Designing with and for Preschoolers: A Method to Observe Tangible Interactions with Spatial Manipulatives

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ABSTRACT

To date, the developmental needs and abilities of children under 4 years old have been insufficiently taken into account in the early stages of interaction design. This paper addresses this gap in the research by exploring how children between the ages of 26 and 43 months interact with spatial manipulatives. To this end, we modified intervention techniques for early spatial learning found in cognitive developmental studies and combined these with design methods used in Child-Tangible Interaction (CTI). From the former we borrowed the Preschool Embedded Figures Test (PEFT), and from the latter a storytelling approach incorporated into structured tasks with hands-on tools. In this paper, we first discuss related work on early spatial learning and CTI methods. Then, we describe a case study conducted with 14 parent-child dyads. Finally, we present the results, which offer insight into young children's mental rotation skills, different rotation action strategies and parental input requirements. Our findings contribute to design methods to elicit age specific knowledge about young children's hands-on learning, and set forth techniques and design considerations for evidence-based CTI to scaffold early spatial thinking skills.

Author Keywords

Spatial learning; tangible interaction for learning; design with young children; child-tangible interaction; design methods.

ACM Classification Keywords

D.2.2 [Design Tools and Techniques]: Evolutionary prototyping, Object-oriented design methods. H.5.2 [User Interfaces]: User-centered design, Interaction styles.

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INTRODUCTION

Children born today grow up in a complex ecology of artifacts, technology, and data. The digital and phsycial become increasingly interconnected, resulting in wide range of hybrid experiences. Nowadays, children as young as 2 years old actively use technology but, unfortunately, they are often left out in the design process [15]. There is a lack of methods to involve children younger than 4 years old in the design process [5]. However, involvement of children early in the design processs is important to understand their needs and abilities [2, 12, 13]. The case study presented in this paper addresses this gap in Child-Tangible Interaction (CTI) research. This paper is part of a larger project that aims to develop design guidelines for CTI tools that develop young children's spatial skills. Our approach combines intervention techniques found in cognitive developmental psychology with design methods that involve young children at an early design phase in the field of child-computer interaction research (see **Figure 1**). The case study presented in this paper, focuses on children aged 2 to 4, which is a critical period for developing spatial skills and establishing effective and durable learning [14].

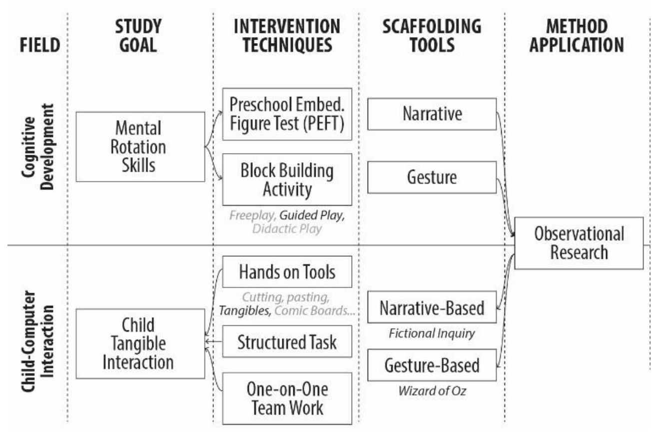


Figure 1. Complementary tools and techniques in two fields: Facilitating learner centered design for children to aid CTI.

We put emphasis on scaffolding spatial skills (i.e., mental rotation), because these skills are linked to children's participation in STEAM fields (science, technology, engineering, arts, and mathematics) later in life [22, 23]. Furthermore, spatial skills are malleable [22, 23] and early physical interactions with manipulatives (e.g., puzzle play, block building activities) improve mental rotation skills (i.e., imagining the change in orientation or direction of objects in mind) [22]. Research has shown that children who play extensively with puzzles between the ages of 2 and 4 have better mental rotation skills by the age of 4.5 than their peers who did not [14]. Building on this work, our research question is as follows: How can we integrate intervention techniques for early spatial learing with design techniques to inform a CTI design?

To address this question, we developed a goal-oriented play activity with spatial manipulatives presented within a storytelling context. We conducted an observational study with 14 parent-child dyads; children were between 26 and 43 months old. In this paper, our aim is twofold: (1) To obtain a first-hand understanding of children's mental rotation skills, strategies and requirements for parental input while interacting with spatial manipulatives, and discuss the results to inform CTI design. (2) To evaluate and discuss the approach that we have developed to inform CTI design. In future work, we will use these insights to provide in-depth knowledge about young children in design that incorporate CTI for early spatial learning and contribute to exchange between theory and practice.

BACKGROUND AND RELATED WORK

This study is grounded on theories and intervention techniques found in two fields: spatial learning as a domain in cognitive development [22, 23], and CTI as a form of child-computer interaction research [1, 16, 17, 19]. In this section, we first describe intervention techniques for early spatial learning, and, afterwards, design methods to inform CTI. We show the value of combining these complementary means to design CTIs for and with young children.

Intervention Techniques for Early Spatial Learning

Mental rotation skills, as a type of spatial skills involve recognizing, describing, classifying objects, shapes or forms. To date, there are only a few intervention techniques that measure preschoolers' mental rotation skills such as the *Block Design subtest* by the Wechsler Preschool and Primary Intelligence Scale (1963), and the *Preschool Embedded Figures Test* (*PEFT*) developed by Witkin et al. (1971) and validated by Saracho (1986). Experimental studies also assess mental rotation skills, but with older children. The intervention tests for preschoolers mentioned here typically involve mentally and physically transforming pieces to fit into particular shapes or locations [14, 23]. Playing with puzzles, wooden blocks, or geometrical shapes are known to be useful for spatial activities (e.g., visual-spatial and organizational processing abilities, nonverbal problem-solving skills) and they foster mental rotation skills of preschoolers [14]. They are also helpful in providing immediate feedback as to whether the piece fits or not through their physical affordances [14].

However, play activities with shapes could be enhanced with complementary tools leading to a more effective spatial learning process at early ages. Examples of such spatial tools are *narrative* and *gesture*. These tools can scaffold early spatial thinking and learning of children between 2 and 4 years of age [10, 14, 23]. *Narrative* is a scaffolding tool for children in processing the spatial information and make sense of the spatial relations [6]. *Storytelling* intervention as a form of narrative has a positive impact on spatial visualization, construction, and rotation skills when incorporated into block building activities [6]. *Guided-play* that uses narrative context in a goal-oriented play activity has a positive impact on early spatial learning compared to free play or didactic play activities with tangible objects [10]. *Gesture* is another powerful tool for spatial learning [7]. It conveys a meaning within space and helps to understand the components of an action that promotes learning of abstract ideas [7]. Furthermore, research has shown that children who *gesture* more while playing with blocks and puzzles have performed better in mental transformation tasks than their peers who did not gesture [7]. The question is how to integrate and modify these tools and incorporate intervention techniques found in cognitive developmental studies into existing design methods to ensure an evidence-based interaction design which is developmentally appropriate for this wicked target age group.

Techniques to Design for and with Preschool Children

Much research on interaction design and children targets 4-year-olds and above. Children before 4 years of age cannot design their own learning goal because, as emphasized by Scaife and Rogers, they neither have the knowledge or expertise to participate in the collaborative models prescribed in participatory design approaches [20]. In addition, children between 2 and 4 years of age are still in the process of generating ideas verbally and they are dependent on their caregivers. To inform the design process, however, most studies rely on verbal methods such as questionnaires, diary-taking or interviews [9, 11, 15]. Only a few studies target pre-kindergarten children under the age of 4 [9, 11, 15]. Some of these studies derived from Participatory Design and Cooperative Inquiry approaches to design that involve young children actively in design process [12].

In the *Mixing Ideas* technique, Guha and her colleagues focus on involving children between 4 and 6 years old in the design process of tangible ubiquitous technologies for preschool classroom [11]. Based on their results they argue that young children need

1) *hands-on tools* such as drawing, cutting-pasting or tangible toys to communicate their ideas and thoughts;

2) *more structured tasks* to participate in the design process rather than open-ended questionnaires or interviews;

3) *smaller groups to collaborate* (if possible one-on-one work) with adults as a team.

However, a study by Barendregt (2013) found that even though drawing intervention is a useful technique for preliterate children, 4-year-old children still have difficulty in using drawing to generate and communicate a design idea [3]. In addition, Hiniker et al. (2017) recently showed that children between 4 and 5 years old have difficulty in generating cohesive design ideas using *Fictional Inquiry* and *Comicboarding* techniques [12]. *Fictional Inquiry* entails creating an immersive fictional storyline to elicit design insights within an imagined reality. In *Comicboarding*, participants are invited to complete an open-ended comic strip to generate novel ideas [12]. Here, the key can be to provide more structured tasks than these design techniques mentioned above for children younger than 4 years old, and to facilitate their involvement in the design process.

Insight in [11, 15] point that *observational methods* can yield better results than relying on children's ability to articulate opinions verbally. These methods allow to observe children's opinions or thoughts in their embodied actions and expressions [11, 15]. Among these observational methods, "*intervention with tangibles*" comes forward as the most convenient way to elicit information about requirements of preliterate children [11, 15]. For instance, [15] used the Wizard of Oz technique, which enabled them to observe and capture how 3- to 6-year-old children would naturally manipulate the toys and use gestures to interact with the system elements [15]. Their aim was to develop and test a tangible tabletop prototype. In this technique, an adult "Wizard of Oz" triggers the game events and provides necessary feedback to children, which helps to discover unexpected gestures that children make for each task [15]. However, they reported that their 3-year-old participants were not able to finish the tasks that needed precise toy movements whereas those older than 4 years old could complete the whole session [15]. Thus, the limitations in design techniques in terms of gathering insight from very young children are yet to be resolved.

A literature review by [18] showed that most existing adaptations of design tools or methods for designing for infants and very young children consist of reducing the complexity of the activities, as well as duration to ensure children stay engaged throughout the task [18]. Still, as given above most of them find difficulty in eliciting the required information from this wicked target age group. To our knowledge, merging techniques in cognitive developmental research and CCI field has not been done before with children between 2 and 4 years old. The wide and complex field of developmental knowledge requires time and dedication to be grasped by designers during design practice. Therefore, there is a need of design tools to bridge this gap [18].

OUR APPROACH TO OBSERVE PRESCHOOLERS' INTERACTIONS WITH SPATIAL MANIPULATIVES

Based on the work presented above, in this study, we combined techniques for early spatial learning found in cognitive developmental literature, and methods used with preschool children in CTI design to be able to extract information from this particular age group (see **Figure 1**). We believe, this combination is important to ensure that we use reliable techniques validated for providing age-specific knowledge about the target age, and to pursue an evidence-based design process.

In order to gain in-depth insight into young children's abilities and needs in early spatial learning to inform CTI design, we followed Guha and her colleagues' guidelines [11] to develop the tools we used in our design approach:

1) We defined age-appropriate *hands-on tools* as spatial manipulatives to interact with (i.e., tangram and Fröbel Gifts) (see **Figure 2**);

2) We created *structured tasks* by using the *hands-on tools* in a goal-oriented play activity integrated into intervention techniques suggested for early spatial learning (i.e., *storytelling* and *PEFT*) (see **Table 1**);

3) We tested the developed design materials with *small groups* as parent-child dyads (see **Figure 3**).

Hands-On Tools: Age-Appropriate Spatial Manipulatives

As age-appropriate *hands-on tools* for spatial learning we used one set of tangram figures (7 pieces) and one set of Fröbel Gifts (7 pieces) (see **Figure 2).** We employed these manipulatives as two different types to validate if a difference occurs to the manipulatives in children's spatial cognitive abilities at this age period. The curvilineal objects from the larger Fröbel Gifts were chosen to be comparable with tangram set (see **Figure 2**).

Figure 2. A set of manipulatives selected for play sessions: Above selected objects were from the Fröbel Gifts set, and below objects were from the tangram set.

Tangram is an ancient Chinese game that consists of 7 geometrical pieces and 5 shapes (2 big triangles, 1 middle triangle, 2 small triangles, 1 square, and 1 parallelogram), and the same number of pieces, which are fit together making thousands of figure configurations [8]. Thus, it enabled us to create figures to be integrated in a *narrative* context as well as integrating *PEFT* tasks embedded in figures by using triangular shaped objects at different scales and patterns.

Fröbel Gifts are educational toys created by Friedrich Fröbel who coined the term "kindergarten" as a place where children are helped to acquire knowledge about the world through physical objects in primitive forms [i.e., ball (sphere), cube, cylinder, surface (tablet), line (rectilineal sticks and curvilineal rings), point (beads)], and spatial relations through holding, dropping, rolling, swinging, hiding, and revealing [21]. His approach was an important milestone in realizing children's active learning (i.e., spatial learning) through hands-on interaction with manipulatives in primitive forms to make sense of the 3D world, the space as the native environment of human. His aim was to facilitate young children's abstract thinking and encourage them to build associations between primitive forms and the concrete world.

Structured Tasks: Goal-Oriented Spatial Plays

We adopted *PEFT* as a structured and reliable technique for spatial cognition [14, 23] and blended it with the defined spatial *hands-on tools* as an observational design method [4, 11, 15, 20]. We used these tangibles (see **Figure 2**) to create playful fictional stories in which a *PEFT* task was integrated (see **Table 1**). As part of our efforts to develop easy-to-use, low-tech prototypes, as well as to integrate *PEFT* task into a storytelling context, we created paper-based color print story cards: 4 picture cards for tangram figures and 4 for Fröbel Gifts (see **Table 1**). The embedded figures were integrated into the story and presented as a fictional mental rotation problem to be solved by the child. The child was expected to use manipulative objects (see **Figure 2**) for helping a character in the story (e.g., a hungry turtle which needs to eat a leaf from the tree) (see **Table 1**). The task required the child to recognize, find, and locate a tangible matching piece while doing the necessary rotation.

Small Groups: Enabling Preschoolers to Work as Teams

In order to test the design metarials we developed with very young children, we recruited parent-child dyads as play teams. This helped us to gain insight into children's narrative and gestural feedback requirements to complete the tasks. Parental input also informs a prospective CTI about required feedback required for a child teams up with the technology in absence of an adult. We provide detailed information about the recruitment under the Method section.

In the following sections, we first present the method and results of the case study. Afterwards, we discuss our findings and reflect upon our approach.

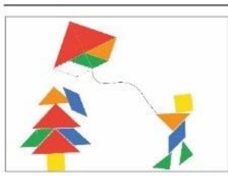
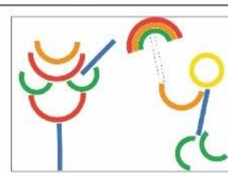
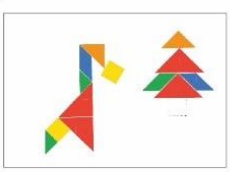
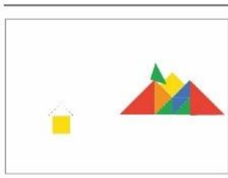
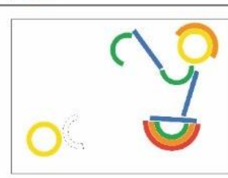
TANGRAM TASKS	NARRATIVE CONTEXT	FRÖBEL TASKS	NARRATIVE CONTEXT
	TASK 1: The turtle wants to eat a leaf from the tree. But the tree is very high. Can you take one leaf from the tree and help the turtle to feed?		TASK 1: The turtle wants to eat a leaf from the tree. But the tree is very high. Can you take one leaf from the tree and help the turtle to feed?
	TASK 2: The kid was running a kite. Suddenly a piece of the kite was stuck on top of the tree. Can you help the child to put the piece back to the kite?		TASK 2: The kid was walking with an umbrella. Suddenly the wind took blown a piece of the umbrella on top of the tree. Can you put the piece back and help the child to fix it?
	TASK 3: The giraffe was so hungry and he accidentally ate the body of the tree. Can you help him to put the body of the tree back under the leaves?		TASK 3: The car hit a huge rock on its way and its tire stuck on the rock. Can you help to fix the car's flat tire?
	TASK 4: The wind was very strong. It has blown the little house's roof on top of the mountain. Can you put the roof back on the house and help to fix it?		TASK 4: The fisherman caught the tail of the fish. The fish wants to run away but cannot swim without its tail. Can you help the fish and put its tail back?

Table 1. The two sets of picture cards with narrative contexts designed with abstract figure configurations.

METHOD

With above mentioned motivations to observe how young children interact with manipulatives, we conducted semi-structured play sessions with fourteen parent-child dyads.

Participation

Fourteen parent-child dyads (M*age*= 33 months, SD*age*= 5.12 months, range= 26-43, 9 girls) were recruited. All of them were typically developing children. Parents informed that tangram and Fröbel Gifts were both novel materials for their children who have not played with them before. Parents signed consent forms approved by Ethical Committee of the university.

Procedure

Each parent-child dyad was tested individually. Before entering the room, the parent was informed about the experiment and the tasks. Then the parent was asked to facilitate the experiment during the play session and present the *PEFT* tasks integrated into a storytelling and illustrated in the picture cards (see **Table 1** and **Figure 3**). They were asked to provide the spontaneous narrative and gestural feedback naturally if required by the child while completing the tasks. Parents and children sat in a quiet room and the whole play session was audio and video recorded. The experimenter was in the room throughout the whole session to videorecord the process, but did not interfere the task.

Figure 3. Children's on-task mental rotation actions.

Parents presented 2 sets of picture cards in a counterbalanced order to the children (i.e., all Tangram tasks first and then all Fröbel tasks and vice versa). Each picture card was presented one at a time to reduce any possible distraction the child might have had. After presenting the story orally, the parent asked the child to find the correct object and put it on the missing piece. Parents were asked not to interact with the manipulatives during the task. If the child asked for help, the parent had to provide verbal and/or gestural information without touching the manipulatives to guide the procedure and would have helped the child to solve the problem in the task. If the child had expressed any tiredness during the play sessions s/he would have allowed to take a break. If the child had not been willing to continue, that dyad would not have included in the sample.

Materials

The tangible tangram pieces used in this study were made of high-density polystyrene, a low-cost material suitable for prototyping, which looks like a wooden toy (see **Figure 2**). The size of the longest side (hypotenuse) of the large triangle piece was 2.5 cm; all the edges of the pieces had a diameter of 10 mm. The wooden Fröbel Gifts used in this experiment were commercially available in the market (see **Figure 2**). Diameter of the biggest half-circle was 5cm, and edges of the pieces had a diameter of 5mm. The size of the materials was decided according to the similar spatial relations between objects enabling to sort according to shape and size as well as the opportunity they provided for creating various figure configurations.

We used different colors for shapes and objects based on the knowledge that children used intrinsic differences (i.e., color, length) among objects to sort and arrange them in block building activities [22]. The size of the papers for picture cards used in the experiment (see **Table 1** and **Figure 3**) was 9.7 inches (255 mm) that were the same size as the iPad2 screen. Each was designed suitably for putting horizontally on the table when presented. The shapes of the figures were in the same size as the tangible objects. The sizes of materials were defined in case a tablet app would be needed as an extension for the prospective tangible system in our future work.

Data Analyses

With the help of video recordings of the parent-child play sessions, our data set was composed of the transcriptions of children's rotation abilities and behaviors while interacting with manipulatives, and spontaneous verbal and gestural feedback from the parent if they needed to complete when they were on-task. On-task behaviors refer to any type of task-related behavior that the child intends to make as an effort to engage in the task (e.g., duration time spent on-task, type of rotation errors children make). Thus, we stopped coding on-task behavior related data when the child said that the task was done. Then, we identified themes relevant to the effectiveness of our design method and the types of insights provided. Qualitative analysis was used to describe the varied on-task behaviors and rotation action strategies employed by children.

RESULTS

In this section, we first present the results about children's spatial abilities and needs including their rotation action types, region of interests, and their abilities to stay on-task while playing with the manipulatives.

Children's Spatial Abilities and Needs

Since the sample size of children in this study was limited, it was hard to present a statistically significant outcome for children's spatial abilities according to age. However, our observations showed that there were differences between children's skills and needs in terms of the time they spent on-task, the accuracy in completing the tasks, the amount and purpose of parental gestural or narrative input when unable to complete the task correctly. Although the younger children tended to spend more time or required more feedback to complete the tasks, surprisingly enough some children outperformed their older peers. In this study, we focus on the types of rotation actions, mistakes or different spatial thinking strategies that children employed while on-task to inform a prospective CTI design.

Children's Rotation Actions:

As explained above, the tasks in the design required children to listen to the story. Then, they needed to find the missing piece on the picture card, and take the correct object to fill the missing piece, which we referred as the Region of Interest (RoI) of our prospective interactive surface. According to our observational notes, children employed four types of rotation actions when filling the RoI (see **Figure 4**).

The first rotation type was the expected rotation action: 1) putting the correct object on the RoI and completing the precise rotation action according to the orientation of the missing piece (C&C). However, we found that some children also tended to 2) put the correct object with an incomplete rotation (C&I), 3) put an incorrect object with a correct rotation (I&C), which happened when they took an object with the same shape but in a different size or 4) put an incorrect object with an incomplete rotation (I&I).

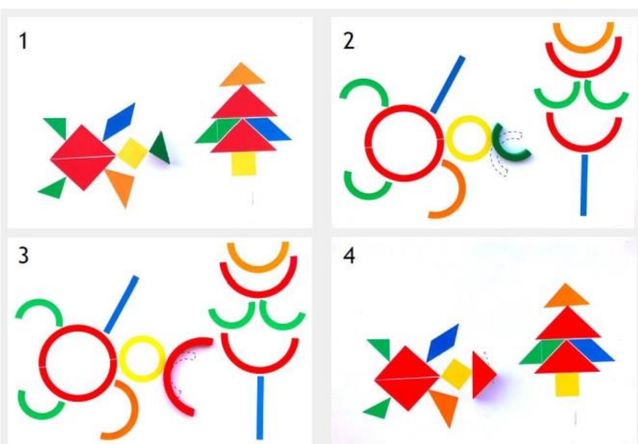


Figure 4. Rotation action types: (1) Correct object & Complete rotation (C&C); (2) Correct object & Incomplete rotation (C&I); (3) Incorrect object & Complete rotation (I&C); (4) Incorrect object & Incomplete rotation (I&I).

The Region of Interest (RoI) for the Prospective CTI:

In addition to the rotation action types that children employed, we also observed different locations on the picture cards that young children put objects other than the the missing piece which was as the actual targeted location for the task within the RoI (see **Figure 5**). As can be seen in the figure, some children were interested in putting the objects on the figures or shapes rather than the missing piece.

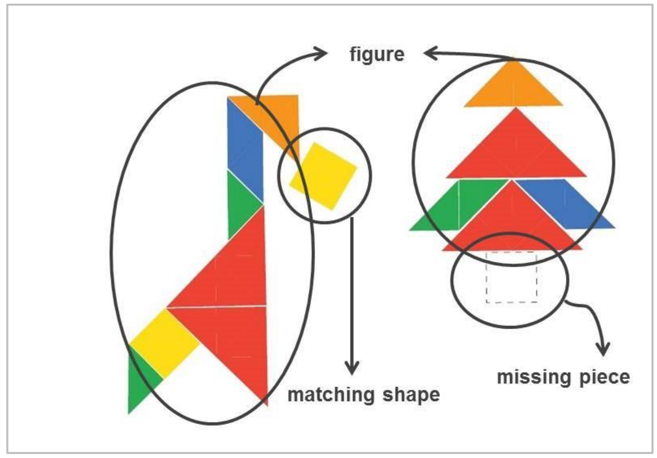


Figure 5. Different locations occured in participants' pointing gestures and rotation actions.

Interactional Affordances of Hands-On Tools:

The quantitative analyses showed that the tasks designed with tangram and Fröbel Gifts in this study reveal no significant differences in terms of the type or amount of parental narrative and gesture produced by the participants, including the total duration of completing the tasks, $ps > .05$. Thus, the children who did well with tangram, did well with Fröbel Gifts too. Children's on-task behavior took approximately 70 seconds for each task; thus, the whole play session took approximately 20 minutes for the children to engage in tasks. The time spent on-task was negatively correlated with children's age, both in tangram and Fröbel Gifts ($r(14) = -.68$, $p < .05$ and $r(14) = -.58$, $p < .05$, respectively). Thus, regardless of the type of manipulative (i.e., tangram or Fröbel Gifts) younger children spent more time on-task.

In the next section, with the help of our observations we describe the insights about varied on-task behaviors and rotation action strategies of children, and discuss the insights about children's parental feedback requirements elicited from our approach.

DISCUSSION

The overarching goal of this study was to understand very young children's mental rotation abilities while interacting with spatial manipulatives and elicit their parental input requirements to inform a prospective CTI design. Given the limited research about how to involve very young children in the design process, our approach was to combine techniques in cognitive developmental research and design studies. The aim was to observe and understand young children's mental rotation skills in this early stage of our design process. To that extent, this case study helped us to gain in-depth insight for conducting research with young children both in terms of:

- Identifying the appropriate tools and methodology for the design of CTI scaffolding young children's spatial learning;
- CTI design that can respond to very young children's spatial needs and abilities.

In the next section, we discuss the insights extracted from this approach, and present the lessons we have learned in this study.

Insights about Children's Early Spatial Needs and Abilities for CTI Design Considerations

Rotation Action Types:

As can be anticipated, there are differences in the ability levels among children between 26 and 43 months of age according to the varied rotation action types that the children carried out on-task and the region they interacted to on-task. As shown in **Figure 4** and **5**, some children employed rotation actions in different locations other than as expected to be located on the missing piece. We could not have foreseen and identified this information without children's involvement in this early design phase. For instance, the types of rotation actions included children's various cognitive spatial strategies such as picking a similar shape in a different size (e.g., bigger triangle instead of a small one) or putting the correct shape in incomplete orientation or location, *or* putting two leaves instead of one to feed the turtle just because the story says the turtle is "very" hungry. Thus, those children who made mistakes informed us more about what we could not predict rather than confirming what we already knew.

On the other hand, the younger children with further developed skills who outperformed their older peers surprised us about how spatial abilities and needs of children might vary within this age period. Our observations imply that younger children who outperformed their peers with less developed spatial skills used the stories more than their equally performed older peers. We observed that older children recognized the missing piece area on the picture so easily that they did not even need to hear the story as soon as they were familiarized with the first few tasks. Seeing the missing piece itself prompted them to complete the mental rotation tasks immediately and accurately. A possible interpretation for this might be that older children had more developed symbolic representation of a "missing piece" (what it looks like and what it stands for in a picture) than younger children.

Besides, some younger children had difficulty in recognizing or noticing the missing piece on the picture card even after getting familiarized with the tasks. Thus, this might imply that these tasks can help younger children in recognizing a novel symbol for their age and storytelling could have a scaffolding effect in exploring it. Another implication is to adjust the difficulty level of the tasks according to child's ability level such as increasing the number of missing pieces in a more complex shape, or reduce the salience of color cues. Since the mental rotation skills are found to be malleable within this threshold in developmental studies, this child-centered approach showed us that developing a CTI that can respond to children's varied mental rotation skills in playful activities is a worthy endeavor. In that sense, parental input extracted in this study helped us to gain insights into types of feedback requirements of children while trying to complete the tasks to inform the feedback mechanism of the CTI in case if the parent is absent.

Children's Parental Input Requirements:

As mentioned in previous sections gesture is another scaffolding tool for mental rotation skills [7]. In this study, we observed different types of gestures used for multiple purposes. First, children with less developed spatial visualization skills needed more gestural input from their parents in addition to the narrative context. Gestures (i.e., pointing, repetitive pointing, and iconic gesture) helped younger children to figure out the components of the narrative (e.g., shape, location, size, color) as well as to recognize the figures in the story. Thus, the types of gestures elicited in our study showed differences according to the purpose of use, or to the children's requirements such as focusing attention, or helping to notice a verbal or visual component of the story (e.g., shape or a figure). For example, parents used iconic gestures, which depicted the physical aspect of a shape or a figure to help the child process the semantic or spatial information in the task (e.g., drawing the long neck of a giraffe with finger pointing to help the child to recognize it on the picture, or showing the legs and arms and the body of a turtle to help the child distinguish it).

Moreover, as anticipated, younger children's attention span was short and they could easily be distracted. In that case, parents' use of repetitive pointing on the picture card helped younger children to focus their attention on the task. For instance, younger children who had difficulty in recognizing the missing piece in the picture required parent's repetitive pointing gestures (in some cases more than once) to be able to notice the blank area outlined with dash. Otherwise, the child might be distracted due not to noticing the blank area.

Another occasion for gesture requirement is that children within this age span needed to produce pointing gestures themselves as an interactional behavior in their communication instead of giving verbal answers. For instance, they used pointing as a response to parents' questions such as "*which one do you think is the turtle here in this picture?*" The child pointed to a figure or shape as a response instead of giving a verbal answer. On the other hand, some children (regardless of their age) used gesture as a sign of excitement if they recognized a figure on the picture card. They said out loud the name of the figure immediately when they saw the picture before hearing the story (e.g., "*Mom! Look! There is a kite in here!*", or "*Wow!*

Isn't this a giraffe?"). While doing so they used repetitive pointing on the figures as a reflection of their excitement and desire to share it with their companion. Thus, we infer in a CTI design, these gesturing purposes should be recognized well to respond to child's differing needs and abilities when a parental input is absent.

The gesture categories (i.e., pointing, repetitive pointing, beat, iconic) that occurred in this study showed us that young children's communicative requirements are not only limited with verbal input while playing with manipulatives in a goal-oriented rotation action. In that sense, the purpose of gesture use that the children required might be varied and classified to inform the input-output (I/O) between the child and the tangible system. For instance, some younger children wanted confirmation from their parents when they picked an object to solve the problem. They continued their action when the parent provided a positive feedback. If not, they made a strategy switch and changed the object with another one. A related finding is that a tangible interaction system might provide action-sensitive object recognition system to obtain the embodied data from the moment that the child picks an object until the rotation is completed. This recognition should include spatial categories of the objects such as the location, the orientation, the size, the amount, the color information along with the duration that the object stays at that stand.

Furthermore, if or when the child shows an object to the input device (e.g., sensor, camera), a gesture can activate an additional spatial information about that specific object (e.g., shape, size, orientation) in a narrative form or when the system is aware of the child's successful actions, it can mute the feedbacks. Being able to provide a simultaneous feedback to the child about her gesture would also encourage her to engage and proceed in the task. More of such design insights will be further discussed and evaluated in this ongoing study with involving other stakeholders such as designers, game developers, developmental psychologists and children.

Insights about the Design Technique and Approach

Insights about Hands-On Tools:
For the effectiveness of the tools and techniques we looked if the 3D manipulatives and the printed picture cards (considering the high abstraction level of the 2D figures in the pictures) were age-appropriate. We also examined whether the type of tangible forms have a different result on children's interactions with them. As presented in the results section, the type of manipulatives used in this study (i.e., curvilineal and triangular) did not have differential effects in terms of time, verbal and gestural feedback requirement on children's tangible interaction abilities at this age period. Hence, we decided to continue using these manipulatives in our future work. Still, we interpret that further research can be conducted to evaluate if this approach can be applied to other types of spatial manipulatives (e.g., puzzles, wooden blocks, constructional kits, etc.).

A drawback of the printed picture cards was not the abstraction level of the figures, but the fixed shapes within the picture which could not be removed. Some of the children's first attempt while solving the problem was to pick the matching shape (see **Figure 4**) on the figure and replace it on the missing piece before using the objects. For example, if the turtle needs a leaf from the tree, then we take a leaf from the tree, and that makes total sense. However, this was not possible in this prototype. Still, after one trial along with the parent's feedback, children could use the object materials to simulate an interactive game. This limitation of the paper-print will be improved in further prototypes by using removable shapes (e.g., stickers) in a context that an adult companion (e.g., designer or parent) will play the role of Wizard of Oz.

Insights about the Structured Tasks:
Even though it took younger children more time to complete the tasks, we observed that all children understood the narrated stories, engaged in the rotation actions through the intervention with tangibles. They completed the tasks, even if they employed incorrect shapes, incomplete orientations or unexpected locations. They engaged in a mental rotation activity that might facilitate their spatial thinking skills, which itself is a valuable spatial and interactional experience for children at this age period. The storytelling context integrated into the *PEFT* tasks was helpful for children (and some parents) to understand and recognize abstract figures in the picture cards. For instance, some parents could figure out how to orient the picture card after reading the story. The story also helped most children understand the requirement of the *PEFT* task without any additional information from the parent. With a story context, even our youngest participant who was 26 months old showed an enthusiasm to engage in all tasks, spending approximately 100 seconds to complete each one of them, and could participate throughout the whole experiment. Furthermore, some children wanted to continue to play with the manipulatives freely after finishing the tasks.

The results suggest that providing manipulatives with a storytelling context not only helped us conduct a more structured design method, but also invited children to solve a *PEFT* task that involves mental rotation thinking. We could extract useful findings from children with less developed mental rotation skills who require more parental input to complete the tasks. Our technique was convenient to observe and extract insights about these children's needs and abilities while playing with tangible objects. However, the task in this case was too easy for children with further developed spatial visualization skills. Thus, we believe that a more complex *PEFT* task could be created to observe these children. The low difficulty level of the task did not help us to extract any type of verbal or non-verbal requirement for the older group. Nevertheless, it informed us about their mental rotation ability level. For instance, we interpret that more complex *PEFT* tasks (e.g., embedding multiple missing pieces, less salient color cues) could be developed and integrated into stories for facilitating children's with further developed mental rotation skills targeted in this study. We infer that the type of difficulty level would also support to use a variety in spatial language (e.g., size, scale, shape, location, or orientation) rather than describing the shapes with their color names or nouns.

This study showed that children at this age range make different rotation attempts (e.g., working on different parts of the picture other than the missing shape, or working with an object other than the matching object), which also involve an ability to make a mental rotation (e.g., recognize, classify, scale). We will value and take into consideration those attempts in our further design phases. The variety in such rotation action types, ability levels, and gestural and narrative input requirements of children extracted from our case study will inform further feedback mechanisms that the system will provide to the child. Making a mistake is part of the active learning process. All incorrect object or incomplete rotation actions that have occurred in this study can lead to an exploration of new information for children's spatial thinking strategies.

All in all, we believe the set of information gathered with the modification of techniques, involvement of parent-child dyads presented in this case study will be useful in providing in-depth insight about how children at this age group are able to think and behave while interacting with spatial manipulatives. In a broader level, we hope the insights can also inspire designing child-centered design and playful learning experiences to enhance the participation of children younger than 4 years old in the design process.

CONCLUSION

This paper combined intervention techniques for early spatial learning from cognitive developmental studies with design techniques used in child-computer interaction research. The goal was to better understand the needs and abilities of 26- to 43-month-olds for spatial learning. These insights are used to develop an evidence-based and age-appropriate CTI design that scaffolds spatial learning.

In this paper, we first reviewed the literature on spatial learning techniques found in cognitive developmental studies, and design methods for younger children found in child-computer interaction research. We combined complementary methods and tools of these two fields in a case study with children between 2 and 4 years old. The aim was to gain insight in their *hands-on* interactions with spatial manipulatives (e.g., Tangram and Fröbel Gifts). Combining *PEFT* with storytelling offered a structured technique to study children's age-specific mental rotation needs and abilities. The methodological approach enabled us to observe and extract meaningful insights about young children's mental rotation skills, and the type of language and gesture feedback they require from parents or other caregivers.

The techniques and materials used in this study have limitations when it comes to informing CTI design. However, design methods that involve young children in the design of CTI have been scarce and, thus, need further investigation. Even though children between ages 2 and 4 have difficulty in communicating their views and ideas verbally, a lot can be learned about their cognitive abilities by observing their behaviors and interactions in goal-oriented hands-on activities, as such the set-up framed with storytelling context presented in this paper. In this study, an exchange was realised between theory and practice-based knowledge about young children. We hope this can serve as an example for exploring new methods, techniques and tools that enhance young children's participation in design.

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