Knowledge Gaps in Hands-on Tangible Interaction Research

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ABSTRACT
Multimodal interfaces including tablets, touch tables, and tangibles are beginning to receive much attention in the child-computer interaction community. Such interfaces enable interaction through actions, gestures, touch, and other modalities not tapped into by traditional desktop computing. Researchers have suggested that multimodal interfaces, such as tangibles, have great potential to support children's learning and problem solving in spatial domains due to the hands-on physical and spatial properties of this interaction style. Despite a long history of hands-on learning with physical and computational materials, there is little theoretical or empirical work that identifies specific causes for many of the claimed benefits. Neither is there empirically validated design guidance as to what design choices might be expected to have significant impacts. In this paper I suggest several avenues of investigation, based on my own research interests, which would address this knowledge gap. I provide summaries of theoretical mechanisms that may explain claimed benefits, outline how the specific features of tangible interfaces might support or enhance these mechanisms, and describe current and future investigations that address current gaps of knowledge.

Categories and Subject Descriptors
H5.2. Information interfaces and presentation: User interfaces. K.3.m Computers and education: Miscellaneous.

General Terms
Design, Theory.

Keywords
Multi-modal user interfaces, tangible user interfaces, touch interfaces, child-computer interaction, digital manipulatives, hands-on interaction, hands-on learning, research agenda.

1. INTRODUCTION
Multimodal interfaces involving hands-on actions, gestures, and touch are becoming increasingly available with the commercialization of touch interfaces and growth of tangible computing research. Children as young as two-year-olds are using tangible prototypes and touch-based tablets to interact with digital media. Far predating such technical development is a long history of pedagogical approaches that facilitate hands-on learning with physical materials. In Europe and North America, this tradition can be formally traced to Froebel and Dewey [9, 14], but surely children's playful learning through interaction with natural and crafted physical materials predates written history.

Recent technical advancements combined with a rich history of hands-on learning result in a unique and timely research opportunity to better understand how hybrid digital-physical materials may be designed to support, enhance, and perhaps change children's lives. Multimodal interfaces, such as tangibles user interfaces and touch tabletops, have achieved much attention in both the human-computer interaction and learning science communities (e.g. [35, 46]). These new forms of technologies may change everything from the way children do written work in the classroom to how they interact with their grandparents at home. It is critical that technology development is grounded in research that investigates what makes effective interaction – how we think with our hands, how we express ourselves through gestures, and how movement is formative in human thought. Research is necessary to understand and enable the real benefits of these increasingly popular technologies. In a special issue of *Personal and Ubiquitous Computing* on Tangibles and Children, the editors emphasize the need for "… research on tangibility that transcends system descriptions, focusing on empirical investigations to inform theory and generate design guidance"[46]. Providing such a theoretically grounded research base for innovative technical development has great potential to provide design guidance for multimodal interfaces and positively influence children's digital experiences with these new forms of technology.

One area that may be revolutionized by tangible and touch technologies is hands-on problem solving in spatial domains. Focusing on theorizing and empirically validating design guidelines for spatial domains is novel and likely to be fruitful due to the physical and spatial affordances of tangibles, and to a more limited degree, touch interfaces. Research is needed in order to better understand the motor-cognitive mechanisms that underlie spatial problem solving, design computational supports for these mechanisms, and evaluate putative benefits [4, 46]. This research area is important not only because a variety of real world challenges require spatial thinking (e.g. molecular biology, environmental planning, object oriented programming), but also because an embodied account of cognition suggests that spatial reasoning forms the basis for the development of all abstract thought [16].

In this paper, I lay out a (partial) research agenda for understanding how tangible user interfaces may support and augment children's spatial problem solving. These areas are primarily influenced by my own research interests. I focus

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primarily on tangibles because they offer unique opportunities to support multimodal interaction through touch, vision, and audition; as well as offer physical and spatial properties not available with desktop systems. I discuss spatial problems that are content-free (e.g. jigsaw puzzles), as well as problems that require learning about domain-specific concepts (e.g. sustainable land use planning problems). Through content-free spatial problems, children may learn strategies and skills that enable spatial reasoning. Through domain-specific problems, children may apply spatial reasoning and develop an understanding of domain-specific concepts. There is a rich body of research about children's problem solving and conceptual learning in spatial domains. Due to lack of space, I will not mention more than a few key references. Instead, I focus on three threads of inquiry into how tangibles may support specific aspects of problem solving in order to illustrate typical approaches to child-computer interaction research in this space.

My intention is to provide inspiration, insight, and ideas for researchers eager to move forward with rigorous work in this field. Thus, this paper can be viewed as both an educational piece for other researchers and a call to action for research that I think will substantially impact our understanding of how to design tangible interfaces to support children's spatial problem solving.

2. HANDS-ON INTERACTION

Intelligent behavior develops not by thinking, but through acting physically in the world [37]. An embodied account of development suggests that Piaget underestimated children's cognitive abilities, and that through facilitated interaction with the physical world, children can learn and solve concrete problems in specific domains long before they can solve them symbolically or express related concepts verbally[18]. Central to this claim is the view that sensory-motor activity is critical to cognitive development [17]. This stance is reflected in the pedagogical "hands-on" traditions of Dewey, Froebel, Montessori, and more recently Papert, in which it is claimed that children develop cognitively from physical engagement in reasoning with materials in real world settings [9, 14, 34, 36]. Such claims are not accepted uncritically. For example, Uttal and others point out that successful learning outcomes associated with manipulatives typically require extensive teacher support, and that children must be able to see the relationship between concrete and abstract relations for knowledge transfer to occur [13, 44].

2.1 Hands-on Interfaces

One form of hands-on interface is a tangible user interface. Unlike physical manipulatives, tangibles involve using real physical objects that are linked to digital representations [40]. They involve input objects that have physical and spatial properties linked to computational models, in contrast to keyboard or mouse that act only as input devices. By linking physical materials with digital (abstract) representations, tangibles may address Uttal and other's criticisms by enabling children to explicitly see the relationship between concrete and abstract representations. Another form of hands-on interface is a multitouch interface. Touch interfaces, such as tablets and touch tables, enable hands-on interaction with screen-based digital representations. Hybrid tangible and touch systems are also becoming available (e.g. Microsoft Surface table).

Various researchers have suggested that digital learning materials in the form of tangibles, and to a lesser degree multitouch interfaces, might benefit children's learning in a variety of domains (e.g. [1, 29, 38]). However, little research exists that investigates the benefits of these claims [4, 30, 46]. A comprehensive review of early research focusing on children's learning and tangible user interfaces describes theoretical foundations and summarizes case studies, but none of these studies provides linkages between theory and interface designs, or outline empirically validated evidence of benefits [35]. Most current work in the field still invokes high level theories to explain possible learning effects without empirical validation [4]. There continues to be a lack of theoretically grounded guidance for designers as to what design choices might be expected to have significant impacts.

2.2 Spatial Problem Solving

Problem solving is a complex skill that, depending on the nature of the problem, involves different cognitive processes including divergent thinking, convergent thinking, visual search, spatial reasoning, mental visualization and justification; as well as metacognitive processes and non-cognitive variables (e.g. motivation, affective state) [42]. For domain-specific problems, it also involves conceptual reasoning. Spatial problem solving involves problems in which spatial characteristics of the problem are integral to successful solutions. Characteristics of space that may be important to the problem include object location, position, orientation, shape, size, proximity, grouping, or other spatial relationships. Examples of spatial problems that may be encountered by children include puzzles; mazes; simplified geographic, urban, ecological, or biological planning problems (e.g. creating a toy town, farm, or park); architectural, engineering, or transportation structural problems (e.g. making a building from blocks, laying down toy train tracks); geometric modeling (e.g. shape sorting); and organizing one's bedroom!

Research is needed to understand the role of hands-on interaction in spatial problem solving, what kinds of behaviours are most productive, and how to design interfaces that support these behaviours.

3. THEORETICAL GROUNDING

Exploring this research space requires theoretical grounding followed by empirical work. In the next subsections, I suggest three theoretical areas that I think deserve attention. For each, I provide a summary of the theory, links to further readings, and an explanation of how the theory articulates mechanisms by which tangible interface features might be designed to support and augment hands-on spatial problem solving with computational materials. There may be additional theoretical avenues worthy of exploration, but these three are good starting points.

3.1 Two-Handed Inter-Hemispheric Interaction

Interaction with tangibles and some touch surfaces is often two-handed. Evidence from cognitive neuroscience suggests that the actual handling of objects is important in creative tasks such as problem solving [21]. The right brain hemisphere is associated with the production of ideas or problem solutions. The left brain hemisphere is largely responsible for logic and selecting from this vast set of choices presented by the right hemisphere. Communication between the two spheres is enabled by the corpus callosum. Inter-hemispheric interaction (IHI) is the interaction of the right and left brain hemispheres through the connecting brain tissue of the corpus callosum. Creative problem solving requires this back and forth communication between the two spheres. Researchers have shown that mental and physical operations that require IHI have been linked with enhanced performance on divergent thinking tasks [19, 21, 28, 41].

One way that IHI has been enhanced in lab experiments is through bilateral eye movement exercises in which participants scan their eyes back and forth. Other bilateral movements may have a similar effect. From here I suggest that handling objects with two hands – in particular, moving objects from one hand to the other – may stimulate IHI. This may in turn improve the creative problem solving ability of those using both hands to manipulate physical or digital objects as part of a problem solving task.

What is not known is whether these ideas hold and if so the magnitude of their effects. We do know that tangibles can be designed to encourage this kind of two-handed interaction with everyday objects. This idea has been explored in an unpublished M.Sc. thesis (described below) [8]. Future research with children is necessary. I summarize this knowledge gap with the following high level research question: *Does facilitating two handed interaction improve children's divergent thinking in spatial problem solving?*

3.2 Complementary Actions: Coupling Internal and External Resources

Studies have shown that humans, and children in particular, rely on being embedded in an environment to help develop and coordinate their use of internal cognitive resources with external tools and representations required to solve problems [10, 43]. One of the ways they do this is by using actions to improve their cognitive purposes. Complementary actions are actions that recruit external elements to reduce cognitive loads [25]. Another way to say this is that certain gestures or actions on objects may offload some aspect of a mental process to actions in the world. The result of such an action may aid memory, improve perception, or simplify mental computation needed to solve a problem. In a jigsaw puzzle task children may use complementary actions for all three of these purposes, although they are largely unaware of these benefits. For example, children can improve memory by using space to organize piles of pieces. They can simplify perception by rotating rotate pieces to see how the pieces look in different orientations rather than moving themselves or trying to mentally visualizing the piece in a different orientation. These two strategies are complementary and epistemic because the act of moving pieces changes the world in order to simplify (and change) the task. Through the development and use of complementary actions, a child may be able to solve a problem that is otherwise too difficult.

Tangibles have similar characteristics as physical objects and thus may facilitate complementary actions through two-handed manipulation of objects, digital feedback, tactile feedback, and the use of structural aspects of 3D space. Touch interfaces also enable direct manipulation of objects. However, unlike physical objects, these objects can be manipulated in two dimensions of physical space or three dimensions of virtual space. For these reasons, tangibles, and possibly touch interfaces, may enable more effective and efficient spatial problem solving than physical or mouse-based interfaces [4]. What is not known is how to design specific interface features to facilitate complementary epistemic actions for a particular problem. We also do not know if using complementary actions in problem solving improves conceptual learning associated with that problem. Future research is necessary. I summarize these knowledge gaps with the following high level research questions: *What kinds of tangible and touch interface features support complementary actions for particular types of problems? Do these features enable children to solve harder problems than they might without such support? Does more this type of problem solving improve conceptual learning related to the problem's content domain?*

3.3 Learning Through Co-Evolution of Ideas and the Environment

The theory of mutual adaptation explains how children's ideas and actions change in an environment where they can modify their ideas over time through modifying the spatial structure of the world in some way [32]. In spatial problem solving, this may involve complementary actions that simplify the task, but manipulating the environment also leads to changes in the understanding of the ideas represented through the environment. In the context of solving a problem, the ideas may be about the underlying domain concepts.

This theory can be demonstrated through the example described in [39]. When children solve simple arithmetic problems with physical math manipulatives, they are using spatial problem solving skills and developing an understanding of concepts related to arithmetic (e.g. division). This approach may enable children to both the change the way they group the manipulatives in space and change their ideas about number concepts. In an experiment, children with a nascent understanding of division were asked to share a bag of candy with four friends. Children were allowed to restructure the environment by organizing piles of candies into various groups until a satisfactory solution was reached (i.e. four equal groups). A second group of children solved the problem using a graphical representation (i.e. drawing pictures of the candies to be shared). Children who learned through spatial reconfiguration of the actual candies were later better able to transfer their understanding of spatial groupings to symbolic representations of division problems in arithmetic.

Tangible or touch interfaces can be designed to enable dynamic spatial reconfiguration of the problem space [4]. Unlike physical manipulatives, the digital component of a tangible or touch system can result in feedback in the form of graphical or symbolic representations about the laws governing the problem. It may also enable feedback about the history of interaction. The combination of spatial and digital features and a dynamic system (rather than static materials) may enable children to adapt their understanding of such laws, which in turn, may be transferred to new problems and potentially to new domains.

What is not known is whether tangible or touch manipulatives for arithmetic problem solving are more effective than virtual manipulatives used in [39]. Studies of mutual adaptation have so far focused on learning arithmetic, not spatial problem solving. It is unknown whether the findings will apply to spatial tasks. Studies of groups of children mutually adapting their ideas are also needed. I summarize these knowledge gaps with the following high level research questions: *Are tangible or touch manipulatives effective for spatial problem solving? Does learning how to solve a specific spatial problem transfer to similar problems? Do tangibles or touch tools that enable mutual adaptation and improve spatial problem solving in one domain enable such understanding to transfer to other spatial domains? What features best enable social mutual adaptation?*

4. STUDIES: PAST AND FUTURE

In this section, I provide summaries of research I have been involved in that begins to address some of the knowledge gaps identified above. Rather than present the full details of studies here, I provide a concise overview of the work and provide pointers to the original publications. I follow this with ideas for future work that builds on or extends current work through study design variations, improvements, or replications with different audiences. In this way, I hope to open up this research space to other researchers interested in understanding how children's hands-on interaction supports spatial problem solving performance and skills development in a variety of contexts.

4.1 Comparative Studies: Two-Hands

One thread of investigation suggested by the research questions above is to understand how enabling children to use both their hands to manipulate tangible objects may enhance inter-hemispheric interaction (IHI), which in turn may improve problem solving outcomes.

One way to approach this is to conduct comparative studies of children using single and two-handed multimodal interfaces for a problem solving task involving divergent thinking. The goal would be to compare how children perform with single and two-handed interaction, and to determine if two-handed interaction can boost the number, type or quality of solutions.

4.1.1 Past Work

One area that we have explored involves an investigation through a comparison of two-handed and single-hand touch, and mouse-based interaction focusing on divergent thinking performance with adults [8]. The goal was to determine if two-handed interaction as afforded by a desktop-sized touch screen affects divergent thinking, which is a key aspect of many spatial problem solving tasks. We conducted a between-groups evaluation of 65 adults using one of three interface styles. Divergent thinking was measured using a computerized version of an assessment tool called the alternate uses task (AUT). Participants were asked to interact with 3D models of a series of everyday objects (e.g. shoe, brick, socks) and generate new uses for each (see Figure 1). Verbal data describing uses was analyzed to compare divergent thinking outcomes. Measures from the AUT included expert ratings of fluency, originality, level of detail, categorical distinctiveness, and usefulness. The study rests on the assumption that the three interface styles differ in their influence on divergent thinking primarily in terms of the IHI enabled by two-handed interaction with AUT objects.

Preliminary results of this unpublished Master's thesis found no significant differences in divergent thinking performance that could be attributed to interface style. It is possible that two-handed interaction does not boost IMI to the degree that it affects divergent thinking as measured by the AUT. However, we suggest that display size, which may have enabled eye-movement-based IHI for all the participants, may have contributed to this result. Other issues including oral language proficiency may have masked expected effects. We also suggest that the lack of significance may be because the AUT is not sensitive enough to capture differences between groups resulting from two-handed interaction.

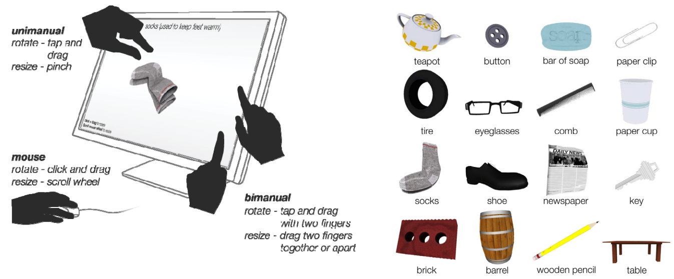

Figure 1. Computerized AUT (left); AUT objects (right).

4.1.2 Future Work

One avenue for future work would be to conduct a similar study with different age groups of children who are pre-screened for language proficiency. Some groups could be constrained to single-handed interaction while others would be encouraged to use two-handed interaction. One consideration when conducting this type of study with children would be the age at which children develop functional fixedness. Functional fixedness occurs when a child is hindered in reaching the solution to a problem by their knowledge of an object's conventional function [12]. It occurs at about the age that children enter school.

Since it is possible the computerized AUT might vary from the original paper test in terms of representational cues (e.g. 3D objects). We suggest that there may be value in investigating of the effects of representation modality as well as interaction mode on divergent thinking by comparing performance between paper, computerized, and physical object based versions of the AUT.

4.2 Comparative Studies: Spatial Puzzles

Another thread of investigation suggested by the research questions above is to investigate how specific affordances of tangible interfaces enable successful behavioral and cognitive strategies that support content-free spatial puzzle solving. Content-free puzzles are those that do not require domain knowledge for successful completion, such as jigsaw puzzles, tangrams, and 3D building puzzles (e.g. Equilibrio).

One way to approach is this is to conduct comparative studies of children using traditional and multimodal interfaces for the same spatial problem solving task. The goal would be to compare how the properties of physical and digital interfaces involved in the task affect patterns of hands-on actions, problem solving strategies, and outcomes. Another approach would be to compare different forms of tangible interaction. Another approach would be to compare tangible and touch with other forms of interaction. Comparative studies have the potential to provide evidence regarding the relation between interface features and problem solving outcomes. However, consideration must be given to both creating comparable designs (e.g. control functions, feedback salience) and creating designs that take advantage of the affordances each style of interaction provides [46].

4.2.1 Past Work

One area that we have explored involves an investigation of how complementary actions were affected by interface style for a spatial puzzle task. We conducted a study comparing children's performance using mouse-based, tangible and cardboard jigsaw puzzles (see Figure 2). A jigsaw puzzle is a prototypical activity that requires complementary actions to successfully solve it. We identified and coded three main classes of hands actions depending on the role they served in cognition (see [2, 3] for more details). One class is non-complementary actions, which are used when a child manipulates a piece simply to move it into its correct position. Another class is complementary pragmatic actions, which are used when a child manipulates a piece to determine its placement and correctly places it. A third class is complementary epistemic actions, which are used when a child manipulates a piece in order to simplify the problem space. For example, a child may organize puzzle pieces into groups, which simplifies the puzzle solving task by offloading memory to spatial location.

Figure 2. Comparative study: mouse-based (left) and tangible (right) jigsaw puzzles.

Data analysis focused on analysis of hand actions types including a temporal analysis. Briefly, we found that the spatial features of the tangible puzzle (e.g. 3D interaction space, table edges) provided opportunities for epistemic actions that resulted in the highest completion rates with a slight time cost [2, 3]. Analysis of the temporal sequences of events in successful pairs reveals a shared pattern of interleaved sequences of communication, epistemic actions, and direct placements. Analysis also revealed a positive correlation between higher number of actions on pieces and successful puzzle completion. Based on further analysis we suggested that an optimal strategy does not involve the minimum number of actions to complete the puzzle, but rather 'extra' actions that serve epistemic functions. Epistemic actions involved making piles of pieces, using one hand to push a pile of pieces around and the other to select (i.e. bimanual asymmetric interaction), moving around the table to get a different perspective, and connecting pieces off the table with two hands (bi-manual interaction).

In a later jigsaw puzzle study with adults, we compared how tangible versus touch interaction affected complementary actions and performance [45]. Using a within-subjects design, sixteen adults completed two comparable puzzles (see Figure 3). The goal of this exploratory study was to better understand the differences in strategies, sequences of hands-action types, and performance between interactions with virtual puzzle pieces (touch) and physical pieces (tangible). We found that players used more, shorter, complementary actions in the tangible condition, and finished puzzles faster (at the $p < 0.01$ level). In particular, we noted how players used the edges of the tabletop to organize and store pieces, offloading memory and reducing the number of steps in puzzle solving. Although a virtual "edge" area was available in the touch puzzle, players rarely used it. We found that bimanual interaction was observed in both interaction styles. However, in the touch group they were mostly symmetric (e.g. using one finger of each hand to rotate a piece). In the tangible group bimanual actions were more varied and asymmetric, which may better support IHI.

Figure 3. Comparative study: touch and tangible puzzles.

4.2.2 Future Work

Our early work suggests that table edges, offline space, and 3D manipulation space are all important factors in supporting complementary actions. One avenue for future work would be to compare graphical, tangible, and touch interfaces for other spatial puzzles (e.g. tangrams, 3D building). See [15] for some recent work in this area. Another avenue for future work would be to conduct a study using touch and tangible tabletop jigsaw puzzles for children of different age groups. Since children are still developing problem solving skills, it would be useful to compare results to the adult study. It may also be informative to compare different ages in order to look for a trajectory of developing skills and determine what design features may support younger children to succeed. One improvement to early data analysis methods would be to account for individual differences such as ability, gender, and age, by correlating these with performance measures (e.g. time to solution) in order to clarify if individual differences affect performance and strategy.

4.3 Case and Comparative Studies: Contextualized, Problem Solving

To fully explore this research space, it is important to move past content-free tasks, such as puzzles, and study interfaces and materials to support children in solving contextualized, ill-structured problems. In these tasks a spatial problem is situated in a domain-specific context (e.g. sustainable land use planning) with opposing or contradictory evidence and opinions, and there is not a single, correct solution [26]. To succeed children must both solve spatial problems (e.g. where to position resources) as well as learn domain-specific concepts (e.g. the pros and cons of hydro-electric versus natural gas for generating energy). These kinds of ill-structured spatial problems are a suitable test bed for tangibles research because their successful solution requires 1. Consideration of the physical and spatial elements of the problem that can be represented with physical objects; 2. Iterative problem framing and reframing that is enabled through computational models; 3. Integration of subject-matter content that is enabled by digital media.

One way to approach this research is to use findings from content-free puzzle studies to design interfaces for specific content domains. Exploratory single case studies can be used to determine if previous findings hold and to reveal new issues for investigation. Later comparative studies can be used to understand the tradeoffs between interaction, interface, and learning designs.

4.3.1 Past Work

One area that we have explored was a case study of primary school children's interactions and learning with a tangible tabletop system for land use planning. The system was designed to facilitate learning about key concepts in sustainable land use planning (described in [5]). The case study was comprised of theoretical underpinnings that informed design choices, a detailed description of the system (called Towards Utopia, shown in Figure 4), a design analysis and rationale, and a summary of a pre-test and post-test clinical style learning evaluation with 30 individual children. One key design requirement was that the system should enable dynamic, spatial reconfiguration of its components to support mutual adaptation and knowledge transfer.

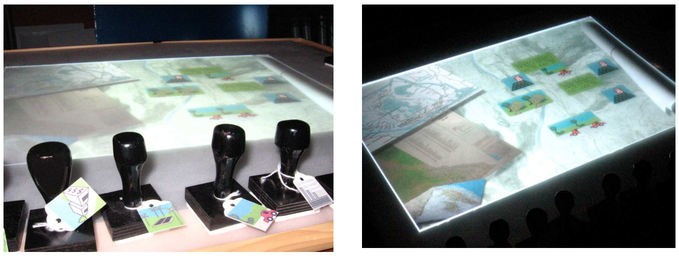

Figure 4. Tangible sustainable land use planning activity.

We observed that all children were able to quickly learn how to use the "stamps" to designate land use types on the tabletop map, check the results, and change land uses until a successful solution was found. We observed children using two hands asymmetrically to organize and use stamps, using table edges to store and organize stamps (epistemic actions), and using a trial and error approach consistent with dynamic spatial reconfiguration. Learning results from clinical style interview showed an increase in post-test scores compared to pre-test scores. The average learning gain score was a 22% increase, which was significant at the $p<0.001$ level (non-parametric statistics). The standard deviations for pre-test and post-test are relatively small, indicating that participant scores were fairly tightly clustered around the mean scores.

While these results provide evidence of short term learning benefit, we do not have a control group or a comparison with other learning approaches or materials. Thus, we cannot say that children learned better or differently with our system compared to another. However, it is clear that students significantly increased their scores after using the system. In future designs, a follow-up activity assessing knowledge transfer would enable stronger claims to be made. In addition, in this study it is not possible to isolate one feature of the prototype (e.g. dynamic re-configuration) from others (e.g. 3D interaction space).

4.3.2 Future Work

One avenue for future work is to explore if results from single case studies are generalizable. To do this requires creating different ill-structured spatial problems using the same interface strategies identified in previous research. Another avenue for future work that we have currently begun involves comparing different approaches for supporting collaborative mutual adaptation with pairs of children. We are redesigning the Towards Utopia system to enable collaborative activity that may support mutual adaptation. To support collaboration it is important that children have a shared focus around which negotiation can occur [11]. In addition, children need to have a reason to negotiate with each other. True collaborative tasks create positive interdependence, requiring the coordinated activity of multiple children for success [27]. One way this is often instantiated in CSCL is through variations on the "jigsaw" script [6] in which each child only has access to part of the solution [33].

In a tangible system, access points enable multiple children to participate as a group and interact with the system. In Towards Utopia, access points are enabled by 13 land use stamps. However, previous non-tangibles research has shown that multiple access points may result in a non-collaborative situation of parallel play [24]. One option is to design a constrained input system that has limited number of access points. This approach requires sharing and coordination [22] since a limited number of access point can also lead to competitive behaviors [31]. Another approach is to design co-dependent inputs; that is, while they are sensed individually, the system responds to them collectively. Each child needs to take a specific action in order for the system to respond in the desired way.

Research is needed to determine how a constrained versus a co-dependent approach influences children's co-evolving interactions and ideas. Our new design of Towards Utopia supports pairs of children to adapt their ideas by trying out different spatial configurations (as in [5]) and also triggers opportunities for discussion during spatial reconfiguration. We will compare how constrained versus co-dependent access points support children in productively negotiating with each other during the land use planning task, and if such interactions provide benefits for conceptual learning.

4.4 Designer Studies: Making Knowledge Accessible and Usable in Design Practice

Another pressing problem associated with child-computer interaction research that is often neglected, is determining how to get resulting design knowledge into design practitioners' hands. Design cards are a method that has been suggested for making research-based design knowledge into a form that is accessible and usable for designers [7, 23].

4.4.1 Future Work

We are currently working on a set of design cards for tangible learning. The goal of the project is to take information in the form of design guidelines from research papers and distill and illustrate the guidelines on design cards. For example, we have taken guidelines from [4], including guidelines related to complementary actions and mutual adaptation, and created preliminary cards, called the Tango set (see Figure 5). Future plans are to run a design-in-use study to evaluate if the cards present design knowledge in ways that are useable and accessible to researchers and designers of tangibles for children.

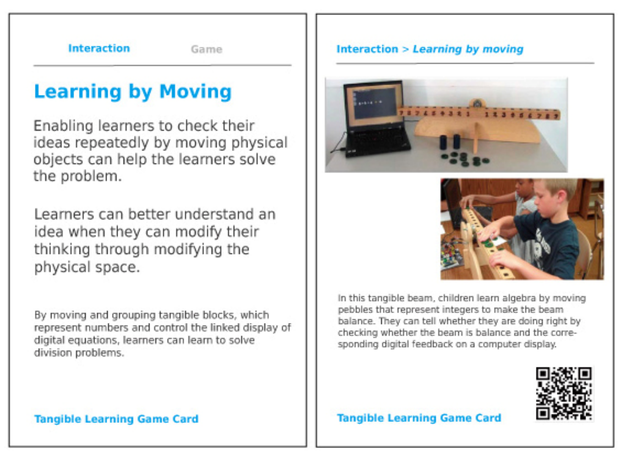

Figure 5. Tango card for mutual adaptation (draft).

5. SUMMARY

In this paper I have identified three threads of research, provided summaries of some of my work in each area, and made suggestions for future work. I encourage interested readers to read my original papers in order to understand the details of each piece of research, and follow links in these papers to read works of other researchers working in this space. By focusing on research questions derived from theory, I hope to provide a grounded research agenda that will enable other researchers to move forward with rigorous empirical work. Without such work, the HCI and educational technology communities interested in children's hands on interaction may remain focused on performance, observation of behaviors and experiential measures, and neglect important details about how manipulating objects in space helps, changes or limits children's ability to think with and through those objects. Of course translating theory to empirical study designs is difficult and each methodology has its limitations. Single case studies are often not generalizable. Comparative studies often have multiple factors that vary between interfaces. No single approach is right to address all questions. However, taken together, a body of research can be undertaken that contributes to better understanding of how and why tangibles might support the development of children's spatial problem solving skills.

Research outcomes in this space will make important contributions to communities including learning sciences, educational technology, educational psychology, computer-supported collaborative learning (CSCL), interaction design for children, child-computer interaction, and cognitive development. Knowledge transfer to other researchers, undergraduate and graduate students, and industry practitioners may enable the design of effective tangible and touch interfaces for numerous educational and professional domains that include spatial problems solving in science, art, engineering, and design; and may be transferable to other user groups including teens and college students.

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