KOÇ UNIVERSITY

GRADUATE SCHOOL OF SOCIAL SCIENCES AND HUMANITIES

Developing Transmedia Learning Environment to Facilitate Spatial Skills of Preschoolers:
A Child-Centered Approach to Design

by

Gökçe Elif Baykal

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This is to certify that I have examined this copy of a PhD dissertation by Gökçe Elif Baykal and have found that it is complete and satisfactory in all respects, and that any and all revisions required by the final examining committee have been made.

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STATEMENT OF AUTHORSHIP

This dissertation contains no material which has been accepted for any award or any other degree or diploma in any university or other institution. It is affirmed by the candidate that, to the best of her knowledge, the dissertation contains no material previously published or written by another person, except where due reference is made in the text of the dissertation.

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ABSTRACT

Technology has become an integral part of children's everyday life and children as young as 2 years old are using and interacting with computing devices [20]. Although technologies targeting children supposedly promote education and/or learning, the abilities and needs of children under 4 years of age are yet to be realized in child-computer interaction (CCI) field [2, 37]. Thus, incorporating research into technology design to gain insight about very young children's skills and requirements is a gap in CCI. To fill this gap, this dissertation combines intervention methods and techniques found in cognitive developmental research with theoretical and methodological approaches from CCI.

This thesis presents a cross disciplinary research on developing methods and design guidelines for a tangible system that might support children's spatial learning between 2 and 4 years of age. Since the design methods and knowledge about developmental needs and skills for this target age group are scarce, a design research comprised of case studies and workshops was conducted with a child-centered approach. To summarize the research process, first literature on both early spatial learning and technologies for children's learning were reviewed to explore the tools and techniques and to pursue an evidence-based design process. Subsequently, a case study was conducted with 14 parent-child dyads to extract information about very young children's spatial skills and feedback needs while interacting with spatial tools. Finally, idea generation sessions were held with diverse stakeholders such as designers and cognitive developmental experts including parents to examine how to develop a child-centered design approach for early spatial learning. All these studies conducted throughout the process resulted with the research output given below.

Based on the literature review, a theoretical framework was presented to describe and analyze the complementary natures of early spatial learning and the potential benefits of child-tangible interaction (CTI) design [Section 4: Paper I]. Grounded on this theoretical framework, a method was developed to observe the spatial skills and needs of children between 26 and 43 months old while interacting with spatial manipulatives [Section 4: Papers II and III]. The results of the case study also helped gain insights about very young children's parental feedback requirements (i.e., gesture, narrative input) and scaffolding spatial tools to inform tangible system for early spatial learning. Depending on the results of the case study and the literature review, a card-based design tool was customized to translate the findings and the knowledge about very young children's early spatial learning into design [Section 4: Paper IV]. The customized card set was used and evaluated through a series of design workshops with an interdisciplinary design team (e.g., experts in cognitive development, interaction design, game design, children's media). The user study through workshops showed that the content and design of the card-based design tool should be adjusted according to different phases of the CTI design.

The findings and evaluations of this research contribute to the child-computer interaction field by providing age and domain specific knowledge about very young children, and an exchange between theory and practice-based knowledge in an interdisciplinary design process. Moreover, the further direction of this thesis is to develop a tangible system design prototype for early spatial learning and evaluate it with children within the target age group.

Keywords: Child-computer interaction, spatial learning, child-tangible interaction, preschool children's learning.

TEZ ÖZETİ

Teknoloji çocukların gündelik hayatının ayrılmaz bir parçası haline gelmiştir. Günümüzde çocukların 2 yaşından itibaren dijital teknolojiler ile aktif etkileşim halinde oldukları kabul edilmektedir [20]. Çocukların kullanımını hedefleyen medya teknolojilerinin pek çoğu eğitim veya öğrenme amaçlı tasarlanmış olmasına rağmen, çocuk-bilgisayar etkileşimi alanında 4 yaşından daha küçük çocukların gelişimsel beceri ve ihtiyaçları henüz yeterince keşfedilmemiştir [2, 37]. Bu nedenle, okul öncesi dönemdeki çocuklara yönelik üretilen teknolojilerin tasarımında gelişimsel ihtiyaç ve becerileri değerlendirme konusunda bir araştırma açığı bulunmaktadır. Bu boşluğu doldurmaya yönelik bir adım olarak, bu doktora çalışmasında bilişsel gelişim alanında önerilen müdahale araç ve yöntemleri ile çocuk-bilgisayar etkileşimi alanındaki çocuk-odaklı tasarım yaklaşımlarını bir araya getirmek amaçlanmaktadır.

Bu araştırmada 2-4 yaş arası çocukların mekânsal becerilerini destekleyen elle kavranabilir bir arayüz tasarım süregini bilgilendirmek ve bunun için ne gibi araştırma yöntemleri kullanılabileceği sorgulanmaktadır. Bu yaş aralığındaki çocukları tasarım sürecine dahil etmek için kullanılabilecek tasarım yöntemlerinin yetersizliği nedeniyle, bu araştırma sürecinde çocuk-odaklı vaka çalışmasından, uzman görüşlerinin alındığı tasarım atölye çalışmasına kadar farklı yöntemler kullanılmıştır. Özetle bu araştırma sürecinde ilk olarak erken yaşlarda mekânsal becerilerin gelişimi konusunda ve öğrenme sürecini destekleyen yeni teknolojiler konusunda ayrı ayrı alan yazın taramaları yapılmıştır. Daha sonra, 14 ebeveyn-çocuk ikilisinin katılımıyla gerçekleşen bir vaka çalışması yapılmış ve çocukların mekânsal becerilerini kullandıkları aktivitelerde ne tür beceri ve ihtiyaçları oldukları gözlemlenmiştir. Son olarak, tasarımdan bilişsel gelişim alanına farklı alanlardan uzmanların katılımı ile çocukların mekânsal becerilerini erken yaşta geliştirmesi amaçlanan bir etkileşim tasarım aracına ilişkin beyin fırtınası ve fikir geliştirme çalışmaları yapılmıştır. Tasarım sürecindeki tüm bu çalışmalar aşağıdaki araştırma çıktılarını ortaya koymuştur.

İlk olarak yapılan alan yazın taraması sonucu mekânsal becerilerin erken yaşta gelişimi ile elle kavranabilen araçlar ile etkileşimi destekleyen teknolojilerin öğrenme sürecine potansiyel faydalarını gösteren bir teorik çerçeve ortaya konmuştur [Bölüm 4: Makale I]. Bu teorik çerçeveden yola çıkarak, 26 – 43 ay arası çocukların mekânsal becerileri ve gelişimsel ihtiyaçlarına ilişkin bilgi almayı sağlayacak bir tasarım yöntemi geliştirilmiştir [Bölüm 4: Makale II ve III]. Bu vaka çalışması sonucunda aynı zamanda çocukların mekânsal becerilerini kullanırken ebeveynlerinden aldıkları geri bildirimler (ör: dil, jest) incelenmiştir. Geliştirilen tasarım yöntemi ile elde edilen bu verilerin elle kavranabilen bir teknoloji tasarımını bilgilendirmesi amaçlanmıştır. Alan yazın taraması ve vaka çalışması sonucu elde edilen bilgiler kart-tabanlı bir tasarım aracına aktarılmış ve bu kartlar farklı alanlardan gelen (ör: tasarım, bilişsel gelişim, çocuk medyası) uzmanlar tarafından bir tasarım atölye çalışmasında kullanılmıştır [Bölüm 4: Makale IV]. Çalışma sonucunda kartların tasarımı, içeriği ve kullanımı değerlendirilmiştir. Değerlendirme sonucunda kartların tasarımın farklı aşamalarına uygun şekilde sadeleştirilmesi gerektiği ortaya çıkmıştır. Bu çalışmalardan ortaya çıkan sonuç ve değerlendirmelerin çocuk-bilgisayar etkileşimi alanına belirli bir yaş aralığı ve gelişimi hakkında katkı sağlanmaktadır. Bu çalışmanın bulguları, mekânsal becerileri destekleyen interaktif uygulamalar için bir tasarım kılavuzu oluşturmaktadır.

Anahtar Kelimeler: Mekânsal-uzamsal beceriler; çocuk-nesne etkileşimi; okul öncesi dönem çocukları; öğrenme.

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DEDICATION

I dedicate this thesis to my dear nieces and nephews Defne Baykal, Işık Utku, Umut Utku, and Çınar Baykal. They were my source of inspiration for realizing the value and joy of observing a child as a thinker, learner, communicator, and designer. I would also like to dedicate this work to all children who will hopefully enjoy learning by using the prospective technology design based on or inspired by this research.

LIST OF PUBLICATIONS

Papers included in the PhD Dissertation

Paper I. Baykal, G.E., Veryeri Alaca, I., Yantaç, A.E., Göksun, T. (2018). A Review on Complementary Natures of Tangible User Interfaces (TUIs) and Early Spatial Learning. In *International Journal of Child-Computer Interaction,* 16 (pp. 104-113).

Paper II. Baykal, G.E., Veryeri Alaca, I., Yantaç, A.E., Göksun, T. (2016). Developing Transmedia Puzzle Play to Facilitate the Spatial Skills of Preschoolers. In *Proceedings of 15th ACM Interaction Design and Children Conference* (pp. 631-636). ACM.

Paper III. Baykal, G.E., Van Mechelen, M., Göksun, T., Yantaç, A.E. (2018) Designing with and for Preschoolers: A Method to Observe Tangible Interactions with Spatial Manipulatives. In *Proceedings of FabLearn Europe 2018* (forthcoming - accepted as a full paper).

Paper IV. Baykal, G.E., Göksun, T., Yantaç, A.E. (2018). Customizing Developmentally Situated Design (DSD) Cards: Informing Designers about Preschoolers' Spatial Learning. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems,* (p.592). ACM.

Other publications during PhD that were not included in the Dissertation

Obaid, M., Baykal, G.E., Yantaç, A.E., Barendregt, W. (2017). Developing Prototyping Method for Involving Children in the Design of Classroom Robots. *International Journal of Social Robotics,* 1-13.

Van Mechelen, M., Høiseth, M., Baykal, G. E., Van Doorn, F., Vasalou, A., & Schut, A. (2017). Analyzing Children's Contributions and Experiences in Co-design Activities: Synthesizing Productive Practices. In *Proceedings of the 2017 Conference on Interaction Design and Children* (pp. 769-772). ACM.

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Jennings, N., Gruber, F., Lahusen, S., Hildebrand, E., Koray, S., Baykal, G.E., Paula, G., Toro, Y., Klempin, A., Sirichotchumanarn, P., Termisirikamol, W., Talbot, S., Stein, K., and Götz, M. (2016, May). What shapes my self. In (Ed.) Götz, M. *Identity, Televizion, 29/2016/E.* Munich: IZI-Publications. 14-19.

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TERMINOLOGY

Child-Computer Interaction: The discipline of Child Computer Interaction (CCI) is a subfield of Human-Computer Interaction (HCI). CCI is a scientific investigation area focusing on the interaction between children and computational-communication technologies. It combines inputs and perspectives from different disciplines to inform and support research and industrial practice that aim to design interactive systems for children [16].

Child-Tangible interaction: The child tangible interaction (CTI) is a conceptual framework developed by Antle (2007) for the design of tangibles and interactive spaces. The framework refers to the interconnection of children's actions in space, perceptual, behavioral and semantic mappings, and the social affordances of tangible systems with the aim for designing and analyzing tangible systems for children.

Spatial skills: Newcombe and her colleagues (2013) divided spatial cognition into two main spheres to define the subdomains of spatial skills; navigation and mental rotation . The former is related to inter-object (extrinsic) representation and transformation, which involve more than one object in relation to others, and refers to being able to take perspective according to different frames of reference. The latter is related to intra-object (intrinsic) representation of individual objects and ways to transform them, which is also referred as the ability of tool-making. Intrinsic skills are regarded as one of the underlying adaptive characteristics of human species. To date, only intrinsic (mental rotation) encodings and transformations have been assessed in relation to STEM. Thus, in this dissertation the focus is on the mental rotation skills of children with reference to their early spatial learning.

Spatial tools: *Spatial Intelligence and Learning Center* (SILC) characterized spatial tools and combinations of tools that are most effective for improving spatial learning for different groups and for different stages of learning. SILC defined specific tools that can most effectively be applied to spatial problems – analogy, language, gesture, sketching, and maps/diagrams. These tools highlight the role of relational information that is at the core of spatial reasoning. Importantly, different tools do this in different ways, some primarily highlighting the quantitative, continuous nature of spatial information (gesturing, sketching, maps and diagrams), others primarily highlighting the qualitative categorical nature of spatial information (language), and yet others highlighting both (analogy). In this dissertation, we only focused on gesture and language which are referred as spatial tools.

Scaffolding: The concept of scaffolding (as used in this thesis) captures Vygotskian approach and refers to the help children require to complete a task before they can complete it on their own. Once children internalize the process to help them accomplish a task, they can complete the process individually. As emphasized by Hourcade (2015) some research on children's technologies refers to the technologies providing the scaffolding, instead of an adult caregiver [17].

Preschool Embedded Figure Test: Preschool Embedded Figure Test (PEFT) is a measure that intends to investigate the development of mental rotation skills of preschool children. The test is comprised of a series of complex figures in which a simple form is embedded, and children has to identify it. The test was developed by Witkin et al. (1971) and was validated by Saracho (1986). The test has been used as a measure in various studies and was suggested as a training tool to be integrated in play activities with spatial toys.

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DISSERTATION

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1. Introduction

Today, we live in a complex ecology of artifacts, technology, and data. As the digital and physical environments become increasingly interconnected, young children grow up with a wide range of hybrid experiences in their immediate environment. Children as young as 2 years old become active users of technology [22]. This has resulted in debate about the kinds of technologies that preschool children need to be provided [15,25]. Tangible technologies that combine digital and physical aspects of interaction are mostly favored for children's learning among other media technologies [25,21] However, to date, developmental needs and skills of children under 4 years old have been taken into account inadequately in child-tangible interaction (CTI) design [22]. This dissertation addresses this gap in the child-computer interaction (CCI) field of research. Based on the quest to fill this gap, this dissertation was conducted in three phases: 1) a literature review in two fields (i.e., early spatial learning in cognitive developmental area and tangible technologies for learning in CCI) [Section 2, Figure 1; Section 4: Paper I], 2) a study with parent-child dyads to observe target children's spatial skills and requirements [Figure 3, Section 4: Paper II and III], and 3) an evaluation of a card-based design tool to translate the insights and knowledge gained in previous phases to an interdisciplinary design team [Figure 4, Section 4: Paper IV]. The child-centered approach in this dissertation incorporates age and domain specific knowledge found in cognitive developmental studies into design methods to inform a tangible system for early spatial learning. The results in this thesis will inform a prospective CTI prototype as design guidelines for creating early spatial learning resources.

The focus of this thesis is on developing a CTI design for early spatial learning of children between 2 and 4 years old. This age period is particularly important, because it is a critical time point for developing spatial skills and establishing effective and durable spatial learning [20]. Scaffolding the development of spatial skills (i.e., mental rotation) is important because these skills are linked to children's further STEAM (science, technology, engineering, arts, and mathematics) success [31]. Moreover, spatial skills are malleable [31] and early physical interactions with manipulatives that involve spatial visualization or assembly such as puzzle play or block building activities improve mental rotation skills (i.e., imagining the change in orientation or direction of objects in mind) [33]. There are only a few intervention techniques (e.g., Preschool Embedded Figure Test) validated for understanding preschool children's mental rotation skills and could be used as a training to think spatially at early ages [20]. Other tools (e.g., gesture, narrative, guided-play) are also suggested for improving these skills within this age period. Thus, the initial inquiry of this dissertation was to investigate the possibilities of emerging technologies that might scaffold the tools and techniques suggested for early spatial learning. A review of literature in CCI research on technologies for learning and overview of theories and findings in cognitive developmental field formed the theoretical ground of this thesis. In light of this literature review, a theoretical framework that displays the complementary natures of tangible user interfaces (TUIs) and early spatial learning is presented in Paper I [Figure 1, Section 4: Paper I].

Based on our literature review, our next attempt was to bridge between this theoretical and empirical knowledge found in cognitive development and design relevant knowledge and practice. Due to limited knowledge and methods to provide information about very young children's spatial skills, we faced two main challenges during the exploration and ideation process in this work.

The first was to explore and gain in-depth insight into very young children's spatial skills that we were designing for, and the second was to be able to translate our knowledge based on our literature review [Section 4: Paper I] and results based on our case study [Section 4: Paper III] to designers to elicit design insights. For the former, we designed a semi-structured play experience with spatial manipulatives guided by storytelling context to elicit spatial skills of this age group. We created a paper prototype as a design tool, and conducted one pilot study [Section 4: Paper II] and one case study [Section 4: Paper III] with this paper prototype. As a result of this case study, we presented a method to observe very young children's tangible interactions with spatial manipulatives [Figure 3, Section 4: Paper III]. For the latter, we customized a card-based design tool, Developmentally Situated Design (DSD) Cards [4] for our work to make the age-specific knowledge in the literature, and our case study findings accessible to our interdisciplinary design team [Figure 4, Section 4: Paper IV].

Thus, in this dissertation, the design relevant knowledge is presented in the forms of a case study with paper prototype, developing a card-based design tool, and conducting workshops with experts from different disciplines to inform a prospective CTI design. Based on these formative design studies, we conclude with reporting on lessons learned through these studies, design implications and describing one design solution for our prototype that is currently in progress (Figure 2).

1.1. Aim and Scope

The Heckman Equation indicates that the economic investment in early development has a return rate 7 to 10 percent which includes sustaining and developing effective educational resources [13]. While a vast number of unregulated and untested tools are entering the market, incorporating research into production throughout the design process is crucial [15].

This project aims to develop a guideline for a research-driven interactive CTI design that incorporates spatial skills. Recent studies have shown that spatial skills (i.e., mental rotation) relate to further STEAM achievements and can be improved during preschool years with early interventions and trainings [34,35,32]. Thus, understanding and developing tools to facilitate these skills are important. Efforts to improve spatial skills as significant predictors of achievements in STEAM fields are suggested as economically feasible due to being effective, durable, and transferable [31,32]. Early spatial activities (e.g., block-building, puzzle play) are suggested to support early spatial learning [20,33]. Moreover, use of verbal (e.g., spatial language, storytelling) [7] and non-verbal (i.e., gesture) expressions [8] in play activities have scaffolding effect as a guide for preschoolers' spatial learning. Then, how can these tools be enhanced in the everyday life experiences and learning environments of preschoolers? How can they be integrated in their regular block building or puzzle play activities?

The **first goa**l of this project is to **gain in-depth insight into preschool children's spatial skills and feedback needs** to inform a CTI design for early spatial learning.

The second goal is to **find age-appropriate tools and techniques to involve preschool children in the design process** and incorporate evidence-based research into technology design to scaffold early spatial learning.

The third goal is to **translate and make the knowledge** about the **spatial skills and needs of preschool children** readily accessible **to the designers** via a design tool.

Last, prototyping of a CTI design for early spatial learning is already underway, and in the near future, we will test and evaluate the prototype with preschool children.

1.2. Dissertation Outline

This dissertation work is composed of 3 parts. The first part consists of background and motivation that set forth the theoretical ground of this design research, research description that includes research questions and the design methods and tools used throughout the design phases. The second part consists of four papers that present the output of the different stages of this design research. These papers were published in international journals and peer-reviewed conference proceedings. Finally, the third part includes two sections related to the research contributions, and general conclusion along with the future work.

2. Grounding in the Literature and Motivation

There is increasing acknowledgement of spatial skills as an important aspect of cognitive domain that is separable from other developmental or intellectual abilities [33]. Children use their spatial skills to understand the world and to represent the relations within and between objects (e.g., shapes, location, paths, configurations) that are essential for everyday tasks [24,31,33]. Children can practice these skills through hands-on interactions with physical objects (e.g., puzzle play or block building), including visualizing how objects fit together in mind [33]. Longitudinal studies have shown that early spatial experiences in such activities have significant impact on school readiness and further STEAM skills [34,35]. Importantly, children who played with puzzles extensively between the ages of 2 and 4 have better mental rotation skills later than their peers who did not [20].

Moreover, there are tools that support children's spatial thinking skills. For instance, g*esturing* about rotating objects as an embodiment in practice is found to improve mental rotation skills of 4-year-old children [8]. Another tool is *narrative*. There is evidence that using spatial language (i.e., using words like on, in, and under) while block building play activities help young children solve spatial problems and improve children's spatial skills [33]. Also, narrative when provided in the form of storytelling and incorporated into block building activities has a positive impact on realizing the spatial relations between objects in kindergartens [7,23].

To explore what type of interactive technologies and experiences can leverage the spatial tools that young children need throughout their early spatial learning process, we have conducted various design explorations, including a literature review on technologies for early learning [Section 4: Paper I]. With reference to preschool children's learning in particular, we focused on the interactional capabilities afforded by TUIs. TUIs have a great potential for enhancing early spatial learning especially because they enable graspable, embodied, and spatial interaction more than other types of technologies [2,19,21]. Furthermore, learning is suggested as one of the major application domains of TUIs since they offer hands-on activities or manipulation of physical objects through a range of possible combinations between physical and digital representations [19,21,27,37]. Ishii and Ullmer (1997) described such possible interactions in three categories: (1) Interactive Surfaces (an active interface between physical and virtual worlds), (2) Coupling of Bits and Atoms (seamless coupling of graspable everyday objects), and (3) Ambient Media (use of sound, light, airflow, and water movement for background interfaces) [19].

Furthermore, there are various examples of TUIs that enhance *narrative-based* (e.g., KidStory [30], StoryMat [28], TellTale [1]) and *gesture-based* (TICLE [29], Curlybot [10], Topobo [26]) input, fostering very young children's spatial thinking skills. Still, these paradigms do not provide a theoretically grounded guidance that explains the means of spatial learning process to inform a CTI design process for early spatial learning [2]. We presented a detailed literature review on understanding how tangible technologies might serve early spatial learning [Section 4: Paper I]. Based on both our literature review and design explorations, we have developed a framework (Figure 2) that illustrates the complementary natures of the requirements and scaffolding tools suggested for early spatial learning and the interactional possibilities offered by tangible technologies [Section 4: Paper I]. This theoretical framework of this dissertation leads to the research questions presented in the following subsection.

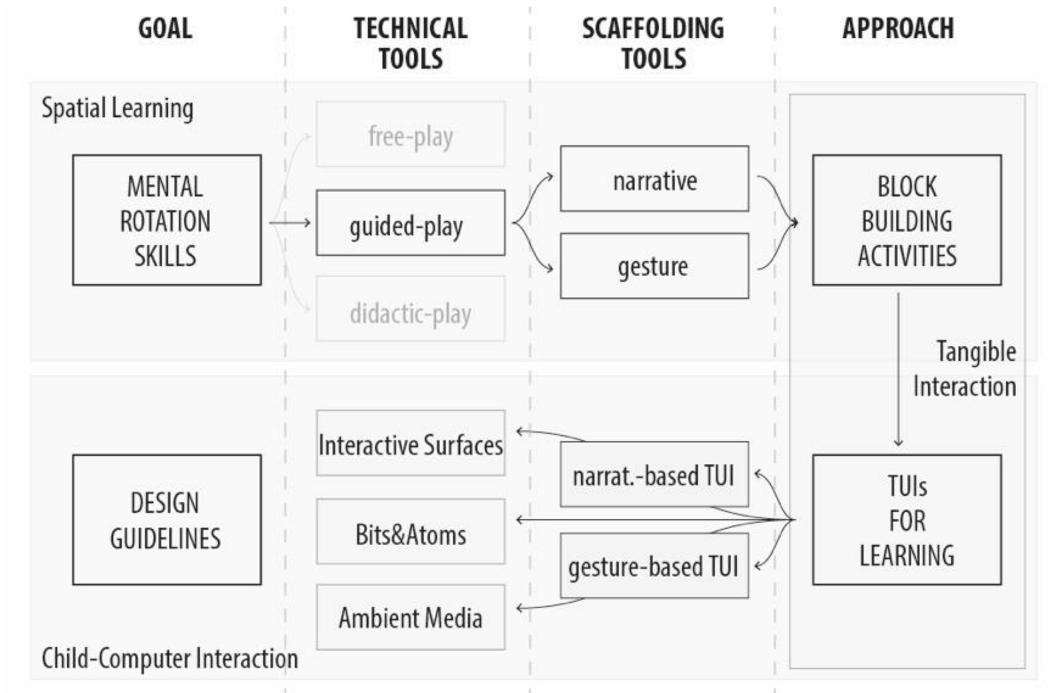


Figure 1. A framework on how two research areas might complement each other: Spatial learning of very young children and TUI design for learning (Paper I).

2.1. Research Questions

With the overview of early spatial learning in cognitive developmental studies and technologies for children's learning that maintain the tangible aspects of interaction in CCI field, we introduced the theoretical framework of the complementary natures of two fields [Figure 1, Section 4: Paper I]. Based on this theoretical framework, a series of research questions (RQ) came out in the following order:

RQ1. How can we gain insight about very young children's spatial skills and needs to inform a prospective TUI design for early spatial learning?

This question led us to investigate the tools and intervention techniques suggested to measure early development of spatial skills (i.e., mental rotation) in the cognitive developmental research [Section 4: Paper I]. We also investigated design techniques that involve children under four years old in CCI fields [Section 4: Paper II]. The insufficiency of such design methods and techniques that involve children under 4 yielded the next research question.

RQ2. How can we integrate intervention techniques for early spatial learning with design techniques to inform a CTI design?

Building on the previous work we created a method for observing preschool children's interactions with spatial manipulatives by combining the tools and techniques in both fields: From cognitive developmental research, we adopted *Preschool Embedded Figure Test (PEFT)* as a validated measure, which is suggested as an age-appropriate intervention technique and integrated it with block building play activities guided by storytelling context, suggested for early spatial learning. We merged these with tools and techniques suggested in observational research in CCI. We employed spatial manipulatives (i.e., tangram and Fröbel Gifts) as *hands-on tools* and developed structured tasks and combined these techniques in a paper prototype. We recruited parent-child dyads to test and evaluate the paper prototype [Section 4: Papers II and III]. This method helped us to observe our target aged children's interactions with spatial manipulatives as well as to gain in-depth insight about their spatial skills (i.e., mental rotation) and parental feedback requirements. This study led us to the following research question.

RQ3. How can we translate the knowledge we gained about very young children's developmental needs and abilities in spatial learning activities to our interdisciplinary design team?

In pursuing this quest, we found a card-based design tool originally created for making knowledge about children's developmental needs and abilities readily accessible to designers. We customized this card-based design tool according to the developmental domain that we focus on (i.e., early spatial learning as a cognitive developmental domain), focusing on our target children between 2 and 4 years old [Section 4: Paper IV]. We evaluated this card set through design workshops with experts from different backgrounds (i.e., cognitive development, interaction design, game design, industrial design, children's media). This study helped us in two ways: 1) to evaluate the cards and define the implications and refinements for designing this card-based tool as a design guideline, and 2) to brainstorm, ideate, and detail a CTI prototype design for early spatial learning that leads to our ongoing work.

2.2. Expected Outcomes

The expected outcomes of this dissertation are to:

- Bridge knowledge between cognitive developmental studies and CCI field [Section 4: Papers I, II, III, and IV].
- Gain and provide knowledge about children under 4 years old to inform an evidence-based and child-centered design process [Section 4: Papers II and III].
- Combine scaffolding tools and techniques suggested for early spatial learning and methods in CCI design to propose age-appropriate design methods that involve very young children [Section 4: Papers II and III].
- Find ways to build dialogue among stakeholders (e.g., parent-child dyads with designers through a paper prototype [Section 4: Papers II and III], or experts from different fields through card-based design tool [Section 4: Paper IV]).
- Cast light on the design of tangible systems to facilitate early spatial learning [Section 4: Papers I, II, III, and IV].
- Report design implications for prospective system design [Section 6].

In this section, the background, motivation, research questions, and expected outcomes were laid out. The following section describes the research methods, tools, and techniques that we used to make the exchange of knowledge possible between two disciplines, as well as to communicate with and extract information from different stakeholders, including children, parents, and experts in different fields of research.

3. Methodology

For developing a CTI design guideline to support very young children's early spatial learning, we involved different stakeholders such as parent-child dyads and experts from different backgrounds (i.e., cognitive development, interaction design, industrial design, game design, children's media) at different stages of our design process (Figure 2). Our first problem statement in the design process was how to gain in-depth insights into 2- and 4-year-old children's spatial skills (i.e., mental rotation) to inform the design. To this end, we developed a paper prototype [Section 4: Papers II and III]. Next, we refined and transferred our findings and knowledge to our interdisciplinary design team bringing together developmental psychologists and designers. Thus, we customized a card-based design tool, which we used and evaluated in a series of workshops for brainstorming and inspiration, concept generation and ideation, and constraining and detailing the design idea [Section 4: Paper IV]. Here, we describe the tools and techniques we used throughout the different stages of our design research.

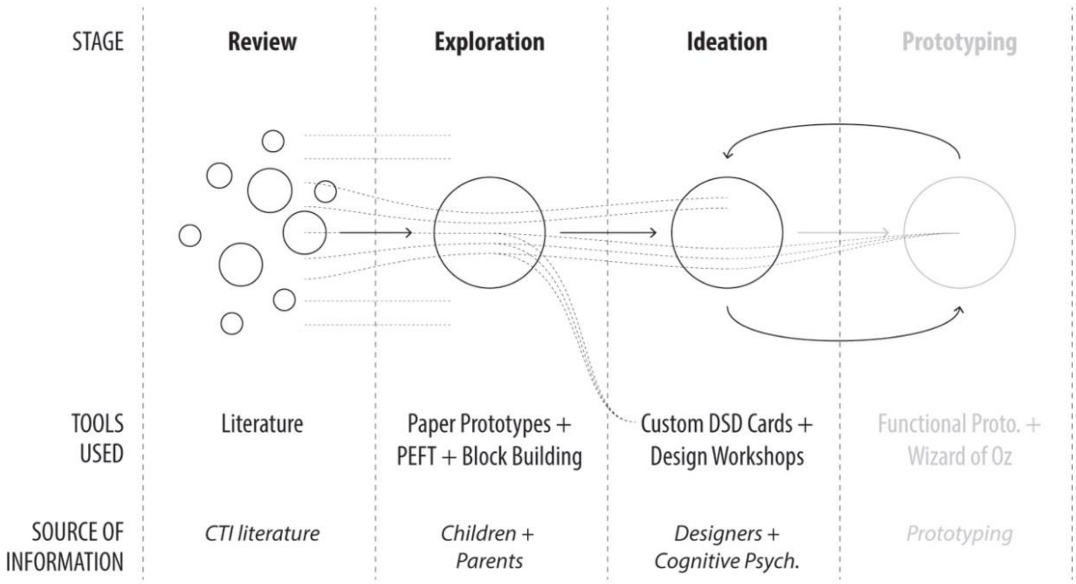


Figure 2. Research stages throughout the dissertation (i.e., review, exploration, and ideation) including the ongoing work (i.e., prototyping).

3.1. Developing the Paper Prototype: Providing insights about very young children's spatial development

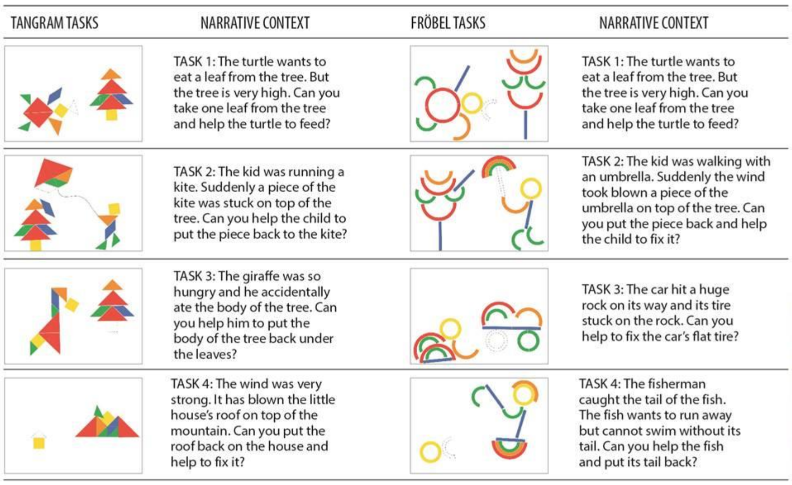
As mentioned above, much research on interaction design and children target children older than 4 years old. This is mostly because, most studies rely on verbal methods (e.g., questionnaires, diary-taking, or interviews) [22,9,12], and children between 2 and 4 years old are still in the process of generating ideas verbally. There are only a few studies that involve children younger than 4 years old in the design process [22,3,12]. However, these studies showed that 3-year-old children have difficulties in generating or communicating their ideas via techniques such as drawing [3], *Fictional Inquiry* and *Comicboarding* [14], and they cannot complete the precise toy movements when asked in *Wizard of Oz* [22].

In the *Mixing Method* technique, Guha and her colleagues argue that young children need 1) *hands-on tools* such as intervention with tangible toys, 2) *more structured tasks* to participate in the design process rather than open-ended questionnaires or interviews, and 3) *smaller groups to collaborate* (if possible one-on-one work) with adults as a team to get involved in the design process [12]. Relying on limited knowledge in previous design research conducted with children under 4 years old [22,3,12,14], we examined the techniques found in two disciplines that might inform each other from a learner centered perspective to aid CTI design for early childhood. To gain in-depth insights into the spatial skills of our target age group, we developed our paper prototypes following the three guidelines suggested by Guha et al. [12]:

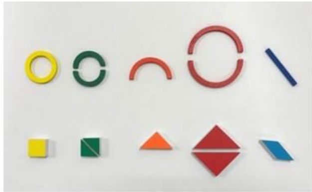
(1) *Hands-on tools:* We found age-appropriate spatial manipulatives (i.e., tangram and Fröbel Gifts) convenient for building different figures as an intervention with tangible toys (see (1) in Figure 3);

(2) *Structured tasks:* We adopted an intervention technique (i.e., Preschool Embedded Figure Test - PEFT) which involves children in a non-verbal problem solving activity employing mentally and physically transforming pieces to fit into particular shapes or locations [20,33]. The test was developed by Witkin et al. (1971) and validated by Saracho (1986) for understanding preschool children’s spatial skills in cognitive developmental studies [20,33]. Then we embedded this test into the spatial figures we built with defined spatial manipulatives (i.e., tangram and Fröbel Gifts). Next, we created picture cards in which we integrated these spatial problems embedded in different figures into a storytelling context (see (2) in Figure 3);

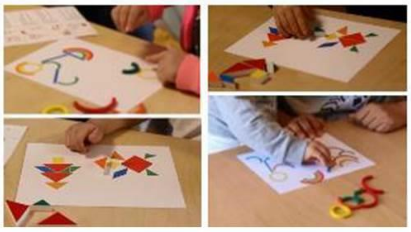
(3) *Smaller groups to collaborate:* We used the structured tasks in picture cards to conduct a goal-oriented play activity with spatial manipulatives with 14 parent-child dyads (see (3) in Figure 3). To recruit children for this study we contacted families with 2- to 4-year-old children that we knew, and asked them whether the children wanted to volunteer. Parents signed consent forms approved by Ethical Committee of the university.



(2) Sets of picture cards with PEFT integrated into story context.



(1) Spatial manipulatives: Fröbel Gifts (above) and tangram (below).



(3) Parent-child dyads in goal-oriented play.

Figure 3. The materials and techniques we used for the paper prototype based on Guha et al.'s guidelines: (1) Age-appropriate hands-on tools (i.e., tangram and Fröbel Gifts); (2) Structured tasks (i.e., Preschool Embedded Figure Test integrated into a goal-oriented play guided by a story context); (3) One-on-one work (i.e., parent-child dyads doing the tasks)

The aim of this paper prototyping study was to gain insight on children's mental rotation needs and skills while interacting with spatial manipulatives (e.g., Tangram and Fröbel Gifts). It enabled us to observe and extract meaningful information about how young children thought and behaved while on-task (e.g., willing to feed a turtle with more than one piece just because the story says the turtle is 'very hungry'), the types of mental rotation errors they made in the task (e.g., working somewhere outside the missing piece which was the actual region of interest in the task, being unable to recognize the exact size or to complete the precise orientation of a piece, being unable to recognize the dash type outline symbolizing the missing piece, etc.), and the types of verbal and gestural feedback they required from their parents when they had difficulty in understanding or completing the task [Section 4: Paper III].

The techniques and materials used in this paper prototyping study have limitations when it comes to informing CTI design. As being explained, design methods that involve young children in the design of CTI have been scarce and, thus, they need further investigation. However, by doing this paper-prototyping study, we demonstrated an exchange between theory and practice-based knowledge to develop the tasks as well as in analyzing the results extracted from the participants. For example, we used Spatial Coding Manual developed by [6] to analyze the spatial language categories (i.e., location, orientation, shape, dimension, deictic) elicited from the parents and children during the play sessions. We will use this information for the feedback design mechanism in our future prototype. Moreover, we found that even though children between ages 2 and 4 had difficulty in communicating their views and ideas verbally, a lot could be learned about their cognitive abilities by observing their behaviors, thinking strategies, and interactions.

In this study, our research-based approach provided us with age-appropriate tools and materials, and child-centered approach helped us to explore the children's interactions with spatial manipulatives. In the following subsection, we describe how we refined and transferred our findings and knowledge to the experts from different backgrounds.

3.2. Customizing a card-based tool: Translating results to the interdisciplinary design team

As presented in the previous sections there is a wealth of emerging theoretical knowledge about the early cognitive developmental abilities and skills regarding the intended age group of this research. However, most of the time designers are not equipped with such knowledge about child development. To fill this gap, Antle and Bekker (2011) created Developmentally Situated Design (DSD) cards to make age specific knowledge in different domains readily accessible to designers [4]. DSD cards were originally created as a knowledge transfer vehicle to inform children's technology designers about children's development starting from 5 years of age. Thus, we customized DSD cards for a specific developmental skill (i.e., spatial learning) of children between 2- and 4-year-olds (Figure 4). We used and evaluated our customized cards after a user study in which 19 participants from different backgrounds used the cards in three design workshops. Our analysis of observational notes and online survey results were presented and discussed how specific card features support or limit the use by our participants [Section 4: Paper IV]. A copy of the customized can be found and downloaded in this link: https://happern.ku.edu.tr/tangible-interactions-for-early-spatial-learning/

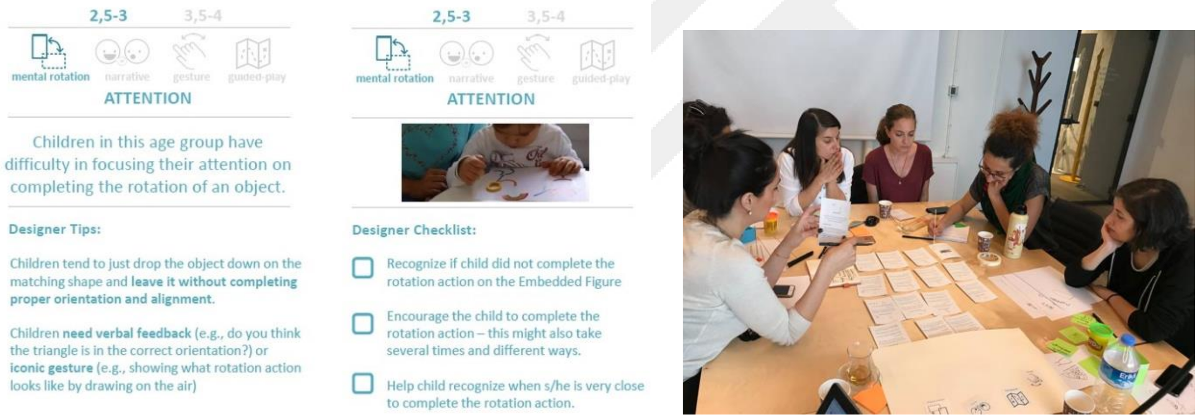


Figure 4. An example of a customized DSD card. Front and back (on the left). Interdisciplinary design team using the customized cards in one of the design workhop sessions (on the right).

We conducted user studies in three whole-day workshops. The aim of the user studies held in the workshops was twofold: (1) to generate ideas for a tangible interaction design to support very young children's mental rotation abilities and develop a design brief for a future prototype; (2) to improve our customization of the DSD cards as a design tool and use them in the further workshops with game designers. The workshops were organized in three levels of design:

- 1st Day: Brainstorming and inspiration;
- 2nd Day: Concept development and idea generation through a persona;
- 3rd Day: Constraining and detailing the design idea.

The participants divided into groups. In each group, we ensured that there were at least two people were from different backgrounds collaborating as a team. As a workshop structure, we employed "opening and closing" as a method used in gamestorming [11] to orchestrate between the three levels of design in the workshops. By doing so, we prepared tasks to be completed, discussed, and presented in half a day. The output of each task preceded and prepared the next step. In other words, the work presented by each team in every half day established the frame of reference for the subsequent session's design task. For example, the output of the brainstorming sessions in the 1st day set the context of the persona created in the 2nd day for concept development and idea generation. In turn, the output of the ideation activities in the 2nd day laid out the themes and design ideas that were elaborated in the 3rd day. This method helped us in two ways: First, no matter if a participant had joined or left the workshop at some point, the tasks could be carried out sufficiently by the team members in the next session. Second, the DSD cards could be used at different levels of the design process throughout the whole workshops. Based on our user study findings and experience, we presented our general considerations for the customization of the DSD cards for informing children's technology designers and developers. We found that customization of the DSD cards was not only necessary when targeting users at different age groups within different design spaces or to bring a common language among people from different backgrounds, but also while using at different stages of a larger technology design process. Thus, this user study does not only contribute to a design practice in a specific domain knowledge, but can also be applied to any type of complex domain space with a wicked design problem or extreme target groups.

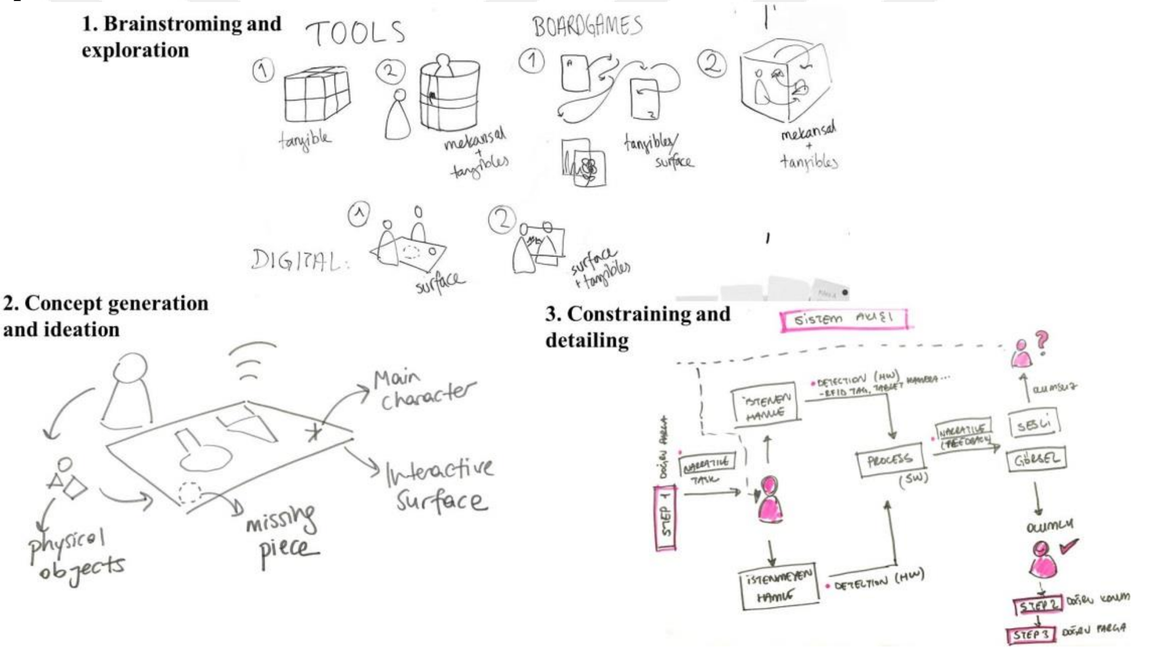


Figure 5. Sketchings from design workshops.

On the ideation level, the workshop outputs showed us that experts' views were in line with the literature and guidelines found for tangible system design for early learning (Figure 5). They emphasized the interaction between children and the manipulatives, how this should be enhanced, and the interactional possibilities should not be limited to an interactive screen (Figure 5.1). The use of interactive, multi touch screen based solution was argued to have challenges for the fine motor skills of this age range. Thus, the prominent result came out of these workshops was defining a tabletop environment which is augmented by a projector from the top. So, the CTI would be ensured whereas the interaction is enhanced by digital affordances of the projector, along with motion capture and object recognition (Figure 5.2 and 5.3). In Section 6, we briefly introduce the design solution for our future CTI prototype based on the series design explorations and ideation process throughout this research. In the next part, these expected results are elaborated and discussed in the published papers and summarized in the research contributions section.

II

PUBLICATIONS

(4. Published Work)

4. Published Work

4.1. Paper I: A Review on Complementary Natures of Tangible User Interfaces (TUIs) and Early Spatial Learning

Baykal, G.E., Veryeri Alaca, I., Yantaç, A.E., Göksun, T. (2018). A Review on Complementary Natures of Tangible User Interfaces (TUIs) and Early Spatial Learning. In *International Journal of Child-Computer Interaction,* 16 (pp. 104-113).

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A review on complementary natures of tangible user interfaces (TUIs) and early spatial learning

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ABSTRACT

Spatial skills are essential for everyday tasks, and technology blends seamlessly into children's everyday environment. Since spatiality as a term is ubiquitous in experience this paper bridges literature in two fields: theories on early spatial learning in cognitive development and potential benefits of tangible user interfaces (TUIs) for supporting very young children's spatial skills. Studies suggest that the period between 2 and 4 years of age is critical for training spatial skills (e.g., mental rotation), which relate to further success in STEAM (science, technology, engineering, arts, and math) disciplines. We first present a review of the empirical findings on spatial skills, early interventions, and tools (i.e., narrative and gesture input) recommended for training preschool children's spatial skills. By situating the work within the use and benefits of manipulatives (e.g., building blocks, puzzles, shapes) combined with digital affordances in interaction design, we address the relevance of TUIs as complementary tools for spatial learning. We concentrate on the supporting properties of TUIs that enable playful learning, make storytelling more concrete, and provide embodiment effects through physicality. Through various products found in the market and literature that address the physical–digital convergence, we invite designers and researchers to consider design practices and applicable technology that build on present efforts and paradigms in this area. To contribute to this area, we conclude with a discussion of the gaps in design methods to develop technologies for children younger than 4 years old, and propose directions for future work to leverage new tools that serve very young children's spatial learning and possible inquiries for dual payoff.

Contents

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1. Introduction

Spatial skills are of great importance for understanding the representations of relations within and between objects (e.g., shapes, location, paths, configurations), which are essential for everyday tasks. Training spatial abilities through hands-on interactions with physical objects (e.g., block building) before 4 years of age is found critical for effective, durable, and transferable learning for children [1–3]. Therefore, understanding and developing age-appropriate tools to facilitate these skills are important. This review of literature is situated at the intersection of two disciplines: spatial learning as a domain in cognitive development, and Tangible User Interfaces (TUIs) as an interaction approach for promoting constructional learning processes of very young children.

TUIs are systems in which physical objects and environments are augmented through embedded computation [4,5]. There is an increasing emphasis on investigating the interactional capabilities afforded by tangible technologies with reference to the area of preschool children's learning [5–7]. Tangible interaction that blends the advantages of digital and physical worlds has a great potential for enhancing young children's active learning [6,8], and cognitive development [4], especially because it enables embodied and inherently spatial interaction more than other types of interfaces [4]. Although learning and cognitive functioning has received much interest from TUI designers amongst other major application domains such as problem solving, tangible programming, entertainment and engagement [4,6,7,9–11], the use of TUIs for spatial learning as a particular domain in cognitive development has been less forthcoming. There is still need for theoretically grounded guidance that explains the means of spatial learning process to inform the TUI design in this regard [4].

Spatial skills are important for a variety of everyday tasks such as tool use (mental rotation) and navigation [12,13], which are important not only in the 21st century, but throughout the whole of human history. Importantly, spatial skills are malleable and can be improved with early training activities especially between 2 and 4 years of age [1]. Hands-on experiences with physical objects such as blocks, puzzles, and shapes at early ages have significant impacts on training children's mental rotation skills (e.g., the ability to perform rotating, folding, bending, scaling, cross-sectioning the two- or three-dimensional forms or shapes) [1,14,15]. Longitudinal studies in developmental studies showed that mental rotation skills are directly related to school readiness and further STEAM success [16–19]. Hence, early experiences with spatial manipulatives might also provide opportunities to close the gap in STEAM interest and entry into STEAM-based occupations in a child's further life [12,13]. It is also informed that when given in the form of a narrative, the input provides effective context for teaching spatial content in block building activities [14,20]. Moreover, embodiment in practice such as gesturing about rotating objects improves mental rotation performance of children at the age of four [21]. Then, what type of interactive technologies can leverage the tools that young children need along their spatial learning activities with such manipulatives?

TUIs offer the physicality of interaction through graspable, embodied or distributed mechanisms to support children's learning [6,22,23]. Moreover, integrating narrative and gestures are defined as typical learning domains that TUIs might enhance [6]. These tangible systems were basically inspired by block building activities [24,25]. Yet, spatial problem solving – which relates to hands-on action, manipulation, and rotation skills – is defined as one of the knowledge gaps for tangible interaction research [26,27]. Research is needed to better understand how TUIs can facilitate very young children's early spatial learning.

There is also lack of constructive design methods generated for and with children younger than 4 years of age in Child-Tangible Interaction (CTI) research. Until recently it was suggested that young children's developmental needs could be adequately met without computation [4]. American Psychological Association revised their guidance, recommending that technology might serve for children's development under age of 2 who are born as *digital natives* today in the period of the 4th industrial revolution. This era is characterized by the blurring boundaries between physical, digital and biological worlds. Thus, understanding behaviors, needs, and abilities of children younger than 4 years of age as active users of physical and technological materials, and delivering design guidelines to develop evidence-based, age-appropriate tangible tools appear as an important responsibility for the child–computer interaction (CCI) community. Our research attempts to address this gap in design knowledge, targeting children between 2 and 4 years of age as a period that is suggested as critical for training spatial skills for effective learning [1]. The primary focus of our review lies on the following questions:

- How can potential benefits of TUIs and training methods for spatial skills supplement each other to facilitate early spatial learning of children between 2 and 4 years of age?
- How can current design methods be tailored to design for the behavioral patterns, abilities, and needs of children under 4 years old, and to what extent can their participatory contribution in design be elicited while interacting with spatial manipulatives?

Regarding each research question, we first summarize the current state of theories and findings around child development in spatial learning and technology design in TUI. We present a review of empirical papers in cognitive development to compile the reliable measures, tools, and intervention models used in understanding children's spatial learning between 2 and 4 years of age. Next, we select current paradigms in the market and design literature that combine the use of physical–digital tools to give an insight on how children at different ages and/or ability levels might benefit playing with TUIs. Last, we report the challenges and gaps in the literature for researchers and practitioners. This review aims to bridge two disciplines to further interdisciplinary practices by considering how interactive technology and developmental trajectories found in spatial learning could, and perhaps should serve each other as complementary fields to provide opportunities for children to think, play, and learn.

2. Spatial skills as a learning domain in cognitive development

2.1. What are spatial skills and why are they important?

Spatial learning and thinking in the early years are essential for a variety of everyday tasks, such as packing a toy box, cutting equal slices of cake for a group of people, or remembering where an object is by cue learning [2,12,28]. Newcombe and her colleagues (2013) divided spatial cognition into two main spheres to define the subdomains of spatial skills; navigation and mental rotation [17]. The former is related to interobject (extrinsic) representation and transformation, which involve more than one object in relation to others, and refers to being able to take perspective according to different frames of reference. The latter is related to intraobject (intrinsic) representation of individual objects and ways to transform them, which is also referred as the ability of tool-making. Intrinsic skills are regarded as one of the underlying adaptive characteristics of human species. Newcombe et al. (2013) inform that, to date, only intrinsic (mental rotation) encodings and transformations, not extrinsic skills, have been assessed in relation to STEM [17]. Furthermore, a very recent longitudinal study by Lauer and Lourenco (2016) showed that mental rotation and spatial reasoning begin as young as 6 months of age [16]. They found that infants who spend more time looking at changed orientation in the displayed images (i.e., Tetris tile pieces) maintain these abilities at the age of 4 in terms of performing better at basic math skills [16]. Building on the previous work, this review focuses on mental rotation (intrinsic) skills and proposed training methods for preschoolers as an input to inform the design studies.

Mental rotation, i.e. intrinsic representation of individual objects, is examined in two key dimensions of spatial reasoning: (1) intrinsic-static skills (e.g. recognizing, describing, classifying the spatial attributes of an object, and the relation of parts within an object); and (2) intrinsic-dynamic skills (e.g. the ability to perform rotating, folding, bending, scaling, cross-sectioning the two- or three-dimensional forms or shapes). The Spatial Intelligence and Learning Center (SILC) had been working on developing measures, tests and instruments to focus on preschoolers' intrinsic spatial understanding [29]. These include measures to assess children's recognition of basic 2D and 3D geometric shapes, their comprehension of spatial terms, or ability to employ mental folding, match the shapes, rotate puzzle pieces, and find identical versus mirror images. In some of these measures, sex differences were found (i.e. Children's Mental Transformation Test, which requires to choose the right shape among multiple choices that is made of two separate pieces given in the question) [30], whereas in others socio-economic status differences occur (i.e. Test of Spatial Ability that requires copying a given target arrangement of 2D shapes or interlocking 3D blocks) [15]. The key aspect of spatial skills here is the fact that they are malleable so that both girls and boys with any kind of individual differences can improve these skills with training [2]. Then, how is it possible to train these skills?

2.2. How to improve intrinsic spatial skills (mental rotation)?

Early spatial experiences through materials such as block building activities, shape games, and playing with puzzles help children to develop spatial skills [3]. Children who play with more puzzles between 2 and 4 years of age have better spatial transformation abilities than their peers when they are 4.5-years-old [1]. Guided-play is considered as a scaffolding technique to promote more sustained learning with well-planned materials [31], and employing various spatial tools such as narratives and gestures improves the effectiveness of spatial instruction [32].

2.2.1. Guided-play as a technical tool

When delivering a content to young children, instead of direct instruction and free play, implementation of guided-play is found to be an effective learning tool, enabling child-centered exploration as well as encouraging children to become active and engaged partners in their learning process [33]. Guided play is described by Golbeck (2001) as an intermediate approach between didactic instruction and free play [31,34]. In line with this, Ferrara et al. (2011) observed that guided play encourages parents to use more spatial language during play sessions and enable both children and parents to focus on solving specific problems related to spatial thinking [14]. Shape knowledge of 4- to 5-year-old children, as a key aspect of school readiness, is also significantly improved through guided-play when compared to free play and direct instruction [14].

2.2.2. Narrative input as a scaffolding tool

Language, in the form of a well-organized narration, is suggested as a powerful tool for word-to-object mapping [20]. It also helps to increase engagement in learning spatial concepts [35]. Smith (2009) pointed to a correlation between language and early visual object recognition and noted that 18 and 24 months of age is a critical period in terms of learning object names and developing object recognition. The relationships among the emergence of whole-object representation of a shape, object name learning, and goal-directed action need to be further investigated [36]. In another experimental study Casey et al. (2008) showed that incorporating a story-telling context within a block building activity has a positive impact on spatial visualization and mental rotation skills in kindergartners [37]. Therefore, ways for enriching the content of a story in a block building activity with spatial terms and concepts to further improve young children's learning are to be realized.

The Spatial Language Coding Manual [38] developed in University of Chicago (SILC) is a useful guide to analyze the content of spatial language produced by parents during play sessions. Three categories of spatial language are coded [1]: (1) dimensions, features and shapes of objects (e.g., big, small, square, triangle, curvy, straight); (2) orientation and transformation (e.g. turn it around, upside-down, flip); (3) location and direction (e.g. on, under, next to, here, there). Here, the categorization of language input presented in the manual provides an insight about what type of spatial information is required by young children in a narrative during a block building activity. Thus, this coding manual might also inform a guideline for a further narrative-based TUI design aiming to facilitate spatial learning.

2.2.3. Gesture input as a scaffolding tool

Gesture is another powerful tool for spatial learning, which is itself inherently spatial. It conveys meaning that is offered in the language, and highlights components of an action that promote thinking and learning of abstract ideas [39]. For instance, children at the age of 3 whose parents used more gestures when using spatial words such as dimensional adjectives (e.g. big, little, tall, short), shape terms (e.g., circle, square), and spatial features (e.g., straight, curved, bent, flat) had more spatial language than their peers whose parents gestured less [40]. Gesture (e.g., pointing) also encourages children as young as 14 months to engage or participate actively in a dialogue and to capture patterns of relationships or categories in guided activities such as joint book reading. Being involved in this interactional behavior also reinforces children's later vocabulary development [41]. In a mental transformation task, 4- and 5-year-old children who gestured more performed better in fitting two shapes together than their peers who did not gesture [32]. Furthermore, providing co-speech gestures along with spatial language is particularly effective in improving the ability to put puzzles together at the ages of 4 and 5 [42].

In most research, gestures of parents and children during play activities are coded separately [40,41]. Parents' gestures are coded according to their purpose: pointing to a shape in a figure or showing a rotation to help the child to engage in the process, and solve spatial problems. Moser et al. (2015) coded 2.5–3-year-old children's gestures in puzzle play activities (i.e., 3D geometric pieces on magnetic board, and 2D representations of geometric pieces on touchscreen), beginning when a piece was touched and ending when the touch ended: action fidelity, strategy switch, and goal efficiency (that the pieces are connected within the 2-mm threshold) [43]. We argue that the types, characteristics, and patterns of parent and child gestures in previous research can inform the design of TUIs for spatial learning.

Based on these findings in the literature, we conclude that the spatial information embedded in narratives and gestures can foster mental rotation skills of preschoolers while playing with manipulatives. Guided-play, in turn, can scaffold learning. The following sections will discuss the possible benefits of TUIs in learning and how they can be further improved by the use of narrative, gestures, and guided-play principles.

3. TUIs for learning as an application domain in child–computer interaction

3.1. What are TUIs and why can (and should) they facilitate early spatial learning?

As described in the previous sections, technology became an integral part of children's everyday life and digital technologies disappear or blend seamlessly into everyday objects of children such as smart boards at schools. Children as young as 2 years old are using touch-based devices to interact with digital media [44,45]. Ishii (2008) compared the importance of couplings between physical and digital worlds to the conjunction of sea of bits and land of atoms where the myriad of unique forms has blossomed [46]. This seashore is also regarded as a promising environment that allows children to physically interact, play, think, and learn about the world they are born into. An overview by Learning Science Research Institute highlighted that these computationally enhanced tangible interfaces may provide great opportunity especially for younger children because they allow playing with actual physical objects and these tangibles might range from being completely analogous, in the form of physical representations, to being completely digital [7]. Learning is seen as one of the major application domains of TUIs since they offer hands-on activities or manipulation of physical objects through a range of possible combinations between physical and digital representations [4,6,7,10].

Marshall (2007) described a number of learning domains such as molecular biology education, programming, narrative, and dynamic systems in his analytic framework on tangibles for learning [6]. He claimed that the commonality between types of tangible interface design is that they are inherently spatial; either physically in their use of concrete manipulation, or metaphorically in their representational systems to map the interaction operations (e.g., lights, sounds or graphs in Zuckerman et al. [25,47]). Ishii and Ullmer (1997) described TUIs in three classes: (1) Interactive Surfaces (an active interface between physical and virtual worlds), (2) Coupling of Bits and Atoms (seamless coupling of graspable everyday objects), and (3) Ambient Media (use of sound, light, airflow, and water movement for background interfaces) [48]. As a further step Van den Hoven et al. (2013) categorized the levels of physical–digital integration into three groups: (1) Discrete (a physical input and digital output are positioned vertically on a surface), (2) Collocated (physical input and digital output are positioned and displayed on a surface), (3) Embedded (the system is embedded within a physical object) [49]. The selection of examples presented in Section 3.2 is based on these sets of categorizations of TUIs for learning.

The range of possible combinations of novel links between physical action and digital representations can be one of the primary learning benefits of tangible interfaces for young children [4,6,7]. As also highlighted in spatial cognition literature, tangible interaction is based on physical actions with tangible physical objects that provide spatial properties (i.e., location, orientation, and configuration), and physical attributes (i.e., visual, tactile, and audio) [4,43,50]. Physical action such as gesturing helps young learners to extract information and learn concepts from hand movements [51] as well as demonstrating their own knowledge. The core idea of Papert's Logo *turtle* approach — developed in the mid-1960s is, children learn geometric shapes easier if they use their own bodies (e.g., walking a square) [52–54]. He conceived these computationally enhanced tangibles like the robot turtle as *objects-to-think-with*, in which artifacts and understanding of concepts co-evolve and help with knowledge construction in the learning process [54–58].

Following Papert's approach, several tangible systems have been developed for children as manipulatives. Thus, the relevance of TUIs for children's spatial learning was realized long before the emergence of the term TUI [23]. The following section mainly focuses on TUI examples that combine spatial manipulatives such as wooden blocks, plastic bricks, tangram pieces with interactive surfaces and stimulate children's spatial skills.

3.2. How TUIs can facilitate early spatial learning

The embodiment effects of physical activity, haptic interactions with grasping and manipulating real physical objects, and the embedded computational power within physical manipulatives that the tangible technologies employ can have benefits on learning [6,7]. Some findings favor TUIs over graphical user interfaces (GUIs) with regard to children's engagement [59] and performance [60] in block building and puzzle play activities. However, the advantage of digital materials over physical materials in the context of learning is still controversial, and needs additional empirical validation [11,44].

Research suggests various advantages of traditional materials over digital materials in young children's learning process such as prompting higher parent–child engagement [61], more language production in spontaneous speech [62] along with physical, sensory and metaphoric qualities of material interaction enhancing playfulness [63,64]. Playing with traditional toys prompted more parental language both in quantity and quality than electronic toys designed to teach geometric shapes to children [62].

On the other hand, the unique capabilities of digital materials (e.g., data storage and retrieval, transportation, interactivity) allow for customized cues, prompts, and reinforcements. These functionalities, tailored to the individual have transformed the realm of education by scaffolding guided instructions and independent learning [65]. The combination of various features within the same platform (e.g., animation, game, narrative, audio or visual feedback) stimulates sensory and cognitive skills, while the challenges and feedback provided in the narrative flow enable not only active, but also minds-on engagement [66,67]. The most commonly referred advantage of digital tools over traditional materials are their ability to provide individual experience for children [3,11,68,69]. Through real-time feedback, digital tools and TUIs in particular, provide the opportunity to iterate action with reflection-on-action to enhance leaning [66]. So far, the advantage of TUIs compared to other materials is implied in the function and representation of physical objects in an application, so that the conventional toys can be used as controllers of interactive games [9]. However, more empirical research is needed to investigate the impact of TUIs on learning, especially compared to the use of non-digital physical materials.

Given that both physical interaction with traditional materials and digitally enhanced interactive tools carry advantages and challenges for preschoolers, then what would be the benefits of TUIs which synthesize both platforms to favor spatial skills in particular? As discussed in the previous section, children benefit more from playing with spatial manipulatives if they are guided by a narrative and gesture during block building activities [20,32,42]. There are different narrative and gesture-based examples of TUIs. Thus, the following subsections will present the examples of TUIs to understand how narrative and gesture input might be augmented in TUI design to scaffold young children's spatial reasoning.

3.2.1. Narrative-based TUIs for learning

A story-telling context as a narrative device has a positive impact on preschoolers' spatial visualization, construction, and rotation skills when incorporated into block building activities [20]. Storytelling is also a typical learning domain that TUIs might enhance because the structure of narrative includes a sequence of events [6] and helps children to organize the information they receive. By representing the temporal sequence of events in a narrative in a spatial format [6], much of the activities in TUIs for learning involves interactive storytelling [7,70]. Preschool children often engage in tangible storytelling by using physical artifacts in their immediate environment to create their own stories. Some projects in TUI have taken advantage of this physical aspect of storytelling [70]. For example, Holmquist and colleagues (2000) invented a design for interactive storytelling that allowed users to experience different parts of a story by manipulating physical objects. As such, the boundary between story and interface was blurred [71].

TUI projects based on storytelling include various aspects such as tangible characters (e.g., *KidStory* [72], *TellTale* [73]), room-sized ambient storytelling environments (e.g., *Storyrooms* [74], *Pogo World* [75]), interactive surfaces (e.g., *StoryMat* [76], *Kid-Pad* [70], *LinguaBytes* [77]), tangible word blocks (e.g., *RoyoBlocks* [78]), audio–video or motion recorders (e.g., *Tangicam* [79], *I/O Brush* [80], *Jabberstamp* [81]), and storytelling robots (e.g., *PETS* [82]). However, as Tanenbaum et al. (2010) emphasized tangible storytelling technology often focuses on mapping tangible objects for system outcome rather than focusing on the narrative meaning of the objects itself [83]. Hereby, *Make a Riddle* by Sifteo Inc. [84] is an efficient example for the use of a physical object as an embedded TUI. It is a hybrid tangible-graphical interface that teaches children spatial language (i.e., prepositions) in rhymes through manipulating Sifteo Cubes. In turn, it provides responsive narrative feedback to related motions. When delivering spatial concepts in the form of a narrative, physical objects might help young children connect with the content more readily. Thus, investigating how manipulatives can be enhanced digitally to understand a spatial content easier might illuminate the tangible interaction research and user studies on young children.

3.2.2. Gesture-based TUIs for learning

Gesture-based examples of TUIs are accounted to support children's learning and reasoning [4]. Spatial problem solving, which involves hands-on action, manipulation and mental rotation skills, is addressed as one of the important knowledge gaps in tangible interaction research [27,44]. There are a few gesture-based tangible prototypes that relate to spatial skills. *TICLE* [85] for instance is an archetype that combines physical tangram puzzle play with an interactive tabletop. *Curlybot* [86], a programmable curved object, and *Topobo* [87], a construction kit with modular block building system, are two examples of TUIs that capture physical motion and create a playful robot experience for children. However, to date, knowledge about how and to what extent children's spatial learning benefits from these TUIs is lacking.

The use of manipulatives (physical objects) in teaching and learning, especially during the preschool period has a long history [88,89]. Fröbel and Montessori introduced manipulatives as physical modeling of abstract structures related to spatial reasoning designed to foster preschoolers' learning. Resnick and colleagues (1998) translated Fröbel's and Papert's approaches into *Digital Manipulatives* that enable children to explore mathematical and scientific concepts (e.g., numbers and shapes) through direct manipulation of computationally enhanced physical objects (e.g., blocks, balls, beads, badges) [24]. Fröbel Gifts and Montessori materials furthermore inspired the development of well-known products for children that dominate the market (e.g., wooden blocks, plastic bricks, Lego Mindstorms®, Tinkertoy®, Zome®, Base Ten Blocks®, Cuisenaire Rods®, Fraction Tiles®, Wikki Stix®) [25]. Zuckerman and his colleagues, in turn, extended the work of Fröbel and Montessori by developing an interface design with computationally enhanced building blocks [24,25]. Their work introduced a new classification by situating the use of such manipulatives to encourage hands-on modeling of abstract structures for children above 7 years old [25]. This approach can serve as a basis for further interpretations tailored to the needs and abilities of preschoolers' physical actions and behaviors in play activities with spatial manipulatives.

3.2.3. Manipulatives that might be used in further TUI design for spatial learning

A recent study argued that both canonical and non-canonical shape materials on the market today are inadequate in providing variety for preschoolers in terms of inviting comparison and contrast of different versions of shapes from different categories [90]. Similarly, Verdine et al. (2014) state that most of the research that employed spatial materials in investigating the mental rotation skills of preschoolers is based on building blocks and jigsaw puzzles. However, the use of other types of manipulatives for this age range is yet to be investigated [3]. In addition, TUIs inspired by analogue building blocks (e.g., *Algo Blocks* [91], *Lego Wall* [92], *mediaBlocks* [8], *Electronic Blocks* [93], *Topobo* [87], *Boda Blocks* [94], *LittleBits* [95] etc.), generally receive more attention in the literature [5].

Clements (1998) suggested that manipulatives such as tangrams, pattern blocks, and other sets of shapes can provide a foundation to build imagery for young children and aid spatial visualization. This includes understanding and performing imagined movements of two- and three-dimensional objects [96,97]. Thus, we point to the manipulatives that afford different scales and sizes of different shapes such as tangram [98] (see Fig. 1) or Fröbel Gifts [99] (see Fig. 2) that enable a wide range of figure configurations. A preliminary study indicated that the narrative context helps children's coherence of abstract tangram figures, and triggers rotation of geometric tangram pieces, in particular, between 28 and 36 months of age [100]. Hence, tangrams can also be used for promoting younger children's spatial understanding and abstract concepts.

Here we put emphasis on Fröbel's Gifts (see Fig. 2) not only because they are overlooked manipulatives but also, they are directly linked to spatial learning that can favor a child-centered TUI design [25,101]. Friedrich Fröbel, a German pedagogue and education philosopher who lived in the first half of the 19th century, introduced a child-centered approach to education. He coined the term "kindergarten" as a place where children are helped to acquire knowledge about the world through physical objects, and about spatial relations through holding, dropping, rolling, swinging, hiding, and revealing [99]. He developed educational toys that help children to make sense of the world through primitive objects, which are known as Fröbel's Play Gifts. His approach was an important milestone in realizing children's active role in learning, in particular, spatial learning. Central in Fröbel's approach is children's hands-on interaction with manipulatives. These manipulatives in primitive forms help children to make sense of this three-dimensional world (i.e., space), which, according to Fröbel, is our native environment as human beings. His aim was to facilitate young children's abstract thinking and encourage them to build associations between these primitive forms and the concrete world. The primitive forms consist of *ball (sphere), cube, cylinder, surface (tablet), line (rectilineal sticks and curvilineal rings),* and *point (beads)* to form different series that help children to think about shape, pattern, and space [99].

Spatial manipulatives such as tangram and Fröbel Gifts allow mental rotation actions inviting children to practice *static skills*

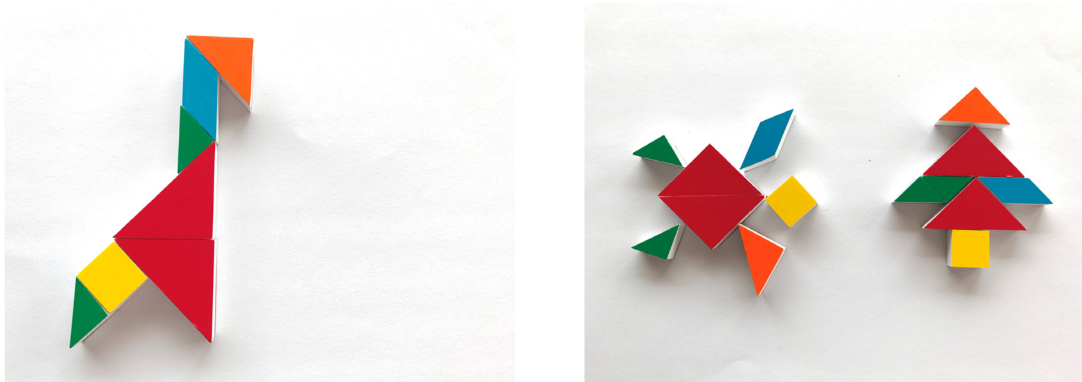

Fig. 1. Examples for figure configurations with tangram.

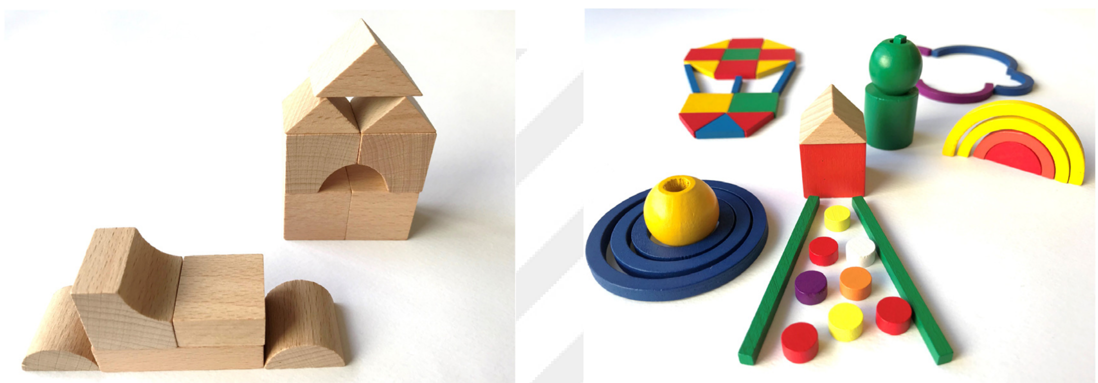

Fig. 2. Examples for figure configurations with Fröbel Gifts.

(recognizing, categorizing, and classifying objects) and *dynamic skills* (rotating, scaling, bending, cross-sectioning objects). In addition, these manipulatives are suitable for creating different figure configurations that can be integrated in narratives and tasks. The scaffolding effect of storytelling can help disambiguate young children's interpretation of how to interact with spatial manipulatives as tangible representations. While enriching spatial visualization, these materials would also provide more variety in spatial properties of objects such as location and orientation embedded in the figure configurations. This will eventually encourage young children to think and act more on mental rotation strategies that require static and dynamic skills.

Some recent works or projects in the industry use physical objects combined with digital tools that trigger spatial thinking. Most of them do not explicitly aim to facilitate mental rotation skills but rather provide children an alternative way of experience for the spatiality of reading a story book (e.g., *Bridging Book, and BooksARalive)*, programming skills to employ navigational skills and spatial language (e.g., *Dash and Dot, and Puzzlets),* or learning mathematics at early ages by using hands (e.g., *Little Digits).* A few of them enhance the use of physical block building activities (e.g., *Osmo Tangram, Koski Game)* and integrate storytelling as well (e.g., *Magik Bricks).* These works exemplify the combined use of physical–digital materials in technology and how they would expand opportunities for children to employ various spatial learning experiences in different settings while making connections among information in a specific context. However, most of these tools target children older than 4-year-olds. There is still little evidence on interactive products for very young children younger than 4 years of age as well as a suitable model for design process evaluating children as active users, players, learners, testers, informants, and design partners [56,102].

In the following section we discuss our insights on the review of two research areas and also review some of the few child-centered design methods adapted or modified to involve children as young as 3 and 4 years of age into design.

4. Discussing current gaps to bridge two disciplines

This paper presented an overview of research that combines empirical findings along with the current stand in children's spatial learning theories and in research about the current state of TUI for learning. The two areas of studies are based on the goal for extracting knowledge about how young children think and behave while playing or interacting with tangible physical objects (manipulatives) that have spatial properties (i.e., location, orientation, and configuration) and physical attributes (i.e., visual, tactile, and audio) [4,9,43]. Both fields investigate children's interactions with manipulatives, mainly using block building activities. Both research areas found narrative and gesture-based tools as scaffolding the learning process of very young children, and developed technical systems and methods by making use of these tools. Here we propose the following framework as a theoretical ground for bridging two research areas. The framework illustrates the complementary nature of two fields in terms of their constructive approach to learning, the integrative scaffolding and technical tools, and goals defined for future work (see Fig. 3).

To explore ways to make both fields' goals meet each other actively, it would be meaningful to look at design methods conducted with children under 4 years old. Although there is a growing concern in generating methods for involving children in the design process since 1980s [56,102,103], we have not encountered a design method specifically customized for children younger than

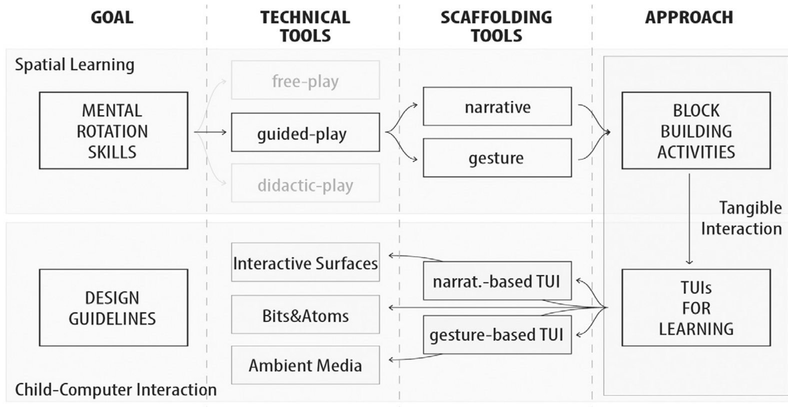

Fig. 3. Two complementary research areas: Spatial learning of very young children and TUI design for learning.

4 years of age [104–106]. We found very few adapted cooperative and participatory design methods with children. Since most child-centered methods rely on the cooperative evaluations and verbalization techniques (e.g., interviews, diary keeping, questionnaires), young children have not been directly involved in design process [50]. This is mostly because young children are less able to read, write, verbalize their thoughts, and concentrate on a task easily [50]. An initial effort by Farber et al., (2002) was to modify Druin's influential Cooperative Inquiry [107] for including children between 4–6 years old [108]. Later, with a similar attempt Guha and her colleagues' developed Mixing Ideas technique conducted with children as young as 3 years old [109]. The lessons learned through these studies showed that young children need more structured design sessions to cooperate, rather work one-on-one in a team, and can employ drawing and cutting–pasting activities to communicate their thoughts [109].

Marco and his colleagues (2013) emphasized that young children are active users of technology and thus entitled to be involved in user-centered design projects [9]. They recruited children between 3 and 6 years of age to the design of a collocated TUI system design. They reported how they used Wizard of Oz method to observe elicited gestures and Peer Tutoring for guiding narrative expressions required by child users. They concluded that the physical nature of tangible technologies fits this very young user profile to retrieve information from their user actions when playing with toys [9]. These studies showed that observational method involving children under 4 years old as users has been the most convenient child-centered design method so far for working with this challenging age group.

What Fröbel and Papert had in common was that they both began with observing children to understand the nature of the learning process, and helped children in the heuristics of playing with manipulatives as *objects-to-think-with*. Today, researchers both in TUI and developmental studies trace the observational path to understand actions, manipulations, and rotation strategies elicited from even younger children's interaction with physical objects. Hereby we argue that, spatial manipulatives not only allow learners to practice mental rotation actions but also enable producing different figures to be integrated in narratives and tasks. Therefore, they can also serve well as low-tech, child-friendly supplies for prototyping to design high tech applications. Since designers or researchers might have difficulty in communicating with children between 2 and 4 years old, such story-based tasks designed with manipulatives [100] might be helpful for involving children in interactional behavior, actively engaging them in a dialogue, and more effectively including them in the design process. The outputs of the experimental designs produced with these manipulatives will also contribute to the current state of the field by providing information about young children's experiences in user studies. Understanding how these facilitating mechanisms of spatial learning work in young children's experiences with different types of manipulatives would inform research on exploring and designing necessary components for playful environments.

Based on the reviewed literature, we can conclude that observing young children's interactions with spatial manipulatives in goal-directed mental rotation tasks in the form of guided-play might be helpful for modifying current methods found in design research, as well as informing narrative and gesture-based tangible systems. Also, methods used to code gestures and narratives used in cognitive developmental studies might also be helpful for providing empirical definitions and analysis elicited from these observational methods. We hope this paper contributes to child-centered user research methods and design studies by presenting information about user needs of children between 2 and 4 years of age, and invite research that explores ways to facilitate spatial learning related to STEAM skills such as mental rotation.

5. Conclusion

Bridging between two disciplines, a series of potential opportunities appear both for early spatial learning theories and TUIs, which in turn might facilitate young children's spatial skills. First, integrating and implementing the reliable intervention techniques and tools suggested in research on spatial learning might also yield an understanding of young children's spatial learning into physical–digital interaction. Second, developing reliable methods in child-centered design practices involving children younger than 4-year-olds might fill an important gap while providing evaluation constructs and measures. Third, bringing out formative evaluations and prescriptive guidance based on observational research that can be used to inform the design through case studies would ensure empirically validated design choices. Fourth, observing children's physical–digital interactions with spatial manipulatives would provide in-depth insights into their learning patterns as well as their user behaviors and thinking strategies. Finally, generating empirical support to elaborate the proposed claims and expanding the opportunities for preschool children's spatial experiences would also open new horizons in future research on the learning benefits of TUIs.

TUIs are constructive, relational and associative systems that bring physical and digital affordances together. TUI learning environments may therefore be helpful in the context of spatial learning. Thus, our aim is to emphasize the importance of producing knowledge and evidence-based tools to facilitate young children's spatial skills, and highlight some of the opportunities for further studies in both areas. As more research is conducted in both areas, more explorations will elicit specificity in theoretically grounded TUI design that is supportive of spatial learning.

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4.2. Paper II: Developing Transmedia Puzzle Play to Facilitate the Spatial Skills of Preschoolers

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Developing Transmedia Puzzle Play to Facilitate Spatial Skills of Preschoolers

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Abstract
This proposed project aims to develop a research-driven interactive product that facilitates spatial skills of preschoolers. Here, we present the preliminary qualitative results of a user study with the paper prototype of *Fungram*, merging physical tangram pieces on the screen within a narrative context. A pilot study was conducted with eight children between the ages of 25 and 48 months, who were presented tangible tangram pieces along with two sets of papers with and without narrative context. Our preliminary qualitative data indicates that narrative context helps children's coherence of abstract figures and triggers rotation of geometric tangram pieces. This study provide insights about children's user needs and action strategies within the proposed use scenario with graspable puzzle pieces related to screen interaction at this age range. We suggest that transmedia play expand opportunities for children to employ their spatial skills in different settings.

Author Keywords
Spatial learning; spatial manipulatives; transmedia play; preschool children; child-centered design; physical-digital interaction.

ACM Classification Keywords
H.5.2 [User Interfaces]: User-centered design, Prototyping. K.3.1 [Computers and Education]: Computer-assisted instruction, Collaborative learning.

1. Introduction

A wide range of research indicates that digital applications promote children's engagement as a playful learning experience only if age-appropriate content and design strategies are implemented suitably [4,8]. We put particular emphasis on young children's spatial skills because recent studies show close relationship between spatial experiences with blocks, puzzles, and shapes at very early ages and longitudinal success in STEM (scientific, technical, engineering and mathematical) disciplines [11,12]. Studies show that young children benefit from e-books or apps more if they use them interacting with other media such as printed books [13], tangible toys or regular home artifacts, expanding learning experience with transmedia practices in a dynamic narrative [5]. Intermediality also supports constructivist learning goals that emphasize the active role of learner involving exploration and experimentation while making connections among information in specific context [3]. We suggest that transmedia activities interacted with or independent from digital affordances would encourage young children to make connections among various settings to engage their spatial skills.

Hereby, we base our design process on a set of findings on spatial learning, the impact of play and narrative on learning process, and how digital technology affordances can scaffold the content design. Children who play with more puzzles between 2 and 4 years of age have better spatial transformation abilities than their peers when they are 4.5-years-old [7]. The input given in the form of narrative provides effective context for teaching spatial content in block building activity [1, 2], and even helps younger children to comprehend more complex prepositions (i.e. under) better [9]. By means of transmedia, the interaction qualities of the narrative space are enriched as the possibility of playfulness of the content is augmented [3]. Thus, we seek ways to combine physical spatial puzzle play within narrative context utilized by digital technology.

We follow a child-centered design process of 5 steps; 1) discovery of cognitive research output suggesting possible ways of training spatial skills at early ages as an input for our content design; 2) interpretation of format design bringing tangible spatial manipulatives merge with touch-screen in a narrative context; 3) ideation of materials and tools that would provide opportunity for the generated idea and explore the possible needs of the target users through preliminary prototypes; 4) experimentation for building the interaction and information architecture required for the content design; 5) evolution of the output by tracking learning and implications. In this current study we present the first three phases, which is derived, in part, from transmedia format design and conducted a pilot study to reinterpret our idea generation.

We chose to use tangram due to various reasons: 1. it is an overlooked spatial puzzle especially for this target age group; 2. it consists of 5 geometrical shapes among 7 pieces (2 identical large, 1 middle, 2 identical small-sized right-angled triangles, 1 square, and 1 parallelogram) enable rotation action; 3. it is suitable to create several configurations of figures to be integrated within a narrative context; 4. flat shapes would allow

Figure 1. On the left the stickers used for making the figures on papers, on the right the tangible tangram set.

Figure 2. A sample of picture presented without a narrative context in the first set.

image processing for each pieces through either color or surface detection integrating OpenCV and mountain camera in the further experimentation phase of our design process.

2. Related Work

There are a few products combining traditional toys that stimulate children's spatial skills such as lego, wooden bricks, tangram pieces on touch-screen. TICLE by Lori Scarlatos (1999) is one of the earliest tangible interfaces designed for children providing multimedia guidance. In this one, physical tangram pieces are used on a projected desktop, using spatiality and connectedness and the physical pieces were represented on a computer screen [10]. *Tangram for Osmo* by Tangible Play Inc. (2014) targets children older than 7 years old and this app enables tangible tangram puzzles match on-screen shapes, however not involve narrative. Recently launched *Magik Play* designed by Magikbee (2015) claims to merge traditional wooden toys with iPad, promoting motor skills, spatial reasoning, and collaboration via dynamic narrative, however not being reviewed yet. Still, none of the products target very young children (e.g. 2-year-olds), which is a critical age for spatial learning [7].

3. Method and Procedure

In line with these background research findings, we investigate 3 main research questions to understand children's action strategy in grasping tangram puzzles in order to interpret further step of interaction design: (1) Can young children recognize abstract tangram figures? (2) Even if they do not recognize the figure, to match the related pieces with the shapes would they follow color cues or shape cues as an action strategy? (3) Would encountering the abstract tangram figures in narrative context affect young children's rotation actions?

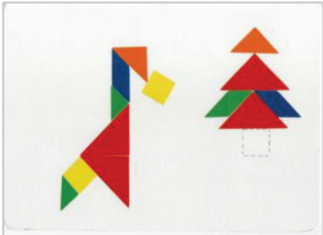
3.1 Participants

We tested 8 children (5 females) between the ages of 25 and 48 months old, with a mean age of 35 months. All children were native Turkish speakers without any developmental disorders. None of them had played tangram prior to this experiment. Each child was tested individually and each experiment took about 15 minutes. Audio-visual records were taken during the experiments. Shadowing method was used to observe and code the user experience process of children.

3.2 Preliminary Paper Prototype: Fungram

We tested the preliminary paper based prototype of the tool along with one set of tangible tangram consisting of seven pieces. The size of the papers used in the experiment (see Figure 2, Figure 3) were 9.7 inches (255 mm) the same size as iPad2 screen, each was put horizontally on the table when presented. The tangible tangram pieces were made of high density polystyrene, a low-cost material suitable for prototyping, which looks like a wooden toy (see Figure 1). 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 figures on the papers were made with paper stickers in the same size and colors matching with the tangible tangram pieces.

We prepared two sets of tasks: the first consisted of only figures without any narrative context (see Figure 2), whereas the second set consisted of figures displayed within a narrative context (see Figure 3). In both sets, the pictures were put in an order in which the figures ranged from easier to harder to recognize.



The giraffe is very hungry. He accidentally ate the body of the tree under the leaves. Can you help him to put the body of the tree back under the leaves?

Figure 3. A sample picture presented with narrative context in the second set.

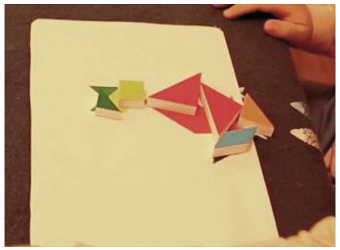


Figure 4. 35-month-old girl follows color cue without fully employing rotation strategy in the first task.

In the first set of papers (see Figure 2), children were asked to identify a tangram figure on the paper (i.e., cat, sailing boat) and then they were asked to put the matching tangible tangram pieces on the corresponding shapes. In the second set of papers (see Figure 3), the figures were introduced to the children by the experimenter within a narrative context and children were asked to solve a problem by finding the right matching shape on the missing piece, which was given in a visual cue of border lined blank. The narrative content provided to the child orally in Turkish by the experimenter. Each picture presented one at a time in order to avoid a possible distraction of attention of the child caused by the simultaneous presence of multiple pictures. This is also how a child would encounter the pictures on the screen in the final product.

4. Results

The preliminary results indicate that narrative input harnesses the intention of rotation as well as helping abstract figure recognition. In the first task of abstract figure recognition, pictures given without narrative context and children were asked what they see on the picture. Gender differences occurred rather than age differences. Regardless of age, none of the females could recognize or identify the figures without narrative input in the first set. They were rather focused on the individual geometrical pieces by pointing them separately. In contrast, all male participants could identify the displayed figure in different ways although not necessarily giving the expected answer. 46-month-old boy identified cat figure as a house made of colored stones, whereas 37-month-old boy thought it was a rabbit. Notably, although 26-month-old boy was the youngest participant, he was the only one who identified the cat figure as a cat. Since, as being abstract figures, we were open to any identification from the child. In the case of not receiving a response or identification, we asked the participants "do you think it looks like a cat?" then girls could recognize the object and affirmed by pointing the related parts. Still, a larger sample would be needed to confirm if this difference is a result of gender or individual differences.

In putting the tangible tangram pieces on the matching shapes, the action strategy of children differed according to their age and individual skills rather than gender. As expected, older participants (48-month-old girl and 46-month-old boy) put the matching pieces on the shapes employing rotation complying with the orientation of the geometrical shapes. Younger children were more likely to follow the color cues and dropped the pieces on the relevant colors disregarding the alignment or orientation of the shapes (see Figure 4). The youngest children (28-month-old girl and 25-month-old boy) could not complete the whole task and lost their attention after putting four or five of the seven tangram pieces on the figure. However, 33-month-old girl, who was younger than five of the other children, showed an exceptional performance in this task. She could achieve to figure out not only rotating the shapes but also flipping the parallelogram piece in its symmetry axis when necessary. Even the oldest participants could not achieve to perform the flipping move in symmetrical axis of this piece.

In the second task (see Figure 2), children were shown pictures with multiple figures given in a narrative context. They were asked to solve a problem given in the narrative by finding the missing piece among the set of tangible tangram and put it on the border lined blank. In order to confirm if the child could recognize

Figure 5. The youngest participant, 25-month-old boy matches the missing piece according to the narrative input. Although he puts the piece in vertical orientation, he pays more attention to rotation and alignment than he did in without narrative condition.

the figures in the narrative, the experimenter asked if she could point to the pronounced figure related on the picture.

When given in narrative context all children could recognize even more complex tangram figures such as giraffe, kite, mountain, and turtle presented in the second task which we thought challenging and children might be unfamiliar with (especially when compared to the ones presented in the first task). Moreover, they performed relatively better in terms of putting the pieces on the relevant shapes, paying more attention to the geometrical cues such as alignment of the edges and rotational orientation of the shapes. This result also included our youngest participant 25-month-old boy (see Figure 5), who could complete 4 of the 6 pictures.

5. DISCUSSION AND FUTURE WORK

In this paper we presented an exploratory study with the preliminary paper prototyping of *Fungram,* a tool incorporates rotation of tangram puzzle activities into a game context guided by narrative. Our aim is to facilitate the spatial skills of children between the 25 and 48 months old. Since well-organized narration is suggested as a powerful scaffold for word-to-object mapping [1] and increasing engagement [9], the result presented here provides consistency with the previous research on spatial learning demonstrates that narrative input can help children to comprehend spatial relations which involve abstraction [1,9].

To our knowledge this study is unique in integrating and introducing tangram to very young children while benefiting the narrative cues. Among other spatial puzzles recommended for preschoolers such as lego blocks or wooden bricks, tangram pieces can be argued for being harder to play for young children. The difficulty depends on the fact that tangram allows highly abstract figures, offer limited geometrical shapes mostly in triangles, enable only horizontal use and not allow making the pieces join together. Thus, tangram can be regarded as requiring higher motor skills, spatial intelligence as well as more patience than a very young child might be expected to show. Although children participated in this study have not encountered tangram prior to this experiment, they did not need additional instruction to understand how to play with tangram pieces. Moreover, we observed that they enjoyed to build new figures apart from the tasks, and expanded their creative use.

We defined three visual cues to help children’s matching and rotation strategy: color, size, and border lined blanks. We observed that although children tend to follow color cue in the first hand, it did not solely invite them to rotate. However, when color cue is replaced with border lined blank along with narrative input, younger children were more likely to rotate the shapes. Still, their rotation action involved two types of violations to be coded in the iterated user study: incomplete orientation of the angles, and careless alignment of the edges while matching two shapes. These action types would need to be considered in designing the screen interaction and content of feedback effect in order to define the optimum span to be tolerated in case the child runs off the borders of a shape in the digital version.

While tangram provides us insights about the action strategies of children, since it is based on 2D figures, it did not enable us to discover the manipulatives with their three dimensional relations. Therefore our future prototype will also include graspable spatial toys such as Fröbel Gifts, which enable 3D forms, figure configurations and wider range of spatial relations (e.g., overlapping, interlocking) between objects that also provide opportunity to promote using spatial language (e.g., prepositions). The data provided from young children's experiences with various spatial puzzles would branch out to numerous venues employing different rotation tasks.

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4.3. Paper III: Designing with and for Preschoolers: A Method to Observe Tangible Interactions with Spatial Manipulatives

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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].

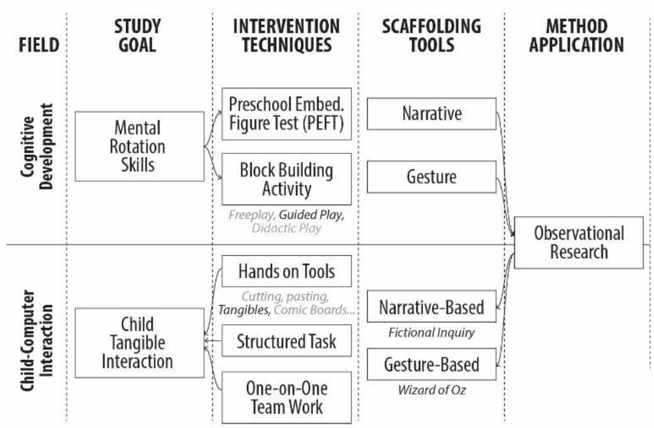


Figure 1. Complementary tools and techniques in two fields: Facilitating learner centered design for children to aid CTI.

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.

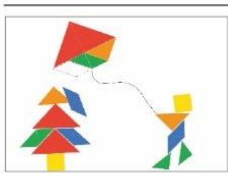
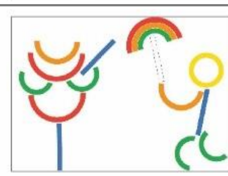
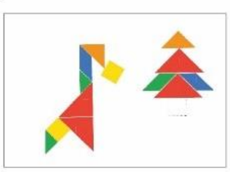
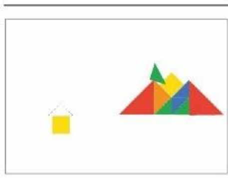
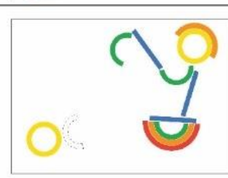
TANGRAM TASKS	NARRATIVE CONTEXT	FRÖBEL TASKS	NARRATIVE CONTEXT
	TASK 1: The turtle wants to eat a leaf from the tree. But the tree is very high. Can you take one leaf from the tree and help the turtle to feed?		TASK 1: The turtle wants to eat a leaf from the tree. But the tree is very high. Can you take 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. The qualitative analysis of data from video transcriptions and observational notes supported the validity of our methods.

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).

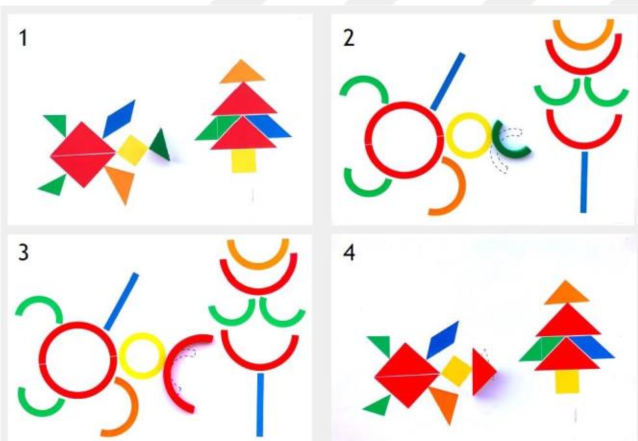


Figure 4. Rotation action types: (1) Correct object & Complete rotation (C&C); (2) Correct object & Incomplete rotation (C&I); (3) Incorrect object & Complete rotation (I&C); (4) Incorrect object & Incomplete rotation (I&I).

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.

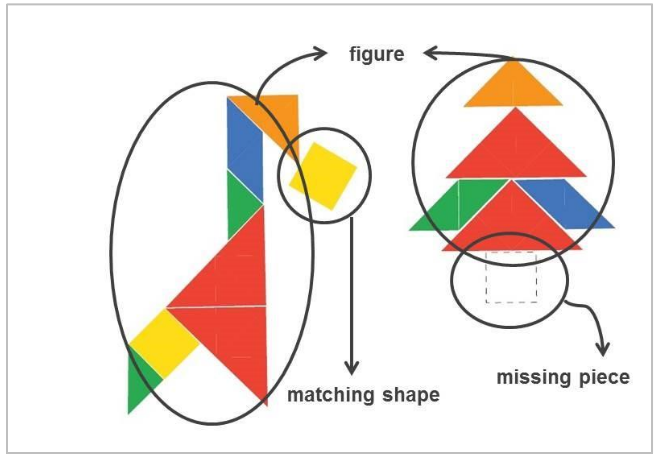


Figure 5. Different locations occured in participants' pointing gestures and rotation actions.

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, *p*s > .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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4.4. Paper IV: Customizing Developmentally Situated Design (DSD) Cards: Informing Designers about Preschoolers’ Spatial Learning

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Customizing Developmentally Situated Design (DSD) Cards: Informing Designers about Preschoolers' Spatial Learning

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ABSTRACT
To date, developmental needs and abilities of children under 4 years old have been insufficiently taken into account at the early stages of technology design. Bekker and Antle [6] created developmentally situated design (DSD) cards as a design tool to inform children's technology designers about children's development starting from 5 years of age. In this paper, we describe how we customized DSD cards for a specific developmental skill (i.e., spatial learning) of children between 2- and 4-year-olds for tangible interaction design. The cards were evaluated after a user study in which 19 participants from different backgrounds used the cards in three design workshops. Our analysis of observational notes and online survey identify and discuss how specific card features support or limit use by our participants. We draw on our findings to set forth design considerations and possible refinements that make age specific knowledge about very young children's spatial learning to inform technologies based on tangible interaction.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous; D.2.2 [Design Tools and Techniques]: Object-oriented design methods.

Author Keywords
Design tools; design methods; child development; child-computer interaction.

INTRODUCTION
This paper describes the customization of a card-based design tool to support interdisciplinary design team in taking into account very young children's spatial abilities and skills during the early design stage of a tangible system for learning. It has long been highlighted in design approaches such as participatory design [25] and child-centered design [13, 10] that, in early design, designers should involve children as participants of a design process or they need to use analytical methods and tools to elicit evidence-based knowledge about children's abilities and needs to inform the design [6].

When it comes to designing with and for children younger than 4 years old there are only a few methods or tools found in the child-computer interaction (CCI) field that involve these very young people to inform interaction design choices [16, 21, 19]. It is mostly very difficult to elicit verbal feedback from this age group to inform the design [16]. In CCI, informing age-appropriate technologies responsive to very young children's learning process remains as a wicked design space. Despite the challenges, techniques such as Wizard of Oz [21], or hands-on tools such as intervention with manipulatives [21, 5, 4] began to be adapted to observe on-task behaviors of children under 4 years old. Still, those studies reported that even 4-year-old children have difficulty in involving participatory techniques such as using drawing [4], Fictional Inquiry or Comicboarding [18] to generate and communicate a design idea, or Wizard of Oz to finish the tasks which need precise toy movements [21]. There is also a wealth of emerging theoretical knowledge about the early cognitive developmental abilities and skills of the intended age group. Then, how can we make this age specific knowledge in cognitive developmental studies readily accessible to designers?

Based on a similar quest, Bekker and Antle [6] created Developmentally Situated Design (DSD) cards that make information about children's developmental stages, ages, and abilities available throughout the design process [6]. Other studies also evaluated card-based design tools and reported their usefulness in particular at early design stage [9, 12, 7]. Still, none of these approaches have focused on delivering knowledge about the developmental abilities of children younger than 4 years old. By targeting this age group, this study contributes to the evaluation and further development of the DSD cards to be applied in wicked design problems. The contribution of this paper consists in the customization of the content of DSD cards relying on; (1) incorporating the literature review in a specific learning domain in cognitive development field (i.e., spatial learning), which is found critical in particular between 2 and 4 years old [20], along with (2) supporting the content with concrete examples and empirical results elicited from our observational case study which we have conducted with 2- to 4-year-old children to gain in-depth insight into their spa-

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tial skills (i.e., mental rotation skills) and ability levels while interacting with tangibles (i.e., tangram and Froebel Gifts).

In this paper, we present the customized design of DSD cards, which are a set of 32 cards (4 developmental concepts on spatial learning x 4 learning processes x 2 age segments). We evaluated cards after three user studies in which 19 researchers and practitioners with different backgrounds (i.e., developmental psychology, interaction design, industrial design, game design, and children's media) used the cards for brainstorming, idea generation and constraining the design idea of a prospective tangible system for spatial learning. We also present suggestions for customized design of the DSD cards, and a discussion of strengths and weaknesses of our approach.

BACKGROUND AND RELATED WORK

This study is derived from the need for translating early spatial learning theories and our case study findings to the interdisciplinary design team of a tangible learning game. As part of a larger project, this paper is built on card-based design tools, suggested to bridge between theory in child development and practices in interaction design for children. In this section, we focus mainly on the customization of the DSD cards along with a brief background information about early spatial learning and child-tangible interaction (CTI) for early learning.

Developmentally Situated Design (DSD) Cards

Cards are one form of design approaches to make academic or conceptual knowledge accurately and concisely presented to designers [6, 9]. Based on Antle's [1] attempt to inform design through creating child-personas in the absence of children in the design process, Bekker and Antle [6] carried this approach a step forward and developed the DSD card tool to provide an easy compilation of child development knowledge for designers.The DSD cards contain age specific information (including three age periods; 5-6, 7-9, 10-12) about children's development in four domains (cognitive, social, emotional, and physical). The cards support designers in creating child personas and design concepts. The DSD cards are effective in providing easy access to theoretical knowledge; enabling to search or browse information related to the design goal or the target age group; using at different stages of design (e.g., brainstorming, inspiration and idea generation) [6]. (The original cards are available at www.antle.iat.sfu.ca/DSD)

The DSD cards inspired development of other card-based design tools such as *Tango Cards*, making design knowledge about tangible learning games accessible to designers [9]. Furthermore, the DSD cards were incorporated into lectures for teaching how to design for children to interaction design students who have no knowledge about child development [12, 7].

Early Spatial Learning

Spatial learning and thinking skills at early years are essential for a variety of everyday tasks, such as packing a toy box, cutting equal slices of cake for a group of people, or remembering where an object is by cue learning [26]. Longitudinal studies showed that early spatial experiences have significant impact on school readiness and child's further STEAM (science, technology, engineering, arts and mathematics) skills [26].

There is evidence that children's early interactions with manipulatives such as block building activities, shape games, and playing with puzzles facilitate *mental rotation* skills (i.e., imagining the change in orientation or direction of objects in mind) [27]. Children who play with puzzles more between 2 and 4 years have better spatial transformation ability than their peers when they are 4.5-years-old [20]. Thus, mental rotation skills in spatial learning are malleable and durable if they are trained before 4 years of age [26].

Employing various spatial tools such as *gesture* (e.g., pointing) [11] and *narrative* (e.g., storytelling) [8] has a scaffolding effect on spatial visualization, construction and rotation skills when incorporated into the block building activities. Moreover, guided-play has an effective role for promoting early spatial learning when compared to free play or didactic play activities with tangible objects [14]. Theories and suggested tools for early spatial learning given here can provide a useful framework for informing tangible interaction design choices to leverage young children's spatial learning activities with manipulatives.

Child-Tangible Interaction (CTI) for Learning

CTI as a framework introduced by Antle [1] in child-computer interaction field points out that tangible interaction combining physical and digital platforms together have a great potential for enhancing young children's learning [23, 22], and cognitive development [2], especially because it enables embodied and spatial interaction more than other interfaces [2]. The types of tangible user interfaces that are suggested for young children's learning blend the advantages of physical objects with digital affordances [23]. Thus, these tangible interactions were basically inspired by block building activities [24, 28]. Moreover, integrating narrative and gesture are defined as typical learning domains that tangible user interfaces might enhance [22]. Still, spatial problem solving which relates to hands-on action, manipulation, and rotation skills is defined as one of the knowledge gaps in CTI research [1, 2, 19]. These tools also need to be explored for facilitating very young children's early spatial learning. A detailed review about the tangible interaction systems that blend the advantages of physical and digital worlds that might serve children's spatial learning will be presented in another study. Based on the complementary nature of CTI framework in child-computer interaction and spatial learning concepts and tools in cognitive developmental studies, here we present how we customized the content of the DSD cards regarding our wicked design problem.

PROBLEM STATEMENT: CUSTOMIZATION OF THE DSD CARDS

Our goal for customizing DSD cards was to deliver knowledge about early spatial learning as a domain in cognitive development and translate the results of our case study to the participants of our user studies. We customized DSD cards that could be used to easily inform designers about mental

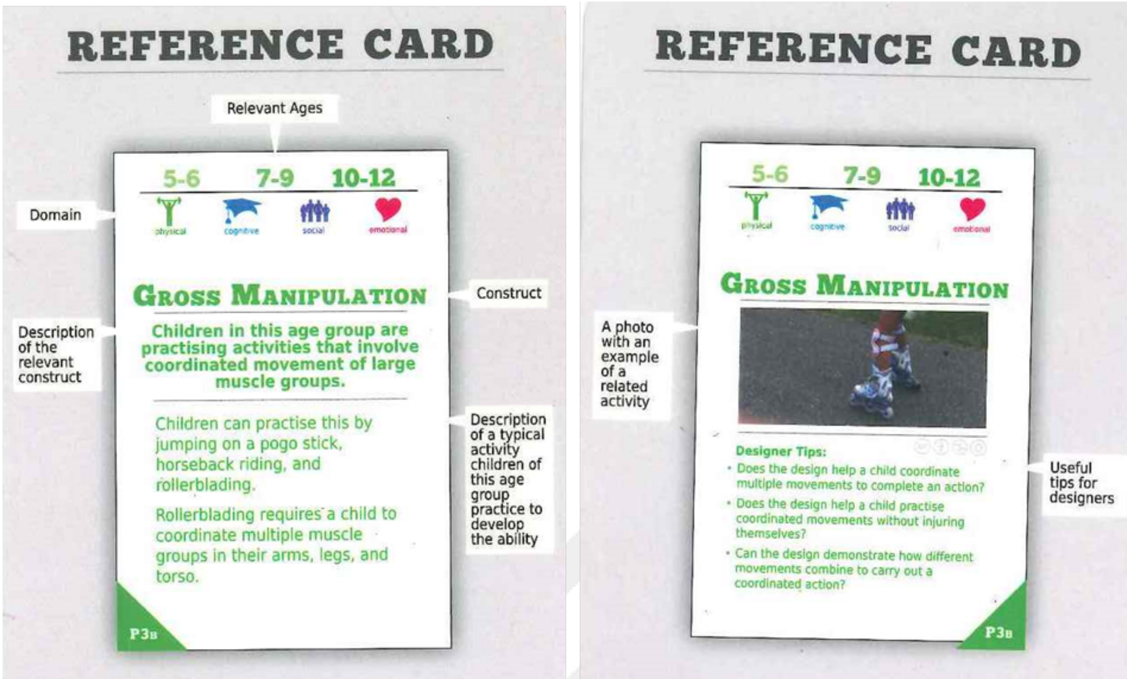

Figure 1. Reference to the original DSD cards created by Bekker and Antle, 2013.

rotation skills and ability levels of children between 2 and 4 years old. We also included spatial tools (i.e., gesture, narrative, guided-play) and intervention techniques (i.e., block building activities, preschool embedded figure test) found in cognitive developmental research. These tools and techniques that facilitate mental rotation skills of very young children are included to provide inspiration for a tangible learning game.

Given that design methods and techniques in CTI for early learning are yet to be developed, the target users of the DSD cards that we have customized for were the design team members with different expertise (i.e., developmental psychology, interaction design, industrial design, game design, and children's media) who came together to work on a tangible interaction design solution. However, we customized DSD cards with possible future target users (e.g., practitioners, parents) in mind.

Customized DSD Card Design

One of the authors in this paper first used the original DSD cards when participated at the "Designing Tangibles for Children: One Day Hands-On Workshop" at Interaction Design and Children Conference (IDC'16) organized by [3]. Then we conducted a literature review of research about design cards including works used DSD cards as a tool [9, 12, 7, 17]. Although we customized the content, we kept the main design rationale of the DSD card template created by Bekker and Antle including size and layout (see Figure 1). Our final customized design was a set of 32 cards (4 developmental concepts on spatial learning x 4 learning processes x 2 age segments). A PDF copy can be downloaded from https://happern.ku.edu.tr/tangible-interactions-for-early-spatial-learning/

Developing Card Content

As being said, our priority to customize the DSD cards was to inform our participants about early spatial learning (i.e., mental rotation) and to translate our results of our case study. Building on design considerations presented in the previous work [6, 9] we have customized the DSD cards by following their suggestions. To include appropriate amount of information we excluded the topics that are not directly related to development of spatial skills. The topics that are addressed by in the original card set included cognitive, emotional, social, physical development of children. Since our design goal focuses on spatial skills as a specific domain in cognitive development, we elaborated the concepts in this specific domain knowledge (i.e., mental rotation). Thus, we first began customizing the topics in the cards by tailoring the theoretical concepts related to spatial skills (i.e., mental rotation) along with the scaffolding intervention tools (i.e., narrative, gesture, guided-play) for this particular skill. To make searching and browsing the information easier we modified the icons as visual identifiers for each concept. We compiled these concepts as the main topics of our customized card set (see Figure 2).

In order to implement a clear information architecture supported through relevant tips and concise examples, we translated the findings of the case study we have conducted with children prior to this study. The aim of our case study was to gain in-depth insight into children's mental rotation skills when interacting with tangibles (i.e., tangram and Froebel Gifts) in a guided-play context provided with a story [x]. We recruited 14 parent-child (children between 26-and 43-months of age) and observed children's on-task behaviors along with the gesture and narrative feedback they required from their

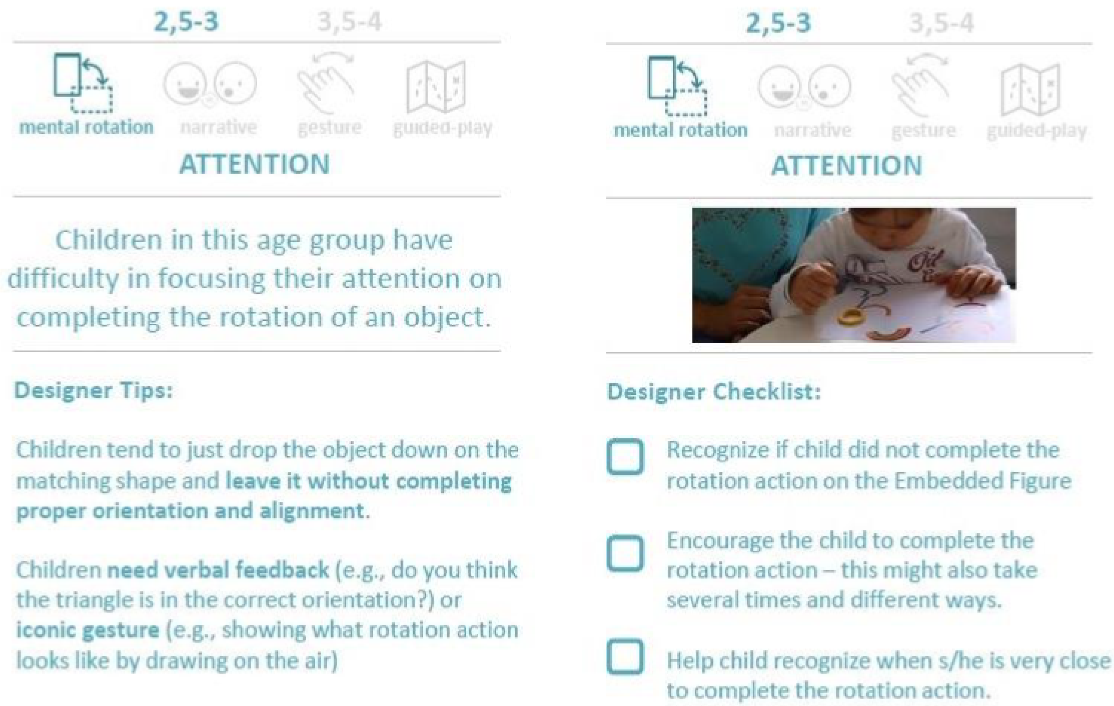

Figure 2. A customized DSD card. Front (on the left) and back (on the right) side.

parents to solve the mental-rotation tasks embedded into the stories. Our results showed that children between 26 and 34 months old required more time, gesture and narrative input from the parent whereas the children older than 34 months old did not have any difficulty on-task. Thus, we developed the card content relevant to two age segments; according to age specific abilities and needs of 2.5-3 and 3.5-4 year olds as two groups.

In the original DSD cards, the topics were framed and described with headers (see Figure 1). For instance the headers in cognitive development were Attention, Problem Solving, Information Processing, and Instructions. We kept these headers in our customized cards to categorize, define and describe our findings retrieved from our case study. We also provided picture examples from our case study that were relevant to the topic and the header on each card. We also kept the subheader titled *Design Tips* in the original set and customized the information under this section based on the literature review and our case study. In addition, to assure a more clear information architecture we included a new sub-header. We titled this section *Designer Check-list* in which reminding prospects were presented. Another distinctive element in our customized cards was the bold-written keywords highlighted in the sentences (see Figure 2). By including these distinguishing visual elements we aimed to support the ease of access to knowledge in the cards. The cards were useful to translate the results of our case study concisely and adequately to our interdisciplinary design workshop participants. In the next section, we describe the methods we used to present the customized DSD cards to our participants.

METHOD

To test and evaluate the customized DSD cards, we first conducted user studies through workshops and then an online survey with the workshop participants. For user studies, we invited practitioners and researchers from different backgrounds. Then, for evaluation of the cards, we conducted an online post-workshop survey with the participants. Here, the procedure and materials of the user studies and online post-workshop survey are described.

Participants

We wanted to recruit participants with knowledge in different fields; psychology (i.e., cognitive and developmental psychology), design (i.e., interaction, industrial, UX, game), and experience in children's media industry (e.g., television, children's books) and early childhood education. Along with personal invitations we made an open call for the workshop. We also wanted to invite people who have tangible interaction design experience in particular, however we were unable to find someone. In total, 19 experts (18 females and 1 male) volunteered to participate in the workshops (e.g., 2 interaction designers, 3 industrial designers, 3 UX designers, 2 game designers, 1 computer engineer, 2 children's media professionals, 2 CG artists, 1 scriptwriter, and 3 researchers in cognitive development). Our recruitment priority was to balance participants' background knowledge (10 designers and 9 non-designers), so we did not seek for a gender balance in participation. Every participant were invited to all workshops, however only 3 participants could attend them all. Still, in every workshop at least 7 and at most 12 people participated. So that, in every team work at least two people from different fields of experience have collaborated. We shared the post-workshop online survey with all 19 participants after three workshops were completed. Sixteen participants filled out the online survey until the deadline.

Procedure

We conducted user studies in three whole-day workshops. The workshops took place at a collaborative working space. One of the authors of this paper facilitated the workshops. The aim of the user studies was twofold: (1) to generate ideas for a tangible interaction design to support very young children's mental rotation abilities and develop a design brief for a future prototype; (2) to improve our customization of the DSD cards as a design tool and use them in the further workshops with game designers. In this paper, we only focus on describing the procedure for the use and evaluation of the customized DSD cards. The DSD cards were used in the workshops in three levels of design:

- 1st Day: Brainstorming and inspiration;
- 2nd Day: Concept development and idea generation through a persona;
- 3rd Day: Constraining and detailing the design idea.

In every workshop we first began introducing and presenting the DSD cards (see Figure 1) along with a 10-minute introduction to spatial skills of young children and examples of tangible user interfaces for learning to the participants in case someone new joins to the workshop. Another reason for a short introduction is because previous work emphasized that [9] a certain level of knowledge about the domain specific concepts is necessary for designers to use the cards effectively. The brief information about the DSD cards included how designers can make use of the content of the cards [i.e., (1) headers - mental rotation, storytelling, gesture and guided-play; (2) subheaders - attention, problem solving, instructions, information processing; (3) Designer Tips and (4) Designer Checklist] to inform about children's age specific spatial skills and abilities (see Figure 1). The participants had the hard copies of card sets throughout the whole workshop.

The participants divided into groups. In each group, we ensured that there were at least two people from different backgrounds collaborated as a team. We assigned each team a task for a target age (i.e., 2.5-3 or 3.5-4 year olds). We provided teams the set of cards relevant to their target age. As a workshop structure we employed "opening and closing" as a method used in gamestorming [15] to orchestrate between the three levels of design in the workshops. By doing so, we prepared tasks to be completed, discussed and presented in half a day. The output of each task preceded and prepared the next step. In other words, the work presented by each team in every half day established the frame of reference for the subsequent session's design task. For example, the output of the brainstorming sessions in the 1st day has set the context of the persona created in the 2nd day for concept development and idea generation. In turn, the output of the ideation activities in the 2nd day has laid out the themes and design ideas

Figure 3. The customized DSD cards being used by member of our interdisciplinary design team.

that were elaborated in the 3rd day. This method helped us in two ways: First, no matter if a participant has joined or left the workshop at some point, the tasks could be carried out sufficiently by the team members in the next session. Second, the DSD cards could be used at different levels of the design process throughout the whole workshops.

Data Collection and Analysis

We captured video and audio recordings while the teams were presenting their work to each other. At the end of each presentation, the participants were asked to discuss the usefulness of the customized DSD cards orally and indicate areas for improvement. We also took observational notes during the design sessions, presentations and discussions. With the help of the video and audio recordings, and handwritten notes, we prepared an online post-design questionnaire to understand how the participants used the DSD cards in their interdisciplinary design process. While preparing our questionnaire, we also used findings and design considerations pointed in previous research [6, 9] to provide evidence of themes reported on card use. We used Qualtrics as an online platform to create and distribute our survey, and to collect and analyze individual responses of the participants. Fifteen closed and 1 open-ended questions were asked to extract information about support and limitations of; 1) the design, 2) the content, and 3) the use of the customized DSD cards along with participants' suggestions for improvements. The qualitative analysis of data from post-design online survey and observational notes supported the validity of our methods. The descriptive statistics of the data extracted from online survey were analyzed and presented with the observational notes taken during the workshops.

RESULTS

In the survey, participants were first asked about their prior experience with the intended age group. Half of the 16 respondents of our survey informed that they had prior experience with children between 2 and 4 years old either in their professional or personal environments, whereas the other half informed that they had not. When it comes to the familiarity with the concepts in the domain knowledge of spatial skills the majority of the respondents (11/16) of the post-workshop survey defined themselves being familiar with the subject prior to the workshop. However, this result contradicts with our workshop observations. During the workshop none of the participants indicated knowing the concepts and theories before and they were glad to be informed. This might be linked with the informative effect of the cards. Participants were also asked to rate the use of DSDcards on a Likert scale. All of the respondents found the customized DSD cards useful as a design tool (9/16 respondents found highly useful and 7/16 found moderately useful). Most of the participants (11/16 respondents) found the information in the cards easy to understand, whereas some of them (5/16 respondents) found the information a little detailed and complex to understand.

In addition, participants were asked to evaluate how they used the cards in their design activities. The questions included how they found different elements of information in the content and the design of the cards. They were asked to rank the given elements from the strongest to the weakest. Here, we first present the results for the general use of the cards in the design process, and than present the evaluations for the content and the design features of the cards.

The Card Use

To understand the purpose of using the cards during the design process we first asked participants to rank their intentions for using the cards from most to least, with (1) being intended most. The online survey results showed that the cards were mostly used to (1) get informed about, (2) validate or confirm, (3) reminded about the spatial skills and ability levels of children. In our observational notes, one of the design teams also informed that they applied the cards when the team members had a conflicting idea about a design solution.

To evaluate the design activities that the cards were mostly employed, we asked participants to rank the phases of design in which the DSD cards were applied most, with (1) being employed most: (1) during the inspiration gathering, brainstorming and kick off to brainstorming; (2) after brainstorming, while generating a design idea; equally when being decided to switch a design idea; (3) while elaborating on and detailing a design idea.

To describe the way how the design teams have used the cards throughout the whole design work, we asked the participants to select a definition that explained best for their overall card use. The responses showed that, with (1) being most likely selected, (1) they first carefully familiarized with the cards, quickly read through all the cards, then browsed and picked out the card that contains information that they are looking for; (2) they first read carefully all the information in detail in the cards, they sorted and grouped the cards to outline their design rationale, they used all the cards throughout the whole design work; (3) they skimmed and scanned through the information roughly, and this information have been enough for them throughout their design work. Next, we present the evaluations for the content information in the cards that supported and limited the card use.

The Content

The content of the cards were evaluated according to the informative elements displayed in Figures 1 and 2, and described under *Developing Card Content*: subsection above. We asked the participants to rank or select the information type that they found the most or least useful in the content of the cards. The survey data revealed the following information about the content.

Among all informative elements *textual examples* and *bold-written keywords* were found more helpful to get familiar and informed about the concepts as well as serving as a quick reminder whenever needed. The respondents also noted that *textual examples* retrieved from the case studies were more useful than the *descriptions* under the *Design Tips* for participants to understand the domain specific concepts and the spatial thinking skills and ability levels of very young children. We observed that participants used *bold-written keywords* as a guide to develop design ideas, whereas the *textual examples* were mostly used to formatively evaluate the design ideas. Furthermore, descriptions in long sentences were also found hard to skim and scan the information. *Bold-written keywords* were again found to be more useful than the *descriptions*, in the sense that they help to distinguish and retrieve a particular card that includes a concept that had been realized or discussed before.

According to the responses, the hierarchy of the information and the wordy descriptions are the features that need to be further improved to aid the understanding of the content. For sorting or grouping the cards, participants mostly used the *Titles*. It was followed by the *Bold-written keywords* and *Designer Check-list*. The information architecture has also links with the design features of the card. The results for the evaluation of the design elements are presented below.

The Design

The design elements of the cards that were evaluated included the tangibility, two-sided use, font size, color coding, use of the picture examples and icons. The results for evaluations of the card design occurred in the participants' spontaneous speeches or behaviors during the workshop or as an additional suggestion for improvement defined in the online survey.

Most of the participants mentioned the usefulness of the physicality of the cards, which enables grabbing, pointing, sorting, or grouping. The blank bullet point signs next to the *Designer Check-list* also reinforced the use of physicality of the cards as a reference. Some participants filled the blanks to show if they could find a solution for that particular design problem. However, one of the key suggestions for design was the difficulty of keeping track of the information in both sides of a card at a time. The participants mentioned the adversity in browsing or processing an information on the front side while trying to keep an eye on the *Designer Checklist* relevant to their design problem. Participants also noted that the number of cards (16 cards for one age segment) was too much as another challenge against information processing. A common suggestion was to reduce the number of cards as well as the amount of information within a card. Participants emphasized that they would prefer bold and punchy keywords with larger font size which would help to capture the information during a fast-paced ideation. We now discuss the results about the strengths and weaknesses needs to be taken further consideration.

DISCUSSION

Based on our study findings together with our participants' implications for improvement we suggest several considerations for the customization of the DSD cards. We believe these considerations will contribute to further improvements for customizing the DSD cards to inform children's technology designer and support their use with more effective design flow.

The survey results showed that the participants used the cards to get informed in early fuzzy stages of a design activity more than to validate and remind about the concepts in the later stages. As a result, there are two main issues to be considered: 1) to improve the information processing of the card content, and 2) to reinforce and facilitate the card use at different stages of a design activity.

Insights for the Information Processing of the Cards

In parallel to the previous research [9, 7], our results showed that extraction and simplification of the theoretical and academic knowledge is one of the key elements that needs to be considered in order to support the information processing in the cards. Based on our observations and as spontaneously remarked by our participants during the workshops, the concrete examples about age specific skills that we have extracted from our case study has been more useful to aid the understanding of the information than descriptions. Thus, conducting a case study with the intended age group feeds the content in various ways; provides real life examples for skills and ability levels of children, valuable insights about unexpected on-task behaviors of children to be implemented into the *Designer Tips*, inspiration about ways to tailor suggested tools or intervention techniques into the design implementation.

Another issue regarding the simplification of the content is the participants' familiarity with the information given in the content. For instance, unfamiliarity with the concepts about spatial skills made designers' use the cards less. For example, P11 with interaction design background said that *"if we have a psychologist in the team we preferred to ask directly to the expert rather than looking at the cards to check and confirm the information, because there were too much information."* On the contrary, the participants with psychology background or having a general idea around the concepts, indicated they read the cards in detail and used them when a designer asked a question. Thus, there is a clash between the level of knowledge of the participant and the amount of information needed and extracted from the cards. This result also goes in line with [9]. In addition to the previous research, our study showed that the domain experts in psychology and the designers who have small children were more interested in reading the information in detail than the designers with no prior experience with children in our workshops. This observation implies that the DSD cards in the original format might not be effective enough to support designers' use without refinements, but they can be sufficient guidelines for people who are already knowledgeable to collaborate with designers of children's technology to find a common vocabulary to reach a common understanding. The cards may also serve well as a parental guideline providing information about domain specific developmental areas or playful learning environments.

However, the main goal of the DSD cards is to make the knowledge readily accessible to technology designers in the absence of children, parents or experts with domain knowledge. Our suggestions for refinements to support information processing lies in the implementing more effective and usable information architecture in the cards which is adjusted for different levels of a design process which we present in detail below.

Insights for Reinforcing the Card Use at Different Levels

As the results showed, regardless of what design phase the participants have joined in the workshop they used the cards mostly during their inspiration gathering, brainstorming and kick off to brainstorming stage of a particular design activity. Their purpose of using the cards was more likely to gather information rather than a constant reminder or source of validation for the refinements throughout the whole design process. In order to secure the card use at all phases of design process, we basically suggest to allocate information and implement information architecture relevant to the design stage.

Implementing effective information hierarchy

For ensuring a clear information hierarchy, segments in the content such as topics, headers, sub-headers (i.e., Designer Tips and Designer Check-list) along with textual and visual examples were implemented as suggested in the previous study [9]. However, as indicated in our observational notes and survey results participants explicitly mentioned, the difficulty in finding concise information within full sentences under Designer Tips and Designer Check-list during their idea generation or constraining stages. The bold-written keywords were more supportive than full sentences especially while browsing, selecting and communicating information shorthand. Keywords were also one of the key elements to bookmark a card for inspiring and/or discussing ideas. Most of the participants indicated that they would prefer seeing the keywords only.

Another difficulty that limited the effective use of information hierarchy was two-sided presentation (Designer Tips on the front and Designer Check-List on the back) of the cards. P14 (a UX desginer) said *"it was hard to keep track of the information on back and front of the cards at the same time. Instead of back-and-front sided use, the cards could be designed with the same size but foldable. It might allow an accordion style expansion in which we could have one or two or even three pages on one side at the same time. It might also help the users to fold and hide, or unfold and open pages with the required information whenever needed."* P13 (a developmental psychologist) collaborating in the same group added that *"In doing so, all the pages would allow to contain information from different fields as a complementary knowledge for the topic. For instance, while the first page would present the information about target age's developmental needs and abilities in a specific area (e.g., recognizing basic shapes is an emergent skill at this age), the second page would inform about a media or* *technology platform that might serve that skill (e.g., tangible objects with haptic feedback), and interactional tips would complement those information in two fields on the third page (e.g., embodied interactions and experiences afforded by TUI can scaffold an effective learning of basic shapes for children at this age)."* Other groups agreed on the need for cards that also includes suggestions for age-appropriate technologies, platforms or feedback affordances that might serve as complementary tools for such developmental processes, and on increasing detailing level in further design phases. Thus, we suggest to refine both sides of the cards as follows.

Adjust the Information for Different Design Levels

Some designers mentioned that the design considerations in question format given in the Designer Check-list has limited the creativity and freedom needed for the brainstorming session. Therefore, the Designer Tips and Designer Check-List can split in different cards for using at different stages of a design process. The latter can be provided in the idea generation and refinement stages rather than brainstorming. For the earlier stage of the design only a refined version of Designer Tips might accompany the brainstorming session. We suggest to refine the Designer Tips by providing keywords and examples only on one side for supporting the usage as quick reminder, bookmarking, or getting inspiration. The descriptions of the keywords can be presented at the back of the cards. So that the designer can easily access to it for informing, validating and confirming the information whenever needed. Similarly Designer Check-list can be refined having only keywords and examples on one side for reminding, determining, bookmarking ideas for outlining the design problem and Check-list at the back to confirm if the design team is on the right track. As being said, examples are the most effective information to help understanding the concepts when one is not knowledgeable about the topic. Thus, finding ways to augment the examples on each card is another important element to be considered.

Augmenting examples with distinguishing visual elements

Our participants indicated that they would prefer seeing more picture examples on the cards. Moreover, the participants who had no prior experience with very young children asked to see some videos from the case studies to get more insight into what a child at that specific age period would behave like different from older ones. However, in the questionnaire participants also responded that they did not use picture examples on the cards to bookmark an information. This goes in parallel with the finding that the picture examples were much less used than the text side in Deng et al.'s study [9]. In order to augment the examples visually in the cards, we suggest implementing QR code on the cards that opens video showing prominent examples for age specific abilities and skills in the particular developmental domain. One UX designer suggested using color to gain information about the ability level in a specific skill of the target age group (e.g., ability to rotate an object precisely). To avoid a wordy full sentence, for instance, color shades presented in a palette might represent the less or further developed states of a particular skill within that age. Such visual solutions can facilitate processing information on the cards faster and more effectively.

CONCLUSION

We customized and used DSD cards which were originally created by [6] as a knowledge transfer vehicle in a domain specific design space targeting children younger than 4 years old. Based on our user study findings and experience, we present general considerations for the customization of the DSD cards for informing children's technology designers and developers. The customization of the DSD cards is not only necessary when targeting users at different age groups within different design spaces, but also while using at different stages of a larger technology design process. Thus, this study not only contributes to a design practice in a specific domain knowledge, but inspires any type of complex domain space with a wicked design problem or extreme target groups. As future work, we will revise the cards relying on the the findings and feedback from our user study, and reevaluate the customized cards in participatory design workshops which enable the participants to contribute to the customization in design-in-use studies, and later in Game-Jam sessions which have real-life constraints. Moreover, a further study that compares the customized DSD cards with another age specific cards would be helpful to validate not only the effectiveness of our customized cards, but also contribute to better design considerations for age specific card-based design tools in general.

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III

CONCLUSION

(5. Research Contributions: Lessons Learned and Design Implications,
6. Ongoing Work, 7. General Conclusions)

5. Research Contributions: Lessons Learned and Design Implications

In this dissertation, we presented our research that examined ways to leverage technology design for early spatial learning by taking into account very young children's developmental needs and abilities. Throughout the doctoral research process, we conducted a review of the literature along with several interaction design studies that created the body of this dissertation. The outcomes were reported in one short paper and three full papers in various international publications. The outcomes of these studies met the expected outcomes listed in the first part [Subsection 2.2]. Below we summarize and discuss our research contributions (RC) along with the lessons learned and design implications based on our research questions (RQ).

RQ 1: How can we gain insight about very young children's spatial skills and needs to inform a prospective TUI design for early spatial learning?

This question led us to investigate and understand how spatial skills defined and can be developed at early ages. Thus, we first conducted an extensive literature review on empirical findings on facilitating spatial skills under four years old, and intervention tools and techniques (i.e., block building activities, guided-play, storytelling, gesture) suggested for early spatial learning in cognitive development research [Section 4: Paper I]. We then addressed the potential benefits of TUIs for spatial learning that maintained the physical and graspable aspects of interaction for learning [Section 4: Paper I]. We discussed the lack of design methods to gain insight about preschool children's developmental needs and abilities. By addressing the complementary natures of early spatial learning and designing TUIs for learning, along with possible inquiries in research, we contributed to bridge knowledge between two disciplines.

RC 1: A theoretical framework that bridges between knowledge about early spatial learning and potential benefits of TUIs for learning [Section 4: Paper I]. With this theoretical framework, we extracted the following design implications and lessons learned for informing a prospective TUI design for early spatial learning.

RC 1.1 Design Implications: Studying the literature in two fields showed us that to gain insight about very young children's spatial skills the design of TUI should employ;

- Block building activities with spatial manipulatives (e.g., wooden blocks, shape toys, construction kits, puzzles, etc.),
- Spatial thinking skills (i.e., mental rotation) such as recognizing, defining, describing the 2D or 3D shapes according to their size, orientation, or location,
- Providing a guided-play for block-building activity that triggers spatial thinking strategies in a goal-directed manner rather than a free play or didactic play,
- Use of spatial concepts in form of narrative (e.g., prepositions),
- Maintaining the physical interaction with the shapes and encouraging use of gestures (e.g., rotating, showing, pointing shapes).

RC 1.2 Lessons Learned: The major take-away message we obtained from studying the literature in both fields was that even though there are some tools and techniques developed to extract information from very young children, we need to find methods to involve children in CTI design for early spatial learning. Therefore, we inferred that adapting and merging the methods found in both fields [Subsection 3.1] might be helpful to enhance the exchange between theory and practice. In order to examine this interpretation in a more detailed manner, we developed a method to observe and gain in-depth insight about very young children's spatial skills [Section 4: Papers II and III]. The research contributions of the developed method are described in the following design phase as a consequence of the RQ 2.

RQ 2: How can we integrate intervention techniques for early spatial learning with design techniques to inform a CTI design?

By doing the literature review, we found intervention techniques (i.e., PEFT and guided-play) and tools (i.e., storytelling, gesture) that were suggested for early spatial learning in cognitive developmental studies. We incorporated these tools and techniques into a playful activity with a tangram set to observe and gain insight into very young children's spatial skills (i.e., mental rotation). This helped us to integrate Preschool Embedded Figure Test into spatial riddles hidden in tangram figures and present them within a storytelling context to the very young children [Section 4: Paper II]. Based on the insights we gathered from the pilot study, we evaluated our method through a further case study with parent-child dyads. In the case study, we incorporated the same tools and techniques into play with Fröbel Gifts. This helped us to compare a different type of spatial manipulatives with a tangram set [Section 4: Paper III]. Furthermore, conducting an exploratory case study with parent-child dyads helped us to gain insight about children's different types of spatial thinking strategies, skills, and feedback requirements within the target age period.

RC 2: A design method that combines scaffolding tools and techniques suggested for early spatial learning with child-centered approach to design [Section 4: Paper II and III]

RC 2.1 Design Implications: Conducting a pilot study that incorporates intervention techniques and tools into tangram play indicated the following premises;

- Storytelling might help children between 28 and 48 months of age to recognize and understand the abstract figures made with spatial manipulatives (i.e., tangram and Fröbel Gifts),
- Storytelling context might also be helpful in providing a goal for children at this age interval to seek a complete rotation and orientation of a shape as given in the story,
- Children might employ different types of rotation actions with shapes other than expected; to complete the rotation in a correct manner they might need additional feedback.

The insights gathered through this study contribute to design considerations for a CTI design setup regarding type of feedback requirements, rotation actions, input output (I/O) mechanisms, and region of interest (RoI) (Section 6).

RC 2.2 Lessons Learned: After conducting the case studies, we presented the lessons learned in detail in Papers II and III [Section 4]. The most important take-away messages were about the strengths and limitations of our paper prototypes.

The strengths of our approach were;

- the playfulness of the tasks created with PEFT and spatial manipulatives and providing them in a story context were helpful for children to engage in the tasks,
- adopting reliable spatial tools and techniques from cognitive developmental studies and incorporating them into child-centered design approaches suggested for

preschool children helped us to ensure a research-driven content for spatial learning,

- the low-cost materials expedited the production and mobility of the tools we used during our studies with children.

The limitations of our approach were;

- applicability of the tasks to children younger than 26 months of age due to the communicative challenges we faced while presenting the materials, including the stories, and
- extracting very young children's views about the design of the content we developed.

Since, our primary aim was to gain insight about children's spatial skills and needs we believe this study might be informative for further studies that aim to involve very young children in the design process as design partners. Such studies that aim to involve children as design partners might extract information about children's views and emotions about the content of the stories and the way they preferred to complete the tasks. Some examples about children's views about the tasks were presented in Paper III [Section 4]. In this dissertation, the design partners were experts from different backgrounds (i.e., cognitive development, game design, interaction design, industrial design, and children's media). Conducting the case studies yield the quest for transferring the knowledge we gathered to our interdisciplinary design team.

RQ 3: How can we translate the knowledge we gained about very young children's developmental needs and abilities in spatial learning activities to our interdisciplinary design team?

Based on the previous inquiries we customized a card-based design tool to translate the theories and findings about children's early spatial skills and learning process. The card set was used by an interdisciplinary design team in a series of workshops. Thus, the main research contribution of this phase of our design is the evaluation of such a card-based design tool to communicate between different stakeholders in different stages of design.

RC 3: A card-based design tool to transfer knowledge about children's spatial skills and developmental needs to different stakeholders in design [Section 4: Paper IV]. The customized cards can be viewed and downloaded in this link:
https://happern.ku.edu.tr/wp-content/uploads/2018/04/Customized-DSD-Cards_Gokce-Elif-Baykal.pdf

RC 3.1 Design Implications: The design implications for customization of the DSD Cards were held in three aspects:

- Developing the card content: Since the original card set was focusing on four different developmental domains (i.e., social, physical, emotional, and cognitive), in this study we only focused on the spatial skills as a subdomain in cognitive development. We developed the content based on the findings in our literature review [Section 4: Paper I] and the findings of our case study [Section 4: Paper II].
- The customization of the design of the original cards: We implemented the content retrieved from our previous studies into the original card design. We conducted a pilot user study before finalizing the customization of the design. Based on the pilot user testing of the customized cards we made the following amendments in the card design; (1) relevant ages, (2) replacing developmental domains with the

scaffolding tools for spatial learning, (3) bolding the keywords to keep track of the information easier, (4) adding a designer check-list as reminders for important design considerations.

- Evaluation of the customized cards: User studies with experts through 3 whole-day design workshops (with 19 researchers and practitioners) along with post-workshop online survey with 15 closed, 1 open-ended questions based on (1) the design; (2) the content; (3) the use were conducted to evaluate the customized cards. The evaluation results were presented in detail in Paper IV [Section 4] providing with more insights about design implications for further investigations.

RC 3.2 Lessons Learned: The user study for evaluation showed the strengths and limitations of the customized cards in terms of use at different design stages and by stakeholders with different levels of knowledge about children's developmental needs and abilities. We describe and discuss the support and challenges of the design, the content and the use of the customized cards in Paper IV [Section 4].

- The tangibility of the cards were the main strength of this design tool because it enabled to grab, sort, point, and communicate ideas between people with different backgrounds in the design team.
- The main limitations were defined as the two-sided use of the cards, the amount of information presented on the cards, and the number of cards used at a time.
- People with different expertise used the cards in different ways. Thus, the evaluation of cards led us to consider refining the content and design of the cards for different design phases, and for users with different backgrounds.

The series of these design workshops with the card set also contributed to our explorations on brainstorming, ideation and elaboration on the future design of our CTI prototype. The interactional features of the prospective CTI design prototype are described in the following section.

6. Ongoing Work

Our literature review, the case study with parent-child dyads, and the design workshops we have conducted with experts from different backgrounds of expertise (i.e., cognitive development, interaction design, industrial design, game design, children's media) showed that tangible aspect of interaction is important for very young children's learning. Thus, we set forth the following outcomes and design decisions for the prototyping of our prospective CTI system.

6.1. Outcomes and CTI Design Decisions

6.1.1. *Design of Input/Output (I/O):* As explained in the literature review [Section 4: Paper I], the TUIs are described in three classes: (1) Interactive Surfaces that offer interface between physical and digital elements, (2) Coupling of Bits and Atoms as seamless coupling of graspable everyday objects, and (3) Ambient Media that make use of stimuli such as sound, light, or motion as background interface [18].

Furthermore, the levels of integration of these physical-digital elements are categorized in three groups: (1) Discrete (a physical input and digital output are positioned vertically on a surface), (2) Collocated (physical input and digital output are positioned and displayed on a surface), and (3) Embedded (the system is embedded within a physical object). Our initial intent was to develop an interactive surface (e.g., tablet or interactive tabletop), which offers collocated or discrete integration of physical elements (i.e., spatial manipulatives) with a digital platform [17]. However, our observations in case studies with children and experts' views extracted in design workshops indicated that fine motor skills of children between 2 and 4 years old might yield some difficulties with touch based screens. Thus, we decided on projecting the stories and visual materials on the table with a camera above the child [see Subsection 6.2., Figure 6a]. Thus, the physical input and the digital output could be positioned and displayed on the surface. Still, the digital output source would be located vertically to the physical input in order to avoid any interruption caused by child's unintentional touch. By doing so, any possible touch-based feedback effect (e.g., visual or audio) that might appear accidentally would be prevented on the region that the child is working on.

6.1.2. *Region of Interest (RoI):* As being explained in detail in [Section 4: Paper III] children who have participated in our case studies tended to work on areas other than the task required (i.e., the missing piece). This led us to extend the ROI from being only the missing piece to the whole picture [see Subsection 6.2., Figure 6b]. We believe children's interaction with the shapes displayed in the story pictures is valuable and contributes to their spatial thinking, no matter the action or rotation being correct or not. Making mistakes is part of learning. Thus, extending the region of interest would also entail to extend the types of feedback mechanisms.

6.1.3. *Feedback Mechanisms:* Again as being explained in detail in [Section 4: Paper III] children who participated in our case studies needed two types of feedback from their parents: 1) verbal (parental input in the form of narrative such as positive or correctional feedback, and providing information about the spatial features of the physical objects or shapes in the tasks) and 2) non-verbal input (parent's gestural input to show the spatial information such as orientation, shape or location of the object, or basically to help the child to focus his/her attention on the task). Moreover, children also employed verbal and non-verbal communicative expressions when they required parental input, such as showing an object to ask confirmation or asking questions verbally to their parents. We believe responding to these types of communicative requirements of children and providing the appropriate information needs further investigation. Within this dissertation we focused on analyzing and designing feedback particularly for children's different rotation actions.

6.1.4. *Children's Rotation Actions:* As being presented in detail in [Section 4: Papers II and III] some children employed different types of rotations when they had difficulty in figuring out how to solve the task. The rotation action types occurred in four categories. 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). In the next section, we present how we plan to implement the design decisions into our prospective CTI System for early spatial learning.

The physical-digital interaction offered by TUIs enable feedback that is genuinely contingent on user's input. This contingency allows feedback to be far more specific in an interactive platform. In addition, children can be given the opportunity to make multiple attempts to solve the same problem if a task proves difficult, and software can be programmed to select different tasks to match the level of expertise that a child has demonstrated in prior tasks in a different difficulty level.

6.2. CTI System Prototype

The setup of the proposed CTI system is illustrated in Figure 6(a). The setup consists of two hardware elements. We use a 15 lumens laser scanned pico-projectors from Microvision [35]. The projector is installed above the table and displays each level on a table surface. This can be any flat surface which provides a natural setting for the application. A camera is attached to the projector and captures the scene. Each frame of the captured video is processed real-time using computer vision techniques. Algorithms are implemented using Python 2.7 programming language and OpenCV computer vision libraries [5].

A region-of-interest (ROI) is defined for each scene. The fixed installation of the projector and the camera enables us to crop the ROI at each captured frame as the first step of the processing. Afterwards, the program checks the availability of a predefined shape and color in each scene. Once the child puts the right tangible object in a correct orientation, the level is completed and the program loads the next scene. Figure 6(b) shows a sample scene with a square ROI. The correct position of the tangible object (i.e., the yellow square) is represented in Figure 6(c). Placing objects with different shapes and/or colors is detected as the incomplete orientation, as seen in Figure 6(d). Figure 6(e) illustrates a situation in which the child places the correct object with an incomplete orientation.

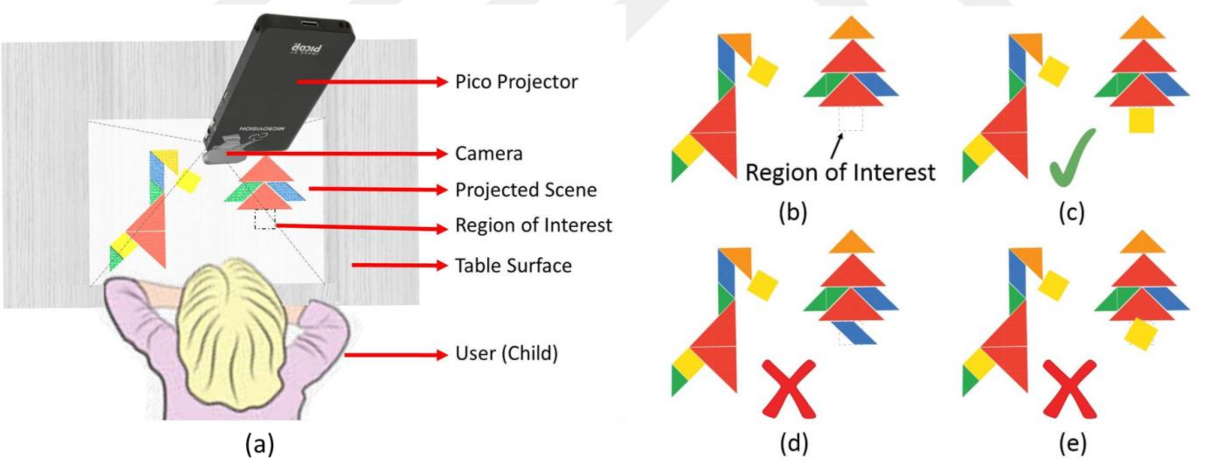

Figure 6. a) The diagram presenting the system setup. b) A sample scene c) A completed scene after placing the yellow square in the correct position. d) Placing a wrong object of shape and color in the ROI. e) Placing the correct object with wrong orientation in the ROI.

We will integrate, test, and evaluate the conceptual design and feedback mechanism through iterative studies with children to decide what sort of feedback is more helpful, fun and what encourages children stay on-task and engages to employ their mental rotation skills. Next, we present how we plan to conduct the user studies with children to test and evaluate this prototype.

6.3. Conducting User Studies with Children

We plan to test the Prototype through conducting series of user studies with children. First, we will start testing the feedback schemes we have identified for the rotation types. We will use Wizard of Oz (WoZ) technique in which the researcher as WoZ will be able to observe the child's requirement, and control and provide the verbal (audio) and non-verbal (visual) feedback accordingly. In this study, the story will be presented audio-visually through the system. According to our previous studies we expect the following user scenarios:

1. If the child *works on the missing piece area* and puts;

1.a. Correct object with Complete orientation (C&C); then WoZ will proceed with the next scene,

1.b. Correct object with Incomplete orientation (C&I); then WoZ will ask if the child is sure about the orientation of the object. If the child 1) completes the orientation then WoZ will proceed with the next scene, 2) employs second incomplete orientation then WoZ will provide verbal feedback, which includes spatial information about orientation of the object, 3) employs third incomplete orientation then the WoZ will provide visual (graphical animation) clue for completing the orientation, and 4) employs fourth incomplete orientation the the WoZ will provide the solution for the complete orientation of the object visually (graphical animation) and proceed to the next step.

1.c. Incorrect object with Complete orientation (I&C); then WoZ will ask if the child is sure about the size of the object. If the child; 1) changes the object with the correct object then WoZ will proceed with the next scene, 2) employs incorrect object for the second time then WoZ will provide verbal feedback which includes spatial information about the size of the object, 3) employs incorrect object for the third time then the WoZ will provide visual (graphical animation) clue for correct size of the object, 4) employs incorrect object for the fourth time then the WoZ will provide the solution for the correct size of the object visually (graphical animation) and proceed to the next step.

1.d. Incorrect object with Incomplete orientation (I&I); then WoZ will ask if the child is sure about the shape or size of the object according to the child's action. If the child; 1) changes the object with the correct object and completes the orientation then WoZ will proceed with the next scene. If the child employs one of the C&I or I&C options described above, then the WoZ will provide feedback that applies accordingly.

2. If the child *works on an area other than the missing piece*, then WoZ will ask if the child is sure about the location of the object. If the child;

2.a. Moves the object to the missing piece area with the correct object and correct orientation then WoZ will proceed with the next scene. If the child; 1) moves the object to the missing piece area by employing one of the mistakes given above (i.e., 1.a., 1.b., 1.c., 1.d.) then WoZ will provide feedback that applies accordingly.

2.b. Keeps failing to find the missing piece area, then WoZ will provide; 1) verbal information about location and spatial features of the missing piece, 2) visual information (highlight as visual clue) about location and spatial features of the missing piece, 3) visual (graphical animation) clue for the solution of the task, 4) visual (graphical animation) clue for the solution of the task and proceed to the next step.

We believe testing these feedback mechanisms with children by using a WoZ technique will enable us to evaluate the expected user scenarios and extract information about whether any other types of feedback are required by the children. We also expect that the results of the study will help to revise our CTI Prototype and iterate the prototype work independently from the WoZ. Furthermore, the results of this user study would also help to develop a guideline for designing our CTI system for early spatial learning.

7. General Conclusions

In this dissertation, we presented the early design phases of developing a CTI system for facilitating spatial skills of children between 2 and 4 years old. To a broader extent, this doctoral research addresses the gap in the knowledge about age-appropriate methods and tools to understand and involve children younger than 4 years old in the design process. We started with developing a theoretical framework grounded on the findings of early spatial learning process in cognitive developmental research and combined it with possibilities found in CTI for learning in CCI field [Section 2: Paper I]. This framework shows the complementary natures between two disciplines in which research is needed to better understand how to leverage tangible systems to support very young children's early spatial learning. However, to inform an age-appropriate tangible system design, there is also need for convenient tools and techniques to understand the developmental needs and abilities of this very young age group.

Due to lack of design techniques and methods to gain insight from our target age group, we adopted a reliable and validated domain specific technique (i.e., Preschool Embedded Figure Test) used in cognitive developmental studies to observe and understand the mental rotation skills and needs of children while interacting with spatial manipulatives. Modifying this method also helped us develop a set of figures embedded in structured tasks [Section 4: Papers II and III]. We presented the tasks in a storytelling context, which could be applied with tangible objects on a paper prototype. Observing parent-child dyads' experiences with this paper prototype enabled us to retrieve information about the gesture and extra-textual narrative input that children needed from their parents. These observations also helped us observe children's various rotational strategies and on-task behaviors, which could have not been foreseen without conducting the paper prototyping study [Section 4: Paper III; Section 6].

This has led us to the next design problem: How could we possibly transfer or translate this exploratory and observational information along with the whole knowledge we gained through the literature review to our interdisciplinary design team? Customization of DSD cards helped us to refine and make the knowledge accessible to the 19 experts from design and cognitive developmental fields in a series of design workshops. To further develop the use of cards we conducted an evaluation with the experts [Section 4: Paper IV]. This evaluation showed that the card-based design tool is not only helpful to communicate the domain specific knowledge and insights to people from different backgrounds, the cards should also be customized and designed according to the different design stages. The customization of the cards can be re-evaluated by comparing other card-based tools with different stakeholders such as parents. We also believe that our customization would inspire research to transfer knowledge about very young children's developmental needs and abilities in different learning domains to designers as well as adjusting the cards according to different stages of design.

After the exploration and ideation in which we consulted and discussed the results and requirements of this very young target age group's spatial learning process, we came up with the following design solutions that must be implemented into our future prototype: Input / Output (I/O) integration of a CTI design for early spatial learning should maintain the tangible aspects of interaction with spatial manipulatives to support children's learning. However, very young children's fine motor skills might cause unintentional touching behaviors on an interactive screen. Thus, the system should enhance the tangible interaction with digital elements, and the tasks should be offered seamlessly in a natural setting such as playing with spatial manipulatives on a tabletop where the digital output source is located above the child [Subsection 6.1]. Relying on this design solution, we planned to project the animated spatial experiences with a Pico projector on a tabletop which enables the child to interact with the tangible objects in a natural setup [Subsection 6.2]. A brief user journey was mapped to design the feedback mechanisms that respond to children's different rotation actions extracted from the previous case studies [Subsection 6.3]. As a first step for our future work, we will start with testing the feedback mechanisms via user studies with children. In further stages, the feedback mechanisms might expand to respond to children's communicative expressions such as recognizing their purpose of gesture to respond to their non-verbal expressions (e.g., showing an object to receive confirmation from their parents as a social contingency), or recognizing their voice in order to respond to their verbal input.

As explained in detail in [Section 4: Paper III], children who participated in our case studies showed more or less developed spatial skills. Thus, in order to respond to children's different levels of spatial skills within this age range, adjusting the difficulty levels is another step for the prospective CTI design. For instance, while some children with less developed spatial skills were having difficulty in recognizing the missing piece as a symbolic representation on one hand, some children with more developed spatial skills did not even need to hear the story context to complete the task. Thus, bringing design solutions for the difficulty level of the tasks such as increasing or decreasing the color cues in the displayed figures is also part of our future research.

Another topic of our future research agenda is to advance the independent use of physical and digital platforms employed in this CTI system as well as their combined use. For instance, we plan to develop triangular use of a picture book, a digital source and physical objects, while making it possible to use these materials in dual combinations (e.g., Augmented Reality), or separate from each other. Thus, enhancing the transmediated possibilities by expanding the spatiality of the tools might open new horizons for CTI research. Although this thesis does not provide an exhaustive practical explanation for TUI design for early spatial learning, it provides a first step and starting point for conversation between theories and techniques for early spatial learning and methods for CTI design with and for preschoolers. Hopefully, future theory and research will carry the discussion forward, to yield a richer understanding of implications for designing TUIs for early spatial learning.

We hope our cross disciplinary work inspires an exchange between theory and practice-based knowledge in different disciplines about very young children. We believe the methods and techniques we used throughout our design process can serve as an example for exploring new ways to communicate between different fields of work, and enhance very young children's involvement in the design process.

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