The CTI Framework: Informing the Design of Tangible Systems for Children

Alissa N. Antle
School of Interactive Arts and Technology
Simon Fraser University – Surrey, B.C., Canada, V3T 0A3
aantle@sfu.ca

ABSTRACT
New forms of tangible and spatial child computer interaction and supporting technologies can be designed to leverage the way children develop intelligence in the world. The author describes a preliminary design framework which conceptualizes how the unique features of tangible and spatial interactive systems can be utilized to support the cognitive development of children under the age of twelve. The framework is applied to the analytical evaluation of an existing tangible interface.

Keywords
Tangible interfaces, spatial interaction, embodied cognition, cognitive development, interaction design, children.

ACM Classification Keywords
H.5.1 [Multimedia Information Systems]: Artificial, augmented and virtual realities, H.5.2. [Information Interfaces and Presentation]: User interfaces.

INTRODUCTION
Tangible and spatial interaction encompass a broad range of mixed reality interfaces and systems which rely on tangible manipulation and physical representation of data, interaction embedded in real physical spaces and related forms of digitally augmented physical spaces [14]. For the purposes of this paper and following precedent in [14], I refer to tangible and spatial interactive systems as tangible systems. Unlike virtual reality, tangible systems can help the user to understand the real world in the real world. The conception of tangible and spatial interactions which may be haptic, gestural, full bodied or spatial, presents new challenges for the HCI and design communities.

Tangible systems, with their powerful ability to engage children in active learning through these new models of interaction, should provide children with unique artifacts and environments for play and learning. Healy provides support for tangible, physically-based forms of child computer interaction when she states that body movements, the ability to touch, feel, manipulate and build sensory awareness of relationships in the world are crucial to children's cognitive development [12]. Conceptual understandings of these new forms of tangible and spatial interaction for children are needed. Developing a conceptual framework for the design of tangible and spatial interfaces based on an understanding of how and why augmentation supports cognitive processes in children is the purpose of this work. By focusing on how children acquire knowledge rather than on specific educational content areas, we can support the goal of generalizability of design knowledge. And in this way, a broad range of opportunities and constraints for augmentation can be identified and developed.

This paper presents a preliminary conceptual framework. It is divided into five themes which are based on attributes specific to tangible and spatial styles of interaction. For each theme relevant theory about children's cognitive development is summarized and illustrated with an example taken from children's everyday lives. Excerpts from a case study are presented which demonstrate the utility of the framework for interaction evaluation.

DESIGN FRAMEWORKS FOR TANGIBLE INTERACTION
Much research on tangible and spatial user interaction focuses on the design of new systems. More recently, there has been a shift towards research based on theoretical and conceptual understandings of tangible interaction (e.g., [13]). The most cited of conceptual frameworks is that of Ishii and Ullmer [16]. They approach interaction from a data-centric view which explores possible types of coupling between material and virtual representations. Other examples of this approach include [29, 37]. Broader characterizations of tangible interfaces have been instantiated in design frameworks which concentrate on the design of the interaction itself (e.g., [7, 14, 18]). Like a constructivist view on learning, meaning is created in the interaction. Design frameworks which focus on spatial aspects have also been put forth (e.g., [3, 33]). The role of

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spatiality is paramount in these interaction models which focus on combining physical spaces or objects with digital displays or sound installations. Hornecker provides a good overview of these different approaches to conceptualizing tangible and spatial interaction [14].

A recent tangible interface framework specific to children presents the classification of tangible manipulatives as “Froebel-inspired” or “Montessori-inspired” depending on intended use [43]. Rogers *et al.* present a conceptual framework for mixed reality specific to children. It focuses on the notion of transformations between virtual and physical dimensions [29, 30]. Related work for children highlights the possibility of using the Heidegger’s distinction between “readiness-to-hand” and “presence-at-hand” to promote reflection in children [23].

What is missing is a design framework grounded in child-specific developmental theories about how children develop intelligence through their physical, social and spatial interactions with the world. The framework presented in this paper is the first attempt to address this gap. It is a work in progress and a continuation of previous work which mines the rich domain of developmental psychology for theoretical descriptions and explanations which can inspire and inform the design of interactive technologies for children (e.g., [1]).

CHILD TANGIBLE INTERACTION FRAMEWORK

The child tangible interaction (CTI) framework is a conceptual framework for the design of tangibles and interactive spaces which support schemata level knowledge acquisition in children. Children are characterized as active learners embedded in a physical and social environment [26]. The framework focuses primarily on children over the age of four and under the age of twelve. The lower age boundary is set by the author’s belief that very young children’s developmental needs can be adequately met without computation. The upper boundary is set at twelve because around this age many children progress into the final stage of cognitive development associated with adult thinking [26]. While some of the theoretical concepts may also be applied to teens or adults (e.g., epistemic action), all of the theoretical concepts are relevant for how children develop intelligence in the world. Thus, the framework can be applied to all user groups who are still developing (or redeveloping) *abstract* cognitive structures. It is less relevant for users who already have well developed cognitive structures associated with abstract thinking.

The framework is not meant to be prescriptive. Rather it is an explanatory framework which can be used in three ways. First, it is meant to provide insight for the *generation* of designs for new kinds of computational artifacts. Second, it is meant to *inform design decisions* during the design of these kinds of artifacts. Third, it is meant to be used as an *analytical framework* for resulting interactions. Prescriptive guidelines for specific ages or stages are not outlined in this paper. Instead the themes presented acknowledge that children have developing abilities which must be considered in design. Rogers and Muller provide a more detailed overview of the utility and constraints of this kind of theoretically derived design framework [30].

The goal of informing tangible systems design can best be done by considering notions from both cognitive development and educational theory. The framework was developed by identifying concepts in the rich literature from both these areas which had direct relevance for the design of computational artifacts based on tangible and spatial interaction.

To date much of the theoretical debate on the value of embodied cognition for interaction design has focused on embodied cognition as a reaction against information processing approaches to cognition (e.g., [41, 42]). While embodied cognition and cognitive science may be philosophically opposed, the framework utilizes concepts from both areas to ensure designers consider the strengths of action-based cognition and the limitations of children’s mental representational abilities in designing tangibles to support abstract thinking.

One critical aspect of interaction design that is not discussed in this paper is that of engagement. The author acknowledges that successful outcomes must include attention to affective and motivational factors in conjunction with motor and cognitive factors. However, a discussion of these factors is outside of the scope of this paper.

CTI Themes

The CTI framework is presented in five themes. Each of the five themes relates to a feature or aspect of tangible systems. The first and last themes are related to the spatial aspects of the system. The middle three themes are related to the various kinds of mappings between the physical and digital aspects of the system. For each theme, theoretically derived design concepts which help explain the abilities and limitations of children are summarized and explicated with an example taken from children’s everyday lives.

1. Space for Action (SA)

Spatiality is a property of tangible systems. Tangible systems provide Space for Action where actions affect computation. Unlike traditional desktop systems which utilize an indirect controller, mouse and/or keyboard for input, tangible systems afford opportunities to capitalize on children's developing repertoire of physical actions and spatial abilities for direct system input and control. Theme parks and interactive exhibitions in museums, art galleries and science centers have created a rich tradition of creating environments which respond to children’s (and adult’s) actions and movement. However, little is known about how to design these environments specifically to support cognitive development. Design requires an understanding of how and why children's actions in space are related to cognitive developmental change.

The Role of Action in Embodied Cognition

Embodied perspectives on cognition suggest an evolutionary view of human reason, in which reason uses and grows out of bodily experience [19, 40]. Direct physical interaction with the world is a key component of cognitive development in childhood. Piaget began a long tradition which suggests that cognitive structuring through schema accommodation and assimilation requires both physical and mental actions [26]. Numerous pedagogical approaches including the Montessori Method and Frobel's Kindergarten curriculum support using bodily engagement with physical objects to facilitate active learning. A classic example of how children use their bodies to learn is the way children use their fingers to learn to count and perform arithmetic operations (e.g., add, subtract).

Design Concepts

- Body-based interaction and control (vs. dialogue-based)
- Age appropriate repertoire of physical actions
- Existing performative knowledge

Pragmatic and Epistemic Action

Pragmatic action involves manipulating physical entities to directly accomplish a task [18]. For example, a child will connect Lego blocks to build a dinosaur that can stand on two feet. Epistemic action involves manipulating physical entities in order to change the nature of the cognitive operations necessary to complete a task. For example, a child may spend considerable time connecting and disconnecting Lego blocks to better understand how different configurations relate to the stability of their creation. Another salient example comes from user studies of the computer game Tetris [21]. One would expect that the foremost task in this spatial building game would be to move geometrically shaped pieces in order to optimally align them in the available space. However, Maglio and Kirsh found that expert Tetris players actually manipulate pieces far more than novice players. They do so in order to better understand how different options might work by changing the task from one of mental rotation to one of pattern matching [21].

Epistemic actions are a frequent way that children utilize their environments to facilitate developing new understandings of how things work. Because children's mental abilities are still developing, epistemic actions are often executed with what Clarke calls external scaffolding [4]. Children manipulate the environment, or objects in it, to offload cognitive processes that are still difficult (e.g., visualizing, remembering) to external aids – aids that include interactions with other children, adults, or aspects of the environment.

Design Concepts

- Epistemic actions
- Offloading difficult mental processes (e.g., remembering, visualizing)

2. Perceptual Mappings (PMap)

Tangibles afford various kinds of mappings between physical and digital space. Perceptual mappings refer to the mapping between the perceptual (often appearance) properties of the physical and digital aspects of the system. Design requires consideration of children's understanding of the relationships between how things appear and how things respond.

Perceptual Affordances

At very young ages children can quickly explore and understand the perceptual affordances of input and then watch, listen and touch to determine the output effects. Perceptual affordances are opportunities for action within the environment for individuals with suitable sensory-motor skills. They do not belong to either the environment or to the individual but to the relationships between the two [27]. Designs which rely on perceptual affordances will allow even very young children to activate the system and subsequently explore the mappings between physical and digital aspects of the system. Norman extended the concepts of affordances to describe opportunities for action which are created through mindful design of artificial objects and environments [24]. These designed affordances may be meaningful to adults but may not trigger intended actions in children. Thus designed affordances need to consider the age appropriate perceptual, cognitive and motor abilities and limitations of children.

Design Concepts

- Perceptual affordances
- Designed affordances

Scales of Experience and Representation

One perceptual issue which may need to be considered in design is the scaling between experience and representation. Humans experience the world at particular scales in time and space [25, 42]. As children learn to represent the world they wrestle with issues of scale. It is common to see a child's drawing of a house represented the same size as a person. Children interpret the world in relation to their own body scale. Digital representation coupled with body-based interaction provides the opportunity to map scales of interest to scales of the child's body and conversely to represent children's bodies at a variety of scales to enhance understandings of scale.

Design Concepts

- Child-body scale as reference

3. Behavioral Mappings (BMap)

Behavioral mappings refer to the mapping between the input behaviors and output effect of the physical and digital aspects of the system. Design requires consideration of children's understandings of how things behave.

Cognitive Mode Switching

Reflective cognition is required to update existing schema and to learn complex structures and concepts [31]. Norman outlines two modes of cognition: experiential and reflective [24]. The experiential mode is that alluded to by proponents of embodied cognition. The mode of experiential cognition provides opportunities for children to explore new concepts, environments and activities. The mode of reflective cognition provides the opportunities, either alone or in conjunction with others, to search for understanding and explanations. Even young children have some metacognitive strategies (e.g., ability to self-regulate and reflect) [5]. However these abilities develop slowly and children need significant support to ensure that they move from an active, experiential mode to a reflective mode where they can acquire new understandings [26].

Marshall *et al.* propose that Heidegger's concepts of *readiness-to-han*d and *presence-at-hand* can be used by designers to actively promote a switch from one form of cognition to the other [23]. These concepts can be explicated through a tool use example. As a child learns to hammer a nail, the hammer may be *ready-to-hand* (experiential). It becomes almost an extension of her arm and fades from her attention; until she hammers her thumb or misses the nail. Then the hammer becomes *present-at-hand*; it becomes the direct focus of her attention (reflective). Rogers and Muller propose that uncertainty and unexpectedness in system events can also promote a switch to a reflective mode of cognition [30].

Choices regarding the behavioral mappings between physical and digital aspects of the system can promote or inhibit mode switching.

Design Concepts

- Experiential vs. reflective modes of cognition
- Ready-to-hand vs. present-at-hand

Cause and Effect

Design of behavioral mappings requires an understanding of how children apply principles of cause and effect. System events which do not conform to these principles may trigger confusion, disinterest or (ideally) reflection. Similarly, events which do conform, will help maintain an experiential mode of interaction.

Several cause and effect schemata can be summarized as principles which children can apply with varying degrees of accuracy at different ages (as summarized in [32]). The principle of temporal precedence establishes the asymmetry of the causal relation since it specifies that causes must either precede or occur simultaneously with their effects. Children as young as three can rely on temporal order when identifying causes. The principle of covariation states that causes and their effects must systematically covary. That is a causal relation describes an invariable connection between events. Young children are tolerant of imperfect variation but older children adhere more tightly to this principle when attributing causes to effects. The principle of contiguity states that causes and effects must be contiguous in time and place or at least linked to each other by an intervening chain of contiguous events. For example, if a significant temporal delay is introduced only children eight year old or older can reliably identify covariation.

Together, these principles make up the "common sense" view of causation which young children develop and rely on. The principles can be tentatively ranked. Temporal precedence supersedes spatial contiguity. Temporal and spatial contiguity may out weigh covariation. There are an assortment of variables which can influence simple causal judgments including: the degree of similarity between causes and effects and the facilitative or inhibitory nature of the causal relations.

These principles can be supported or broken in order to support children to accommodate and assimilate new conceptual structures.

Design Concepts

- Temporal precedence
- Covariation
- Temporal and spatial contiguity

4. Semantic Mappings (SMap)

Semantic mappings refer to the mapping between the information carried in the physical and digital aspects of the system. Design requires consideration of children's understandings of what things mean in various representational forms.

The Problem with Multiple Representations

Manipulatives are objects designed to promote development of children's understanding of specific concepts. However, as Uttal summarizes, children under the age of seven may have difficulty relating physical manipulatives (one form of representation) to other forms of representation (e.g., written) across contexts [39]. This stems from the difficulty young children have appreciating that a single object can represent two different things or be seen in two different ways. Uttal also cites research that describes how allowing children to play with an object may detract from children's ability to see that object as representing something other than itself [39]. This research pertains to preschool children. However, the ability to understand multiple referents and representations develops slowly and individually, rather than all at once.

If it is not possible to reveal mappings, then young children may need to use multiple representations without explicitly understanding the mappings. For example, children may physically rotate a jigsaw puzzle piece to fit either the "picture" or the "form." They can find the correct place for the piece without having to consciously choose one form of representation over the other. In light of these findings, Dourish's case for variable coupling between intentional action and effect in order to allow elements of an interactive system to take on meaning for a child becomes even more important [8].

Design Concepts

- Reveal representational mappings
- Exploration of relationships between entities and representations

Mapping between Representations

Imagination involves the mental imaging or visioning of both concrete and abstract ideas. Maps are one form of symbolic representation of space. Tangible interfaces provide both a model and a control for physical space which is then mapped either directly or indirectly to virtual space. Liben provides empirical evidence that the relation between cartographic map use and the development of spatial cognition in children is reciprocal [20]. As children age, their developing conceptions of space and mental abilities to visualize, transform and change perspective in space, improves their understandings of maps. In turn, their developing conceptions of maps improves their ability to conceive of space and understand spatial information [38]. Explicitly learning about the reciprocal nature of physical and mental representational forms builds children's understandings in both domains.

Design Concepts

- Reciprocal mappings between physical and mental representation

Grounding Understanding in Body-based Schema

The perspective of embodiment provides an understanding of how children's ideas are organized in growing conceptual systems grounded in physical, lived reality. For example, abstract concepts: balancing colors in a picture; balancing a bank account; and balancing a system of simultaneous equations are conceptual extensions of the bodily experience of 'balance' [17]. Children develop abstract understandings by grounding them in and building on concrete bodily experiences. Research by Funk *et al.* provide a salient example by providing empirical evidence that children as young as five can successfully solve abstract kinetic mental rotation tasks by using an internal strategy which includes both cognitive and motor processes. The child imagines moving their hands to solve the task even though the do not actually move their hands [10].

Design Concepts

- Leverage children's understandings of bodily-based concepts to help them understand abstract concepts

Grounding Understanding in Spatial Schema

Spatial schemata are developed prior to abstract schema. Gattis argues that spatial schemata provide a foundation for more abstract reasoning [11]. Spatial schemata aid cognition because their familiar organizational structures can be used to facilitate memory, communication and reasoning. While the mechanisms are debated, it is clear that children use rich spatial schemata as a foundation for the development of other concrete and abstract schemata. For example, children may conceptualize counting as adding to a pile of objects.

Design Concepts

- Leverage children's understandings of concrete spatial schemata to help them understand abstract concepts

5. Space for Friends (SF)

Tangible and spatial computer-mediated systems have both the space and the affordances for multiple users. This presents several unique opportunities. While many topics might be explored under this theme, collaboration and imitation are typical and important ways that children develop schemata. Thus, design requires an understanding of the key factors that a system must embody to successfully facilitate children's collaboration. Design also requires an understanding of the importance and mechanisms of imitation in experiential learning.

Collaboration

Most desktop based systems are constrained to single user interactions. Although children may pass a mouse or game controller back and forth, these input devices are not specifically designed to support collaborative activity. Research has shown motivational and learning benefits for co-located interaction in computer environments [15, 34, 35]. Tangible systems have space and handles for co-located collaboration without the need to share input devices. Research involving tangibles and children's collaboration is a large and active area (e.g., [2, 22, 34]). A discussion of design considerations for tangibles and children's collaboration could easily produce a full length paper. A close reading of theoretical and empirical work leads us to suggest that the following are important design considerations.

Design Concepts

- Interaction supports rather than requires collaboration
- Multiple input units or modes
- Protocol for changing mode or transfer of control

Imitation and Intentional Affordances

A second topic which is often overlooked in this research area is learning through imitation. This topic is particularly relevant for tangible systems for children. Imitation is a dominant mode of learning in young children. When children observe other people using cultural artifacts, they often engage in the process of imitative learning. One form of imitative learning which should be explicitly considered in the design of tangibles are opportunities for what Tomasello calls *intentional affordances* [6, 27, 36].

The theory of intentional affordances extends the Gibsonian work on affordances. It is based on recent work showing the shared neurology of motor and perceptual pathways [28]. Researchers have shown that visuomotor neurons fire when we grasp an item with our left hand, right hand or mouth [9]. It is not the specific movement but the intention to grasp that dictates neural pathways. Rizzolatti suggests that some of these neurons fire not only when we are grasping but when we see another individual grasping and we have the intention to imitate [28]. He calls these neurons mirror neurons. Mirror neurons allow us to understand what other individuals are trying to do. Rizzo suggests that as young children observe others using unfamiliar objects, they attempt to place themselves in the "intentional space" of the other person by trying to discern what the other person is using the artifact for. As children are involved in this intentional mirroring process, they begin to perceive another set of affordances, called the *intentional affordances*, of objects and tools. In this way, children learn how to handle and use new tools. The physicality of tangibles combined with the space for others and the availability of digital feedback provides the ideal opportunity to design intentional affordances.

Design Concepts

- Clues to intentional affordances
- Visual access to performative actions
- Turn-taking of physical or spatial controls

CASE STUDY

Excerpts from a case study are presented in order to demonstrate how the framework can be used to inform interaction analysis.

Analysis: The Aibo and Collaboration Project

Sony's autonomous companion, Aibo, is a sophisticated example of a class of toys which embody a multimodal, tangible approach to human machine interaction. The objective of this project was to explore the features of autonomous, multimodal and tangible interfaces which might be used to support cooperation between small groups of children, aged five to eight, in problem solving tasks. Aibo Model ERS-7 series are autonomous robotic dogs produced by Sony Corporation. The dog used in this study was named Ninja. The dog can be controlled using three input modalities: voice commands, visual cue cards (pattern recognition) and touch (touch sensors for "patting it's head" and control buttons on its back). One hypothesis was that multiple modalities of input would promote synchronous shared control during problem solving. This is in contrast to the social patterns of turn taking or individual control.

Figure 1. Boys showing Ninja visual cue card.

The exploratory study design was based on expectations taken from previous work on interfaces to support collaboration in children [2, 34]. Five pairs of children, aged five to eight, were given three tasks. They had to get Aibo to sit and dance; stand and dance and lie down and dance (Figure 1). The three forms of input control were demonstrated to them. They were given cue cards for sit, stand and lay down. They were given no other instructions on how to perform these tasks. Quantitative data analysis of video recordings of the sessions included coding the frequency of behaviors and verbalizations that indicated joint problem solving. For example, one code was instances where both children were touching dog. Another code was instances of one child touching the dog while the other gave instructions. Instances of collaborative behaviors normalized over total task time showed low instances of collaborative behaviors. Conversely, instances of sequential control and individual problem solving were frequent.

The CTI framework was applied as an analytical framework to understand the unexpected interaction patterns and to help explain the contrary quantitative results. For example, while the interface for Aibo allowed children to use their known *repertoire of physical actions* (e.g., petting the dog) (SA), the mappings between commands and Aibo's actions were not *revealed*, not easily *explored* and not *reciprocal* (SMap). This combined with the autonomous nature of Aibo led to considerable user frustration and helps explain why the interface did not support collaborative activity. Second, the system did not promote the *transformation* of abstract to tangible concepts (SMap). For example, the cue cards were fairly difficult for young children to interpret. This was confounded by incoherent behavioral mappings between causes and effects. There was often a significant *temporal discontinuity* between action and reaction making *covariation* difficult to determine (BMap). Children's inability to apply simple age appropriate principles of cause and effect interfered with their learning of the functions of user interface and understandings of how to control the robot dog.

While multiple control modalities allowed for shared synchronous control, there was no *protocol for mode change.* As a result children often gave commands in different modalities at the same time. The results were unpredictable making true cooperative problem solving through *collaboration* difficult (SF). For example, if one child gave a voice command while the other showed it a cue card, Aibo would often respond to neither, instead responding in some seemingly unrelated manner. One particularly funny observation was when the children were trying (unsuccessfully) to get Aibo to sit and dance. After several attempts to get Ninja to sit, they jumped up, pointed at him and shouted loudly, “Sit Ninja, Sit! Bad dog Ninja!” In an effort to succeed on their task they resorted to their normal, *performative* (and verbal) actions with real dogs (SA). Ninja still did not sit. At both a behavioral (BMap) and semantic (SMap) level, the interface was not suited to support collaboration in children of this age.

CONCLUSION

The five dimensions of the framework define vertical research areas for tangible and spatial interaction and children. Horizontal integration and understandings of the interrelationships between themes provides a further challenge. Research may proceed by exploring the utility of the framework through small empirical studies of prototypes developed based on aspects of the framework. It is not expected that all concepts in the framework will always be applicable. However, as demonstrated in the excerpts from the Aibo case study, the interplay of concepts provides design information and helps us analyze the resulting interactions. Considering the contribution and interconnection of children’s actions in space, perceptual, behavioral and semantic mappings, and the social affordances of tangible systems allows us to intelligently design and analyze tangible systems for children. This paper represents a first step towards producing a conceptual framework from which these objects and environments may be successfully designed and new knowledge may be generated.

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