# Do tangible interfaces enhance learning?

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## ABSTRACT
Conceptual work on tangible interfaces has focused primarily on the production of descriptive frameworks. While this work has been successful in mapping out a space of technical possibilities and providing a terminology to ground discussion, it provides little guidance on the cognitive or social effects of using one type of interface or another. In this paper we look at the area of learning with tangible interfaces, suggesting that more empirically grounded research is needed to guide development. We provide an analytic framework of six perspectives, which describes latent trends and assumptions that might be used to motivate and guide this work, and makes links with existing research in cognitive science and education.

### Author Keywords
Tangible interface, TUI, frameworks, learning

### ACM Classification Keywords
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous. K.3.m Computers and education: Miscellaneous

## INTRODUCTION
Tangible interfaces are gaining in popularity within computing, reflecting a greater emphasis on the role of the physical body and environment in embodied interaction [15, 24, 31]. Most research to date has focused on technical development and the creation of descriptive taxonomies [e.g. 19, 23, 32, 53]. This work has been successful in highlighting the diversity of application domains and the range of possible combinations between physical and digital representations. However, as with early work on graphical interfaces [43], empirical and theoretical work has failed to keep up with the fast pace of development in this area (although see [15, 24]).

One area that has received much interest from tangible interface designers is learning [e.g. 41, 56]. This interest is related to the more general view within education that hands-on activity or manipulation of physical manipulatives can be of particular educational benefit [e.g. 36]. Most work in this area too has focused on technical development; theory and empirical demonstrations of the utility of tangible interfaces for learning have been less forthcoming. This has led to a situation where designers of learning environments have little principled basis on which to decide whether a tangible interface will be suitable for a particular task, which of the many types might be most appropriate, what features of a tangible interface design might be associated with particular benefits to interaction or learning and what features might be more incidental. They must therefore rely upon intuitions about physical interaction, such as that is more intuitive, an approach that Blackwell [7] has criticized as potentially leading to incorrect assumptions.

This paper takes a critical look at the potential of tangible interfaces to support learning. It presents a novel analytic framework derived from an analysis of work on both tangible interfaces and learning with physical materials. This differs from most current tangible interface frameworks, which have focused on describing and categorizing existing systems. Instead, we highlight a number of latent trends within research on tangible interfaces for learning, providing links to existing work in cognitive science and education, providing theoretically motivated categorizations of activity with tangible systems and highlighting our limited understanding of the cognitive and social benefits of learning with tangible interfaces. We call for a greater focus on empirical work in this area.

## TANGIBLE INTERFACES FOR LEARNING
Theoretical work on the use of tangible interfaces in learning environments has been slow to materialize. However, a number of trends and themes are beginning to emerge. In this section, an analytic framework of six perspectives on learning with tangible interfaces is described: *possible learning benefits* considers both theoretically-motivated assumptions and exploratory findings about the benefits of tangible interaction; *typical learning domains* describes the types of learning tasks most commonly supported by tangible interfaces, arguing that in many cases these systems have represented information that might be equally well supported graphically; *exploratory and expressive activity* is a categorization of learning activity that might be particularly well supported by tangible interfaces; *integration of representations* looks at a feature of tangible interfaces highlighted in taxonomic



*TEI'07*, February 15-17, 2007, Baton Rouge, Louisiana, USA.

work, suggesting that tangible interface designers might look towards related work on external representations for guidance; *concreteness and sensory directness* argues that the concreteness and physicality of manipulative objects have historically been conflated and should be treated separately when thinking about tangible interfaces; and the *effects of physicality* looks at more general evidence for the effects of learning with physical objects.

### Possible learning benefits

There are a number of reasons why using tangible interfaces may be of particular benefit for learning. One possibility is raised by Triona, Klahr and Williams [51] in relation to the use of physical materials per se: if perception and cognition are closely interlinked [e.g. 5, 33], then using physical materials in a learning task might change the nature of the knowledge gained relative to that gained through interacting with virtual materials [cf. 31]. For example, three-dimensional forms might be perceived and understood more readily through haptic and proprioceptive perception of tangible representations than through visual representation alone [e.g. 21]. Related to this possibility is the emphasis in Piagetian developmental theory on the manipulation of concrete physical objects in supporting and developing thinking, particularly in young children. It is possible that because tangible interfaces often utilize concrete physical manipulation, they might support more effective or more natural learning [45, 50, 56].

Exploratory work on tangible interfaces has suggested that they might be particularly suitable for engaging children in playful learning [e.g. 39] and that novel links between physical action and digital effects might lead to increased engagement and reflection [42]. As interaction with tangible interfaces is assumed to be more natural or familiar than with other types of interface [15, 28], they might be more accessible to young children, people with learning disabilities or novices [56], lowering the threshold of participation [24].

A number of design-focused projects have suggested that tangible interfaces might be particularly suitable for collaborative learning. They can be designed to create a shared space for collaborative transactions [18, 48] and allow users to monitor each other’s gaze to achieve interaction more easily than when interacting with a graphical representation on a display [48]. They might also increase the visibility of other members’ activity, better communicating the current state of their work [17, 46, 48] and potentially encouraging situated learning [31]. In contrast to the typical desktop setup of mouse, keyboard and screen, tangible interfaces often allow concurrent interaction, sharing control between the collaborating learners [e.g. 56]. However, while equal access may be of benefit in some circumstances, comparative work on pairs of children working with one or two mice has shown that it can actually lead to a decrease in collaborative activity [47]. Stanton et al. [46] have suggested that collaborative activity might be encouraged by increasing the size of tangible interfaces and using props to slow down the pace of interaction and increase the effort required to make manipulations. Fernaeus and Tholander [17] have argued for the importance on planning and social organization of manipulating tangible artifacts outside the space where they are sensed by the system.

Of the potential benefits of learning with tangible interfaces reported here, the view that cognitive benefits will result from manipulating physical materials and that the mental processing of children in the Piagetian stage of concrete operations will benefit from using concrete *physical* objects rely largely on untested assumptions [11, 30]. The other potential benefits have been partially validated through a series of exploratory and design studies. However, little comparative work has been carried out, and it remains unclear which elements of tangible interface designs are critical in supporting learning activities and which are incidental; the roles played by the physical and digital elements in different designs remain to be mapped out. This is proposed as an important direction for future work.

### Typical learning domains

While tangible interfaces have been used to facilitate learning about topics as diverse as color-mixing [42] and computer hardware [13], a number of learning domains are repeatedly seen to be supported by tangible interface designs. These include narrative or rhetoric [e.g. 3, 46], programming [e.g. 17, 48], molecular biology or chemistry [e.g. 20, 21] and dynamic systems [e.g. 41, 56]. Summarizing the learning domains that have been often supported in tangible interface designs highlights an interesting commonality: they tend to be inherently spatial, either physically in the case of molecular models, or metaphorically in the representational systems typically used to represent them.

Scientists and students have used physical models for many years to help understand the three-dimensional structure of molecules. Tangible interfaces built to support learning in these domains have augmented existing physical models by overlaying augmented-reality representations on top of the physical models to provide extra or dynamic structural detail. For example, Gillet and colleagues [21] have used ‘3D printing’ to produce detailed models of complex molecules such as enzymes. These molecules are augmented with extra information such as electron cloud shape, which changes dynamically as the molecules are manipulated.

Narrative, while typically being concerned with a temporal sequence of events is often represented in a spatial format, particularly with children, for example using flow charts, post-it notes or maps to help structure a story. The linear, segmented structure of narrative is particularly evident in Ananny’s [3] TellTale, a toy caterpillar that comprises a number of body segments, which can be used to create a short sound recording and reordered to create oral narratives.

Professional and student programmers make use of graphical, spatial representations when programming and debugging; visual programming environments have been designed for children employing spatial organization of program elements [e.g. 29]. Tangible programming interfaces use physical objects to represent elements of program structure [e.g. 48]. Physical constraints are often used to prevent the user from creating invalid language constructs.

Dynamic systems, such as the flow of materials through a factory or energy through an ecosystem, are often modeled using tools such as STELLA [25], which employ a spatial representational structure. Similar graphical tools have been designed to introduce children to systems thinking, [e.g. 27]. A representative tangible interface for system dynamics thinking is Zuckerman's [56] SystemBlocks. This comprises physical components that can be connected together to provide abstract models of the behavior of dynamic systems.

As we have seen, the most common learning domains supported by tangible interface designs have a physical or metaphorical spatial structure. However, it can be argued that many of these systems offer little cognitive advantage for learning over more traditional graphical interfaces, as the physical form of the tangible interface components provide no information that could not be presented or manipulated in, or constrained by a similar one- or two-dimensional visual representation (although there are, for example, ergonomic advantages in being able to manipulate objects with both hands). Tangible interfaces of molecular models might offer something beyond that possible with graphical user interfaces, namely the extra haptic information about morphology that might be gained through the manipulation of three-dimensional models. Of course, this possibility requires empirical validation.

The discussion of tangible interfaces for learning reported in this section shows that designers have focused largely on one feature of the physical materials used: their spatiality. However, physical objects have several other properties that could be used by tangible interface designers to support learning and that might not be so easily represented in traditional interfaces [7]. For example, they could utilize the mass, texture, temperature or malleability of physical objects to support learning in different domains. Exploring different properties of physical objects is suggested as a future direction for research into the design of tangible interfaces for learning.

## Types of learning activity: exploratory and expressive

While existing tangible interface frameworks focus on the important issue of taxonomy, they have less to say about the types of activity that might be best supported by the technology (although see [24]). A classification of tangible interfaces is presented here in terms of the type of constructivist learning activities that they might best support.

Two types of learning possible with tangible interfaces are through a process of discovery [e.g. 14], where the learner interacts with a model of the world, trying to work out the underlying mechanisms, or by constructing external representations and artifacts [38], making understanding explicit. Here, we adopt Mellar and Bliss's [35] categorization of exploratory or expressive learning activities. This derives from a discussion of how learners might work with models of real-world phenomena to develop their understanding.

### *Exploratory activity*

In exploratory learning, the learner explores an existing representation or model of a topic, usually based on the ideas of a teacher or domain expert. The learner might assimilate this new information, for example by relating it to personal experience, or the model being explored might conflict with the learner's existing level of understanding, potentially leading to reorganization and cognitive growth. An example of a tangible interface that affords exploratory activity is Underkoffler and Ishii's [54] Illuminating Light, which is designed to enable the rapid prototyping of optical layouts. The system comprises a large interactive surface where tangible elements, representing objects like lasers, lenses and mirrors, can be manipulated. It senses the orientation of these elements and projects dynamic simulations of laser light beams onto the work surface as well as numerical representations of distances and angles. The user can thus explore the theoretical model embodied by the system, carrying out manipulations or experiments and observing the results. They argue that this activity could lead to a greater understanding of the laws governing the behavior of light beams.

Two reasons are proposed why tangible interfaces might be particularly suitable for exploratory learning: firstly, if interaction with tangible systems is found to be more natural or intuitive to students than other types of interface, then they may offer a particularly suitable environment for rapidly experimenting and gaining feedback in domains such as laser optics where numerical representations are typically separate from the apparatus used to conduct experiments. Minimal cognitive effort would be required to understand how the system works and more attention could be focused through the interface onto the underlying domain. Secondly, if extra information is gained about a domain or if students' interpretations are guided or constrained by manipulating physical materials, then tangible systems might offer advantages over other kinds of learning environment. However, as outlined previously, these possibilities still remain to receive empirical support.

### *Expressive activity*

In expressive activities, learners create an external representation of a domain, often of their own ideas and understanding. Tools can help learners to make their ideas concrete and explicit, and once externalized, they can reflect upon how well the model or representation reflects the real situation. This description of expressive learning has much in common with Papert's [38] theory of constructivist learning. However, the emphasis here is broader in that it includes system-generated representations of users' activity that might be used to aid reflection after the event, for example system logs produced of users' activity while playing a game. Externalizing ideas might facilitate objective reflective thought by reducing the effort required to interrogate cognitive representations [43]. This might help to make clear inconsistencies, conflicting beliefs and incorrect assumptions [10, 35].

An example of a novel expressive tangible system is Raffle, Parkes and Ishii's [40] Topobo system. This is a three-dimensional constructive assembly system that has joints that are embedded with kinetic memory. Children use it to create model animals that record and play back the ways they are physically manipulated. It can be used to carry out experiments about animal locomotion. Children are often observed to relate movements to their own bodies.

Two reasons are proposed why tangible interfaces might be used to support expressive learning: firstly by recording aspects of learners' interactions with physical objects, tangible interfaces can enable them to construct expressive representations passively, while focussing on another task; and secondly they are novel media, that allow learners to actively create constructions that might not be possible in existing media.

A study by Colella, Borovoy, and Resnick [12] provides an example of passive expressive activity. They designed what they call *participatory simulations* using *Thinking Tags*, small computationally augmented badges that can communicate via infrared and which allow simple representations of information via LED lights. An example simulation was where a group of high school students each wore one of the badges and took part in an activity where a "virus" spread through the population following certain rules (e.g. some people might be more susceptible than others or the virus might have a latency period). Symptoms of being infected by the virus were represented by the LEDs. While taking part in the activity, the badges recorded aspects of the activity, such as who infected them and when. Together these records formed a representation of the spread of the virus that the students used to reason about the disease mechanisms.

The same group at MIT are associated with creating tangible interfaces to provide learners with novel expressive media [e.g. 41, 56]. For example Resnick et al. [41] describe *Beads*, which comprise a small processor and an LED and can be combined together to create necklaces and the like. Beads are programmed with rules determining how they relate to their neighbors in the chain. For example, if a neighbor's LED flashes, then a probability function may determine whether that bead's LED will flash too. Beads can be used expressively by combining them together to create interesting patterns.

Interestingly, both of these examples, while providing learners with opportunities for expressive activity, might also be described as supporting exploratory activity. In the case of the participatory simulation, the learners also explore the mechanisms by which the virus is transferred while taking part in the simulation activity. They might also design experiments to test their hypotheses after working with the expressive representations recorded by the Thinking Tags. In the case of the Beads, children might carry out experiments to determine what rules underlie their behavior. Ackermann [1] has described learning episodes where learners are able to reflectively construct an understanding of the world and then try out their ideas in context as particularly effective in uncovering inconsistencies and gaps. She describes this as a dance between 'diving-in' and 'stepping-out'. Similarly, Mellar and Bliss [35] have suggested that children gain particular learning benefit from constructing scientific models in expressive mode, which they can then explore. It is therefore possible that tangible systems, which combine expressive and exploratory activities, may be similarly effective in promoting learning.

### Integration of representations

Taxonomic frameworks for tangible interfaces have highlighted the integration of physical and digital representations as an important distinction between different types of systems. Integration here refers to the spatial and temporal relationship between representations. Ishii and Ullmer [26, 53] have proposed integration of representations as one of the defining features of tangible user interfaces; Koleva et al. [32] and Fishkin [19] have suggested that the level of integration of representations should be described on a continuum. However, this taxonomic work offers little guidance to the tangible interface designer on how these representations should be combined, the potential benefits of one approach or another, or the potential cognitive effects of combining different representations.

It is suggested that in the absence of a strong theoretical or empirical basis on how tangible interfaces might be designed to support learning, that designers could gain some guidance from the more general cognitive science literature on the role of external representations in learning. In particular, Ainsworth [2] provides an accessible framework of the design factors associated with learning with multiple representations, the functions that these representations can play, and the cognitive tasks that have to be carried out by learners when interacting with them. While space does not allow for a description of this framework here, it might help to guide tangible interface design and experimentation, particularly for systems where the physical and digital representations are not integrated to the extent of being viewed as the same entity. For more integrated tangible interface representations where the physical and digital components are treated as part of the same entity, Cheng's [9] description of the properties of effective representational systems for learning might provide some guidance.

### Concreteness and sensory directness

While the properties of concreteness and physicality are often conflated in discussion of the potential learning benefits of interacting with physical materials [11], here we first discuss the impact that working with concrete representations might have on learning before looking at the effects of physicality in the next section.

Discussion of tangible interfaces often emphasizes the concreteness of the physical representations. For example, Dourish's [15] notion of embodied interaction stresses the 'readiness-to-hand' of task-focused activity with concrete materials. However, focusing too closely on concrete activity can lead to neglect of the complimentary notion of 'presence-at-hand': an attention to the tool or representation itself as the object of activity [8]. This lack of emphasis is particularly pertinent in situations where the goal of the activity is to promote learning. As we have seen, while effective learning about a domain does involve engaged task-focused activity, it also can also involve periods of more objective reflection where knowledge is abstracted and conflicts are resolved [1]. This present-at-hand attention to the tool can take two forms: either practically on how to achieve a task with the interface, or theoretically on the structure of the domain represented by the interface. By focusing primarily on how users work with tangible interfaces in a ready-to-hand manner, Dourish overlooks how they come to understand how to use the interface effectively, how they abstract the underlying rules or laws of the domain and how different levels of representation become integrated. It can also be argued that Dourish's characterization of tangible interfaces as better suited to embodied interaction than more traditional types of computer interface conflates physicality with concreteness, whereas these factors might have differential effects.

Concrete and abstract representations can both be of benefit to learning [22]. In particular, while using concrete rather than abstract materials can often lead to improved task performance, using abstract materials can result in better learning transfer [e.g. 6]. The easiest to use or most concrete interface does not necessarily lead to the greatest performance in problem solving and learning [37, 44, 49, 52]; interfaces that constrain the ways that learners can use them or which introduce interaction costs can lead to increased planning and reflection, which can in turn lead to improved learning. It is possible that if tangible interfaces support easy manipulation of concrete objects, that they could in turn lead to decreased reflection, planning and learning.

A further consideration that remains to be addressed in research on learning with tangible interfaces is what combination of concrete and abstract representations might be most appropriate for the physical and digital components of the interface. The most obvious would be concrete physical and abstract digital representations. This might overcome some of the difficulties learners experience in transferring their knowledge to a new domain [cf. 22]. However, combining more abstract physical representations with a concrete digital representation might encourage learners to plan and reflect more.

Zuckerman et al. [56] have also highlighted the importance of concreteness in discussing manipulatives and tangible interfaces. They propose that tangible interfaces for learning should be categorized as either Froebel-inspired Manipulatives (FiMs) or Montessori-inspired Manipulatives (MiMs), based on the relative emphasis on concreteness or abstractness in the physical manipulatives designed by these two educationalists. FiMs are described as building blocks for constructing concrete physical structures, for example Lego™ or Topobo [40]. MiMs are also building blocks, but are used to construct more abstract conceptual structures. Zuckerman et al.'s own FlowBlocks and SystemBlocks systems are described as MiMs. It is claimed that FiMs encourage design, whereas MiMs encourage more limited exploration and a greater attention to more abstract concepts. In the analytic framework being developed here, FiMs would be classified as concrete materials for expressive learning, and MiMs as abstract materials for expressive learning (no distinction is made by Zuckerman et al. between the level of abstractness of the physical and digital components of the interface).

Considering concreteness separately from physicality in this framework highlights the need for empirical work to uncover the relative effects of concrete and abstract representations in tangible interface designs.

### Effects of physicality

A growing body of literature within the cognitive sciences focusing on embodiment suggests stronger links between physical activity and cognition than had previously been described [e.g. 5, 33]. This work suggests that abstract thought might be grounded in and built on top of sensory-motor systems. Physical activity has been shown to influence and constrain cognitive processes [e.g. 4]. A second body of research within education and psychology has emphasized the role of physical materials and manipulatives in supporting learning [e.g. 36]. Together, this work points to the potential of tangible systems in supporting learning. However, empirical studies comparing the effects of physical and non-physical versions of the same task are surprisingly uncommon. The only unconfounded comparisons found are those carried out by Klahr et al. [e.g. 30], who report no differences in children's learning. They suggest that if there is no learning benefit in using physical materials, then the practical advantages of graphical interfaces in terms of storage space necessary, time to set up, etc. might recommend their use.

More recent work on learning with physical manipulatives describes mixed evidence for their educational benefit [e.g. 55] and it is difficult to determine in cases where educational benefits are found, whether they can be attributed to the physicality of the materials.

Several informal evaluations of tangible systems for learning have been reported as part of design studies [e.g. 17, 46, 48, 56]. However, only two papers have been found that attempt to compare tangible with graphical interfaces in a learning task. Fails et al. [16] describe a small-scale comparison of tangible and graphical versions of the Hazard Room Game, designed to teach children about environmental health hazards. No statistical differences were found between the tangible and graphical groups in learning about the environmental hazards mentioned in the game.

Rogers et al. [42] report a series of studies on color mixing with young children designed to explore the notion of *transforms*, the relationships between physical or digital actions and physical or digital effects. They suggest that transforms that are unfamiliar to the learners – a physical action leading to a digital effect or a digital action leading to a physical effect – can lead to greater interest and increased reflection. While suggestive, this finding warrants further investigation to determine whether it holds for different groups of learners and how long the novelty of the transform can sustain the learner's interest.

Thus, despite the common view that the physical materials used in tangible interfaces are particularly suitable for learning tasks, there is only limited evidence to support this claim. This suggests that intuitions about the benefits of physical manipulation should be abandoned. Instead, empirical research is required to investigate in which (if any) domains and situations physical manipulation will be of benefit to the learner.

## SUMMARY OF FRAMEWORK AND DISCUSSION

Most theoretical work on tangible interfaces has focused on the production of taxonomic frameworks [e.g. 19, 23, 32, 53]. These have been successful in mapping out the space of technical possibilities in this area and producing terminology that can be used to ground discussion of different technical designs. More conceptual perspectives include that of Hornecker who has produced a sensitizing framework of concepts relevant to collaboration with tangible technologies [24] and Dourish [15] who has related work on tangible interfaces to the philosophy of embodiment.

However, where tangible interfaces are used to promote an activity like learning, we suggest that a more empirically grounded framework is necessary to facilitate design. Current frameworks provide little guidance on the cognitive or social effects of using tangibles, whether or why tangible interfaces might promote learning, which features of tangible interface designs might be associated with successful learning and in which domains.

The analytic framework presented here comprises six perspectives that might guide research and development on the use of tangible interfaces for learning. It is summarized in figure 1.

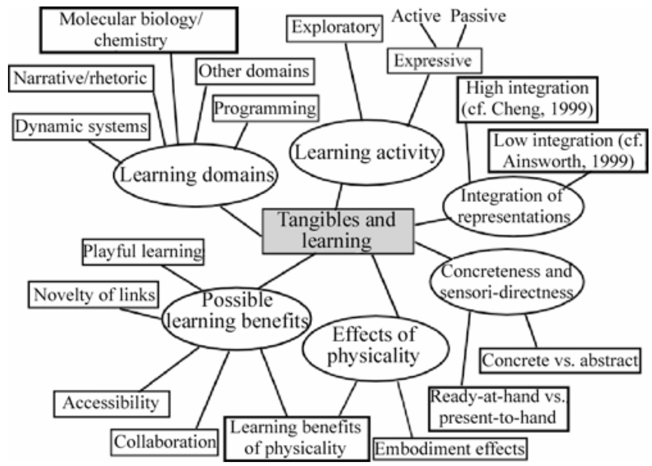


**Figure 1: Analytic framework on tangibles for learning**

Firstly, by describing the potential benefits, the need for comparative empirical studies is highlighted to both validate claims about the utility of tangible interfaces for learning tasks and to determine which of the many features of these systems might be associated with improved learning. Describing the learning domains commonly supported by tangible interfaces demonstrates that designers most frequently utilize spatial manipulation. It was questioned whether the spatial manipulation of physical objects offers significant cognitive advantages over graphical manipulation in many cases. It was suggested that other unique features of physical objects could be exploited in future designs. The terms exploratory and expressive [35] were introduced to describe the types of learning activity that might be engaged in with tangible interfaces. It was suggested that productive learning might result from tangible systems that allow learners to cycle between these two forms of activity. The roles that concrete and abstract representations play in learning were then presented as important to the design of tangible interfaces.

While the physical components of tangible interfaces might intuitively seem best suited to concrete representations, this is not necessarily so [e.g. 56] and the relative benefits of different combinations of concrete and abstract representations remain to be investigated. The level of integration of the physical and digital representations in tangible interfaces has been proposed as a defining feature in taxonomic work on tangibles [19, 32]. However, this descriptive work offers little guidance to the tangible interface designer in how these representations should be combined. It was suggested that in the absence of empirical representations might be used to guide research and development. In particular, Cheng's [9] work on Law Encoding Diagrams might help to guide the development of systems with a high level of integration between physical and digital components, while Ainsworth's [2] work on multiple representations might guide the development of those with a lower level of integration. Finally, the potential effects on learning of the physicality of the materials used in tangible interface design were highlighted. While the intuition that physical materials are of particular benefit in supporting learning is a common one, the evidence to support this belief is limited. If tangible interfaces are to be used to design systems for learning, it is therefore a critical first step to demonstrate the benefit of using physical materials.

## ACKNOWLEDGMENTS

This work was supported by an EPSRC Equator project studentship at Sussex University and by a research fellowship at the Open University. Yvonne Rogers, Peter Cheng, Eva Hornecker, Sara Price and Rose Luckin have all contributed to the ideas developed here.

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