on the research from non-symbolic math, we designed several training modules. For beginning, this paper focuses on the quantity comparisons module that has 6 levels. On each level, the child is trained to compare different ratios starting from 1:2 (easy) to 5:6 (hard). We controlled the placement of objects via circling the input areas. This way, we enable the child to see quantities in different arrangements. The amount of input objects (up to 12), projections and the placement of tangibles on the surface are all randomized.

Technical Details

Hardware

We use a prototype Android device designed in our lab. Instead of a touch screen, it has a Sony CXN020X pico-projector as display. It is equipped with Qualcomm APQ8016 (CPU: 1.2 GHz) processor and 924 MB RAM. Also, we connect a ToF (time-of flight) depth camera, PMD CamBoard pico flexx, which can give pixel depth and IR (infrared) image in 0.1m – 4m range. We mounted the device on an adjustable tripod. The overall setup can be transported easily and does not require any prior installation (Figure 4).

Software Implementation

In the setup, the depth camera and projector do not share the same coordinate space. Hence, we estimate the transformation between them by using 2D-3D matched pairs. Even if the system is relocated, the estimated transformation will be same because the camera and projector are attached together. Since our processing capacity is limited, we keep the tracking procedure simple. Objects are tracked using retro-reflective markers which look very bright in IR image. Also, we apply a depth-based method explained in [27] to understand where the child points (Figure 5). The calculations are done in device CPU. The game is designed as an Android application, written in Java and C++. We used OpenCV for image processing and RoyaleSDK [29] to get 3D point cloud and IR image.

Preliminary User Study

This user study aimed to see children's comprehension of the systems directives, their interaction with the overall setup. We invited parents with 3-5 years old children (M: 3.8) on a volunteer basis. Four children (2 female) played with one training module for 30 minutes. All children go to preschool and have basic symbolic knowledge (counting), except for one. Moreover, we conducted a semi structured interview with parents that involved their child's technology use. One parent said that they banned the tablet usage, because it had a negative impact on the child's attention span and increased his tantrums.

During study, if the child was hesitant to act, we provided simple cues like, "You can put a stone on to







Figure 6: Participants exploratory behavior with the system

the shown area." Besides these, we provided no instructions for the game to minimize our influence on the natural interactions.

Findings and Discussion

Four children completed the designated tasks and were fully attentive. The following findings are common interaction patterns and they may be generalizable to other tangible MR systems for child education and could inspire other interaction design studies.

Unrestricted setup encourages children's exploratory behavior

Our setup invites gestures and tangible use in different trials and lets the children use these interactions the way they desire. We think that children's unprescribed behavior coupled with our unrestricted setup encouraged surprising interactions. For example, in the tutorial session, we show the input circles and urge the participants to put an object there by using pointing icons. Excited by the setup, one child mimicked this gesture to see an effect. Children also touched the projection surface and placed the objects onto the various points to see if they could draw a reaction. By chance, one child brought his toy car to the session. He tried putting the tangibles on the car and carried it to the input circles (Figure 6).

If an unrestricted setup is the source of these free interactions, , we believe that developers of MR educational tools could consider these exploratory behaviors of children, coinciding with the tangible interaction literature [3]. In our study, children interacted with the system as they wanted, which is defined as open-ended play in [26]. Amplifying these interactions via different tangible forms and gestural inputs could be a way start.

Projection draws attention to tangibles and supports engagement

In order for children to continue a training by themselves, their engagement is vital [28]. During our studies, children were excited to see what would happen and were pleasantly surprised with each input due to interactive projection. This sustained their overall engagement in our 30-minute study. In fact, one child wanted to play once more. Even though this might be due to a 'novelty effect', our results suggested that the novelty can be kept alive and engagement can be prolonged thanks to the ability of altering the visuals with projection. These changes can also support the generalizability of the trained concept.

Multi-modal interaction provides a mindful way of interacting with educational tools

Placing the objects to the shown spots required concentration on each input. Referring the insight of one parent, the mindful nature of the game can be very positive on a child's behavior. Additionally, our game requires different actions in each step: 1) placing all the objects, 2) assessing the consequent projected ratio and 3) gesturing at the answer. None of the interaction methods were a repetition of its prior, yet each step was connected. In that sense, we observed how the system made the children focus on each action in order to play. In mixed reality environments maintaining such focus on the taught concept is crucial [19]. If multi-modal interactions are indeed the cause of the mindful behavior, this finding could have a significant impact on the comprehension of taught concepts. We intend to test this assumption by using control conditions that

have one type of interactions, such as gesture only or tangible only trainings.

Further guidance is needed after incorrect answers
During the study, our narrative and audial feedback was understood by the children. Yet, on two occasions, the auditory negative feedback ("Please reconsider your answer.") was not enough to provide a reflection on their answers. Upon the gesturing at the incorrect answer, one child kept on pointing to the same side, whereas another child immediately pointed to the other side without thinking. Designers might include visual effects on the tangibles or on the narrative character to increase this understanding.

Conclusion & Future Work

MR interfaces with tangibles is an unexplored area, however, they offer a great potential for embodied learning. This work-in progress paper presents our observations on children's interactions with a tangible based MR game to guide our further design processes towards developing nonsymbolic math trainings. In this preliminary user study, we explored and discuss initial clues towards its usage, and it might be the first preliminary study in this field. In brief, our initial clues are (1) *Unrestricted MR setup might encourage children's exploratory behavior, and developers of MR educational tools could amplify these interactions via different tangible forms and gestural inputs* (2) *Projection might support the engagement of children with its flexibility to create alterations on the educational materials,* (3) *Fostering multi-modal interactions might provoke a mindful way of interacting with educational tools,* and (4) *Further guidance should supplement auditory feedback to provide reflection on incorrect answers.*

These new initial clues demand further consideration and deeper research, both in terms of psychology and interaction design disciplines. We plan on having longitudinal trainings with more children and control groups to deduce our system's contribution for nonsymbolic math. From the developmental studies perspective, if our training will be measured as effective, we think it will be a significant finding for nonsymbolic pre-K math education.

As for the interaction design outlook, if our new interaction-based clues are confirmed in further studies, it would be an important step towards establishing design frameworks for MR-projection based education systems. We intend to integrate further design frameworks, guided by our observations, to develop our study. Also, the blend between space, objects and virtual projections have the potential to trigger design explorations, and children's interaction with these systems may inspire the interaction design field. For future work, adding these design perspectives could have a positive impact on our system.

Acknowledgements

H.Urey and E.Salman acknowledge the support from European Research Council (ERC) under the European Union's Seventh Framework Program(FP7/2007 2013) / ERC advanced grant agreement (340200) and ERC Proof-of-Concept Grant No. 755154.

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