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Research opportunities: Embodied child–computer interaction

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ABSTRACT

The child–computer-interaction community has been increasingly influenced by an interaction paradigm called embodied interaction. Embodied child–computer interaction is grounded in theories of embodied cognition that include a dynamic systems perspective on children's development, different mechanisms for offloading cognition to the world, and inter-related theories about how movement informs learning and cognition. The last ten years have seen these perspectives on cognition rise in prevalence and acceptance in the cognitive science community. But what is embodied child–computer interaction? How does it change how we design interactive technologies for children? What are the gaps in knowledge that need to be addressed? In this paper, I provide a short introduction to embodied cognition and embodied child–computer interaction, discuss several roles that theories can play in child–computer interaction research, and identify three important groups of theories that have practical application in interaction design. Each area is explained and illustrated with recent work from the field. Opportunities for future research are broadly identified. The main contribution of the paper is the framing and identification of three opportunities for research in embodied child–computer interaction, which I hope will set the stage for future research publications in this international journal of child–computer interaction.

1. Introduction

In first decade of the 21st century, there was a tremendous increase in research into child–computer interaction through gesture, touch, movement and other modalities, which have not yet been tapped into by traditional human–computer interaction. Largely this has been driven by advances in technology, the commercialization of new platforms, and the rise of simple implementations of new forms of interfaces by the Do-It-Yourself (DIY) community. It has not been driven by understandings of children's needs, abilities, or opportunities that have not been met by other forms of interaction including those with natural or physical objects or desktop based computation. Nor has it been adequately informed by understandings of children's motor, perceptual, cognitive, or social development. While this "technology agenda" is not confined to child–computer interaction, the impact of inadequately researched, understood, and designed applications and technologies has had a vast, if largely undocumented, effect on today's children.

Another way to view this is deficit is to consider the amount of resources that are used to develop technologies and applications that are simply ineffective or under-used. Think about the Smart Board revolution. While there is nothing inherently wrong with the technology, the context of use was under-considered. Teachers with little time or training were expected to transform learning with Smart Boards. Similarly, claims are now being made about how platforms like Nintendo Wii and Microsoft Kinect will enable children to exercise in their living rooms through whole body interaction. My own experience with the Wii platform involved watching my two young sons quickly work out how to avoid any gross motor activity whatsoever in playing a Wii game. They simply sat, side by side, fingers twitching Wii mote buttons despite the considerable sum I spent on two glowing light sabers that can be used to house the Wii motes. These are now are lost in the recesses of our basement.

We know so little about how interactive systems and digital media can be designed to effectively support children to learn, play, and interact with the world in ways not enabled by other natural or artificial artifacts. Of course there have been successes and there are opportunities. This paper is about opportunities. Within the paper, I lay out three broad areas that I think are important to explore in the landscape of embodied child–computer interaction research. These areas are primarily influenced by my own research interests. There are other valuable agendas, topics, and approaches not covered here. I focus on single-child embodied child–computer interaction because it is where I began my research career and because studying individual cognition is important to inform social interaction. Much good research reflecting an embodied perspective has been done on social interaction (see for example, [1–3]). I also focus primarily on new forms of interaction in my examples because an embodied perspective on cognition highlights the opportunities and benefits not supported by traditional desktop configurations.

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2. Introducing embodied cognition

For more than 50 years in philosophy and about 15 years in human–computer interaction research, there has been a rethinking of the nature of cognition. Embodiment means how the nature of a living entity's cognition is shaped by the form of its physical manifestation in the world. Embodied cognition is a perspective based on the notion that psychological processes are dependent on and shaped by aspects of the body including body morphology (form), sensory-motor systems, and interactions with the surrounding world [4]. Embodied theories of cognition explicate different mechanisms or processes by which aspects of perceptual and motor processes are tightly coupled to each other as well as to higher order cognitive processes including language and mathematics [5]. The body and the mind are inseparable in the roles they play in much of cognition. Embodied theories of cognition foreground the role of activity in specific physical and social environments, operating at scales ranging from the neural to the social [6]. In contrast to traditional views of cognition, an embodied approach suggests that humans should be considered first and foremost as active agents rather than as disembodied symbol processors.

For those interested in an overview of embodied cognition, I suggest Andy Clark's book, *Being There: Putting Brain, Body and World Together Again* [7]. The book provides an accessible and enjoyable sojourn that introduces embodied cognition. Although it is targeted at philosophers of mind, human–computer interaction or design researchers may find it provides a good overview of the terrain. Clark weaves together seemingly disparate fields in order to provide an alternative paradigm for understanding cognitive science. He provides fascinating descriptions of Jakob von Uexküll's umwelt of a tick (surrounding environment), Rodney Brook's autonomous agent research, Esther Thelen and Linda Smith's application of dynamic systems theory to research about infants learning to walk, Gibsonian psychology, and David Kirsh and Paul Maglio's exploration of epistemic actions and external scaffolding in the game Tetris. Through compelling but not overly academic examples, he explains a theory of mind that involves an integrated account of how we sense, perceive, and think with and through our bodies in ways that are tightly coupled with the specifics of our environment.

Clark's account provides a foundation from which researchers can explore many questions about children, the development of intelligence, and new forms of child–computer interaction.

3. Embodied child–computer interaction

The perspective of embodied cognition and its gradual acceptance in the cognitive science community is an extremely important development, one that has been underappreciated in human–computer interaction research in general, and in child–computer interaction research in particular. Yet a wealth of developmental psychology and media studies literature provides evidence for the importance of understanding the role of action and the environment in the development of children's thinking skills. Piaget began a long tradition when he suggested that cognitive structuring through schemata accommodation and assimilation requires both physical and mental actions [8]. Similarly, Bruner emphasized the role of action in learning [9]. More recently, social scientist Healy argued for the importance of physicality in childhood. She suggested that children's increased access to TV and video games reduces the amount of time they spend on physical, sensorial, and perceptual activities that foster awareness of relationships in the world, awareness that is crucial to their cognitive development [10].

A perspective on interaction that foregrounds embodied cognitive processes is called embodied interaction. Embodied interaction changes how one thinks about children's cognitive development and how one designs interactive systems to support children's learning and development. A commitment to designing to support embodied interaction with interactive systems changes what you need to know and how you use that information. Designers and researchers of interactive systems for children can benefit from understanding and supporting the ways in which physicality supports cognitive development. Whether interacting with computation through a mouse and keyboard, a tangible user interface, or a handheld device, an embodied perspective on cognition both broadens and changes the focus of design to support children's learning, play, and development. Conversely, a lack of understanding of the importance of movement for cognition can only lead to an impoverished view since it ignores the way children (and all humans) create meaning through action. It is important to recognize that embodied interaction does not just apply to physical or tangible user interfaces. All computer interfaces are physical. Embodied cognitive processes are at work during child–computer interaction whether a child is using a mouse in a science lab or a tangible object at an art gallery.

In general, children's embodied cognitive processes mirror those of adults. However, the development of such processes depends on children's individual and age-related physical characteristics, their inherited abilities, and their practical activities played out in a physical and social environment. For example, while the same cognitive processes may operate during a spatial problem solving task such as a jigsaw puzzle, children's limited fine motor dexterity and limited strategies for simplifying the task may impact their behaviors and performance solving the puzzle. Before I discuss specific theories that may be of interest to embodied child–computer interaction researchers, I provide a brief discussion of how theories can be used in child–computer interaction research in order to set the stage for understanding the value and use of the three groups of theories that follow.

4. Using theory in child–computer interaction research

A theory is a model of how something works and why it works. It explains how something works by showing its elements in relationship to each other. Sometimes the relationships are dynamic and change over time as in processes or actions. Sometimes they are static. Theories about children's cognition are largely dynamic.

One distinction between a science and a craft is systematic thought organized in theory. Crafts involve doing. Some crafts involve experimenting. Theory allows us to frame and organize our observations. It permits us to question what we see and do. It helps us to develop generalizable explanations that can be put to use in other places and times by other people. A moment comes in the evolution of a field or discipline where intellectual issues on which the field rests move from rough ambiguous territory to an arena of reasoned inquiry. In human–computer interaction research, we see this as a movement from technology-driven prototypes and single case studies to theoretically informed analysis, designs, and evaluations.

While it is tempting to draw on experimental psychology and the physical sciences that use theory to make predictions and derive testable mechanisms that can be investigated with control lab experiments, this is not always possible or advisable in child–computer interaction research. This approach may be appropriate for fine scale investigations about how small changes in an interface affect some aspect of children's learning, behavior, or other cognitive processes. However, this approach to scientific theory building ignores the variability in children's cognitive development and behaviors (since it seeks to sample a homogenous population), and ignores the contextual variables that influence situated use of interactive products for children.

Theory can also be used to inform case-based analyses that produce descriptions of behaviors and make inferences about underlying processes. It is tempting to explain observations in terms of theoretical concepts. However, establishing causes and effects is not possible with such research designs. In this type of research theory may act as an overarching lens that helps to focus analysis on some aspects of a situation and not others. In this way theory may be used to inform analysis of situations into which a new design will be placed or to inform the evaluation of a new design in a real world setting. Understanding theoretical constructs and processes may provide researchers with insight about what behaviors and interactions to look for, and reveal interdependencies not readily apparent to the uninformed eye. Again, a cause and effect approach to theory building is elusive. And, as Zaman et al. point out, single case evaluations and comparative evaluations are fraught with limitations. Many of these limitations reduce our ability to make generalizations that are transferable to other design situations [11]. Multiple case studies may help to overcome these limitations.

Rogers suggests that a benefit of theory for real world deployments is to use it to better understand and support the interdependencies between design, technology, and behavior [12]. In this way, theories of embodied cognition can be used to frame and inform a design space in terms of understandings of the way children interact with their everyday world and how an interactive product might augment or support such interaction. This approach focuses on understanding the interplay between various behavioral and cognitive mechanisms and how they manifest in a proposed setting and computationally mediated activity.

Along similar lines, Stolterman and Wiberg argue that theory-informed, concept-driven design that aims to explore theoretical concepts in concrete designs is valuable to the human–computer interaction community. Through the exploratory act of designing (and evaluating) a prototype to enable, support, or augment specific cognitive processes, knowledge about those processes in the context of interactive technology is generated. Designed artifacts carry a unique form of knowledge, contribute to cumulative mid-level theory building, and set the agenda for forthcoming research [13].

In these ways theory can be used to ground design in what is known about human culture, cognition, perception, and behavior. In the following sections, I present three groups of theories taken from embodied cognition that I propose have value for informing, inspiring, and advancing design knowledge in child–computer interaction. For each section, I present an overview of the main theoretical ideas, offer suggestions for further reading, provide a summary of one or more recent research projects that utilize these theoretical ideas in child–computer interaction research, and make brief suggestions for future research. Each of these areas offers a plethora of opportunities for further work in embodied child–computer interaction research.

5. Children follow a dynamic trajectory of development

An embodied approach to cognition has broad implications for theories about how children develop as they grow. In his theory of genetic epistemology, Piaget proposed that intelligence develops as cognitive structures are formed from patterns of physical or mental actions, and that the formation of cognitive structures proceeds in stages [14]. Development is conceptualized as a linear progression through discrete stages of reasoning that correspond roughly with children's ages: sensorimotor, preoperations, concrete operations, and formal operations. This approach assumes that the end goal of development is the ability to reason with abstract representations. Genetic epistemology is often conceptualized through the lens of embodied cognition because it emphasizes the emergence of cognitive abilities grounded in sensorimotor abilities. However, even if applied loosely, the ages and stages aspect of Piaget's theory does not adequately consider individual differences in the development of intelligence that result from each individual's unique interactions with the physical world.

In contrast, embodied developmental cognition shifts the focus away from development as a linear progression culminating in the development of abstract reasoning abilities and towards a situated and integrated view of the development of intelligence [15]. The development of intelligence depends on the specifics of the genetic, physical, social, emotional, and contextual environment in which a child is situated. While there may be similar patterns of development, each child is unique. A particular environment may provide opportunities that enable a child to perform coupled physical–mental operations beyond the stage predicted by their age. Keil provides many examples of this in his summaries of various researchers' works that have shown that children failed Piagetian tasks for reasons other than basic competencies related to their ages [16].

For more readings about children's dynamic, embodied development, see Thelen and Smith's book on motor-cognitive development of young children [15], or Gibb's chapter 7 on embodied cognitive development [17].

5.1. Current work

Piaget's ages and stages theory was introduced with some caution into the human–computer interaction community [18]. Ages and stages based guidelines are appealing because they provide a systematic way to determine age-appropriate design considerations (e.g. [19]). However, this approach is problematic because it results in overly prescriptive design guidelines that pay little attention to the diverse ways in which intelligence emerges in a child's interactions with a specific historical, cultural, social, physical, and geographical environment [20].

Taking an embodied perspective on the development of intelligence in interaction design tells us not to look at what most children can do at a particular age, but instead to see development as a trajectory. An interactive product may facilitate physical or social interaction that provides opportunities for children to practice something that they are developing. The job of a designer is not to understand what a child can do and design to support that, but rather to understand what a child is able to practice doing or thinking about and to produce opportunities to practice those skills in a specific context with external aids [21].

This approach was used to develop "Developmentally Situated Design" (DSD) cards. While the cards are categorized into three age groups, the cards provide information to inform or inspire the design of interactive supports for what children are practicing [21], not what they can already do or think. Similarly, Markopolous et al. provide evaluation-based questions that challenge assumptions about developmental stages [20]. For example, under the cognitive category, they ask "Does a child understand what he or she is expected to do?" and "Are the children's problem solving skills mature enough in terms of test tasks?" By questioning, rather than assuming what children can do, we can evaluate products to ensure children are supported as intended. Of course, this takes more work than using prescriptive, age-specific guidelines.

5.2. Future work

What is needed is design guidance that provides information on ranges and progressions of ability and skills rather than discrete stages, and that considers how the physical or social environment may support activities beyond these ranges. This work would serve the dual purpose of informing design research and training researchers. A key distinction should be made in this work between when to design to support existing skills and abilities (i.e. those required to interact successfully with a system) and when to design to support or augment developing skills and abilities (i.e. enable learning or other experiential outcomes).

6. Children offload cognition to the world

Humans, and other creatures, have a range of approaches for altering their environment to improve cognitive performance. An important group of theories for child–computer interaction explains how cognitive performance may be improved by offloading aspects of mental operations to actions on artifacts and external representations, or by using physical constraints in an environment. All of these theories apply to adults as well as children. However, since children are developing cognitively, these approaches have particular value for them. Children may find mental operations associated with memory, perception, or computation difficult depending on the task. They may be able to use their environment in some way to improve their thinking. Freeing up cognitive resources through offloading is important because it may enable a child to successfully perform an activity that would otherwise be too difficult, or because it may enable a child to focus their cognitive resources on key aspects of the activity required for successful completion or learning [22].

6.1. *Taking actions on objects*

One theory that describes this process and focuses on the importance of actions is called complementary actions. Complementary actions are physical actions, which may act alone (e.g. pointing) [23] or be taken on artifacts [24], that reduce cognitive loads. These actions may improve task performance in a number of ways. They may free up *memory* by encoding the state of a process in the external world. That is, using the world as an external memory device. For example, we may leave our keys by the front door. They may simplify *perception*. For example, if we are asked to identify an up-side-down picture of a face, we will likely rotate the picture to an upright position since humans are much better at recognizing faces in the upright position. We move the picture rather than ourselves to simplify perception. They may simplify *mental computation*, either through gesture or through actions on objects.

Epistemic actions are a kind of complementary action taken on objects in the context of a problem solving task. They are physical actions that make mental computation simpler, faster, or more reliable [25]. For example, when solving a jigsaw puzzle, rotating puzzle pieces physically makes it easier (simpler) to identify patterns, improving perception. Sorting pieces into piles (e.g. edge pieces) improves memory and makes subsequent assembly faster. In contrast, pragmatic actions are those physical actions involved in solving a task directly. For example, using the pile of edge pieces to assemble the border of the puzzle involves pragmatic actions once the pile has been created in the first place. In practice, it may be difficult to separate epistemic from pragmatic actions. In particular, the farther away from the end goal, the more actions of each type may cluster together.

For more information on the value of physical actions on objects in children's learning, see empirical work based on the theory of physically distributed learning (e.g. [26]). In addition, Manches and O'Malley provide a good overview of different mechanisms that may influence learning through physical actions on objects [22].

6.2. *Creating external representations*

Complementary actions may involve creating external representations (e.g. symbols, pictures) to improve task performance [27]. For example, we may use pencil and paper to draw or write something down to aid memory or improve computation. By age nine or ten most children can do addition with two digit numbers by writing them down and using steps involving adding single digits and carrying — a task that is difficult mentally but relatively straightforward to do externally once they know the process. There are many other reasons why we create external representations to offload difficult aspects of cognitive activity.

For more information, Kirsh provides a discussion of seven ways of creating external representations to improve cognitive performance with adults [27]. Cox explores reasoning with self-constructed external representations [28] and Ainsworth discusses ways of working with multiple representations that may improve learning [29].

6.3. *Using physical constraints*

Rather than using complementary actions, we may use physical or spatial properties of the environment to improve performance. One way we do this is by using physical constraints to simplify a task [30]. For example, in a jigsaw puzzle, lining up pieces along one side of the box uses the box's side as a physical constraint the organization of the pieces. The box edge reduces the degrees of freedom of the organization space for the pieces from piles on the table (3D) to single pieces butted up along the edge to form a line (2D). Physical constraints (2D edge) may be used alongside spatial structures (linear edge) to organize objects during a task.

For more information, Edge and Blackwell discuss how the representational properties of physical objects enable or constrain manipulation of digital information in the context of tangible user interfaces [31]. Manches et al. discuss how graphical user interfaces constrain children's actions and affect their strategies for number solving problems because children can only move one object at a time with the mouse [32].

6.4. *Current work*

There are various studies that have sought to understand how children may be supported to learn or solve tasks by offloading aspects of cognitive activity to interaction with the world. The following are three that have received some attention in the child–computer interaction literature.

6.4.1. *Actions on objects and physical constraints in number problems*

Manches et al. use theoretical ideas about how children may offload cognition to actions on sets of objects during number problems to inform the design of a comparative experiment. The main tasks involved having young children decompose a number into different partitions. The authors explore, through comparison, the strategies young children use to solve partition number problems with physical blocks, pencil and paper, or with no materials [32]. In the study results the authors highlight the advantages of allowing children to spatially reconfigure groups of blocks physically rather than moving blocks virtually, where the mouse acts as a physical constraint limiting the movement to one block at a time. The finding that children identified significantly more ($p < 0.01$) partitioning solutions using physical objects compared to paper or no materials supports the theory of physically distributed learning [33]. In addition, they report that children used touch (i.e. kept a finger(s) on the block while looking elsewhere) and location (e.g. moved a block close to their body) to keep track of the blocks relative to their bodies, freeing up visual attention for other objects. Children were also observed placing fingers on blocks or moving blocks already used closer to their bodies to help them remember which blocks to move next. The work contributes to understanding how different kinds of actions enable different embodied strategies for solving number problems.

One topic that remains to be explored is determining whether children can apply the strategies they developed with physical objects to problems in the absence of materials. If so, this would support claims that actions with concrete materials can support the development of more symbolic numerical strategies [34,35].

6.4.2. Linked external representations in learning about light behavior

Price et al. use theoretical ideas about how actions on objects combined with active use and creation of external representations aid learning about the behavior of light [36]. Through a comparative experiment with older children they explore how children reason about reflection, absorption, transmission, and refraction through the use of tangible torches and blocks on a tabletop that displays resulting light rays. Based on their findings, the authors suggest that linked physical and digital external representations in a tangible tabletop environment may reduce unproductive cognitive loads and enable active "working out" that is instrumental for learning [37]. They also suggest that the location of digital representations in relation to related objects or actions affects the level of abstraction at which concepts can be represented.

The authors raise the issue that representational designs that may be efficiently processed through offloading may not allow adequate time for reflection in learning. This latter issue has been raised by others (e.g. [38]) and deserves future study. We need to better understand how creating external representations may reduce cognitive loads in ways that benefit conceptual learning, and when such offloading conflicts with learning (e.g. through over simplification as pointed out in [32]).

6.4.3. Complementary actions during spatial problem solving

Antle uses the theory of complementary actions to inform her analysis of pairs of school age children solving jigsaw puzzles (a prototypical spatial problem solving task) [39]. She compares physical, graphical and tangible interfaces in order to explore how different interaction styles facilitate children's hands-on thinking during puzzle solving. Through analysis of hand-action event classes (e.g. pragmatic, epistemic), the author examines the kinds, number, and duration of hand actions used. She also examines the temporal sequence of actions. The results of these analyses are used to make inferences about mental strategies used during the puzzle solving.

The main findings were that the combination of direct hands-on input style with audio–visual feedback enabled an integrated epistemic–pragmatic strategy that evolved during the task [39]. As the task proceeded children used mental strategies more than physical ones, possibly because early epistemic strategies combined with a reduced problem space simplified the task. The author conjectured that this approach enabled individuals to offload cognition as much as they needed based on their abilities, skill level and task difficulty. The author also found that the constraints imposed by a mouse and graphical user interface resulted in a less sophisticated trial and error approach.

Future work needs to be done to see whether the analytical framework can be effectively applied to other hands-on problem solving situations. Replication of this study comparing tangible and multi-touch may improve understandings of how 3D and 2D interaction impacts children's problem solving.

6.5. Future work

In addition to the work suggested in relation to the above three studies, this area is ripe for exploration. New forms of interaction that rely on a wider range of actions, incorporate physical and external representations, and are embedded in real world contexts provide many opportunities to enable children to successfully perform, learn, and play by offloading difficult task components. Designs that enable variable levels of offloading should be beneficial and account for the dynamic development of children. Studies that explore the interplay of action, representation, and context for individual and groups of children will be challenging and offer significant contributions to this research space.

7. Movement helps children think

There are two areas of theory that highlight the importance of children's movement for thinking. Both rely on the theory of mental simulations. Simulations are reenactments of motor-perceptual states that are experienced during interaction with the physical world. During an interaction (e.g. catching a ball), neural patterns of brain activity are formed across modalities. These patterns are integrated into a multi-modal representation in memory (e.g. how the ball looks and feels, and the action of catching). When such an experience is recalled from memory, the multimodal representation is rerun in a simulation that reactivates the same neural patterns even though the person may be inactive. Rizzoloti and Craighero explore this phenomenon through their work with mirror neurons [40]. A mirror neuron is a neuron that fires both when we act and when we observe the same action performed by another human with the intention to imitate. Common coding theory suggests that the mirror neuron system provides the physiological mechanism for a common neural representation connecting perception, execution, and imagination of movements [41]. Other research has shown that people can consistently recognize their own movements even when depicted abstractly [42]. These ideas are important because they explain how children (and adults) learn new movements through imitation. These understandings may inform the design of new forms of interaction (for an example with adults, see [43]). No work yet exists that has applied these ideas to the design of novel interfaces for children.

A second and related area of theory that has been applied to child–computer interaction builds on these ideas and explains how abstract thought is enabled through movement. Research suggests that when children (and adults) learn or reason with abstract concepts, they utilize mental simulations based on concrete motor-perceptual experiences [44]. Conceptual metaphor theory provides one explanation for this process. The theory suggests that neural patterns formed from repeated patterns of physical experience are elaborated through metaphor to structure abstract concepts. For example, repeated patterns of physically balancing the body (e.g. learning to walk, standing on one foot, balancing on a teeter–totter) give rise to neural patterns that provide the cognitive structure for a "balance" image schema, stored as a multimodal representation. This schema is activated when visually seeing balance (e.g. in a painting or photograph) and when thinking about balance in abstract domains such as mathematics or justice (e.g. balancing an equation, balancing the punishment against crime).

Recently, researchers have investigated the possibility of using this process in reverse. They suggest that directing people to move in specific patterns of action may guide and improve comprehension, problem solving, and learning. For example, Wilson and Gibbs found that real and imagined body movements related to metaphor-based phrases facilitated adults' immediate comprehension of these phrases [45]. Thomas and Lleras studied a problem solving exercise that required swinging two strings together to solve. When they directed adults to perform arm movements in breaks in the exercise, those that were directed to swing their arms rotationally versus linearly achieved better outcomes [46]. Cook et al. report a similar effect in a study with children and learning [47]. They found that encouraging children to make gestures while learning a new arithmetical strategy resulted in better retention of knowledge. Children who were told to gesture during learning retained 85% of their post-test gains four weeks later compared to only 33% of children who were told to speak during learning.

7.1. *Current work*

In the realm of human–computer interaction, these ideas have been applied in studies aimed to inform the design of gestural and tangible interaction (e.g. [48,49]) and the development whole body interactive systems (e.g. [50,51]). In a whole body installation about social justice, Antle et al. found that adults who moved their bodies in and out of balance while viewing images of balance and imbalance in social justice issues were more deeply affected by the work [50]. Comparison of pre and post test change in ratings across groups indicated that the whole body group was significantly more affected ($p < .0001$) than the group that used a controller in terms of their willingness to take action towards achieving social justice after using the installation.

One area where these ideas have been explored involves investigation of how these motor-cognitive processes may be used to cue or bootstrap children's learning to use, and learning through the use of whole body systems. Antle et al. used conceptual metaphor theory to design an interactive sound making system for school age children [52]. The interaction layer maps image schematic input actions (e.g. fast–slow, active–inactive, smooth–choppy) to metaphorically related changes in percussive sound parameters (e.g. fast–slow tempo, smooth–choppy rhythm). For example, pairs of children moved more actively to increase the sound volume, and more smoothly to create smooth rhythms. Results from a comparative study indicated highly significant differences in children's ability to use the system to create specific sound sequences compared to an equivalent non-metaphor based system. They were also significantly more able to demonstrate specific sound concepts using the metaphor-based system than verbally explain the same concepts. However, the authors concluded that the design of such systems was not straightforward [53]. They suggested considering interacting factors including the likelihood of specific actions being enacted in a given environment, the discoverability of the mappings, the perceivability of supporting feedback, and the interaction of multiple metaphoric interpretations.

Bakker et al. conducted a related study using similar metaphorical mappings in the design of tangible sound making objects for children [54]. Results from a learning evaluation indicated that all children were able to successfully interact with the tangibles when reproducing sample sounds [55]. They also found that not all children were able to verbally express their understanding of the targeted abstract concepts. Based on this discrepancy they suggest that embodied metaphor based learning systems can serve as a physical handle to reason about perceptual concepts.

7.2. *Future work*

Research in this area is very new and much remains to be done. Conceptual metaphor theory suggests that people unconsciously structure abstract concepts and reason with them utilizing existing image schemas [56]. This process unfolds with development and learning. What remains unknown is whether these conceptual metaphors can be reliably deconstructed to reveal the image schemas that are suitable for enactment through interaction, and whether enabling schematic interaction with digital representations of abstract concepts can be used to support learning comprehension, problem solving, and learning of abstract concepts [57].

8. Conclusion

Giving consideration to the underlying mechanisms that support the interplay of action, cognition, and the environment will enable a commitment to embodiment in children's interaction design. This may represent a major shift in thinking for some designers and researchers. To support this shift, I have provided summaries and further readings on embodied theories of cognition in general, and embodied child–computer interaction specifically. The three areas outlined as focal points for forthcoming research are well theorized but barely touched on in child–computer interaction research. There are many opportunities for research in each of these areas. The studies cited provide templates for further research and offer areas where specific questions remain unanswered. There will surely be other areas ripe for discovery, particularly in the realm of social and emotional interaction.

Research is needed to better understand how to design to support children's dynamic trajectory of development. Approaches may include studies that use dynamic systems theories as a lens to focus observations or evaluations of multiple cases that may create generalizable design guidance about ranges and progressions of abilities and skills rather than discrete stages. Such research may consider how the physical or social environment may scaffold activities beyond these age ranges. It should distinguish between designing to support existing skills and abilities to enable usable products, and designing to augment developing skills and abilities to enable learning and development.

Research is needed to better understand how to design products that enable children to offload aspects of cognition to action in the world so that they may better focus on other tasks, or successfully master difficult tasks. Approaches may include studies that explore the interplay of designs with new forms of interaction and children's behaviors that indicate offloading, or the design and implementation of interface prototypes that demonstrate different approaches to offloading, or field studies of prototypes that enable children to successfully master tasks through offloading difficult aspects. Such research should consider the interplay of action, representation, and context for both individuals and groups of children.

Lastly, research is needed to better understand how to design products that support movement-based simulations or reenactments of motor-perceptual states that bootstrap children's thinking. Approaches may include design explorations that provide guidance about how to elicit and enable movement–metaphor relations or mixed methods studies that investigate the benefits and limitations of using movement based systems to enable reenactment of perceptual-motor states in different learning contexts. Such research should consider the interdependencies of context, salience of feedback, discoverability of mappings and the role of individual differences and interpretations as children interact with these systems.

It remains to be seen how emerging forms of interaction will compete with traditional interfaces. However, with the uptake of touch interfaces (e.g. Apple iPhone) and whole body systems (e.g. Microsoft Kinect), it seems likely that understanding the implications of embodied cognition for design will become increasingly relevant for all designers. As new forms of interactive technologies emerge, designers and researchers who give consideration to the ways in which cognition is rooted in embodied action will contribute to children's successful development into active, thinking adults. I hope that this paper provides some starting points for those interested in this research trajectory.

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