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Tangibles: Technologies and Interaction for Learning

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INTRODUCTION

With recent developments in computing and networking, new kinds of interfaces, such as tangible interfaces, and consequently new forms of interaction with technology, have emerged. 'Tangibles' generally refer to interfaces where computational power is embedded in everyday artefacts or customized objects, which can be wirelessly networked or linked to various forms of digital representation. The emergence of increasingly small microchips and digital sensing technologies means that embedding technology in both artefacts and the environment is becoming more commonplace.

In the field of human–computer interaction (HCI) this group of technologies may be described as graspable interfaces (e.g. Fitzmaurice et al., 1995), tangible interaction (e.g. Ullmer and Ishii, 2001) and tangible bits (e.g. Ishii and Ullmer, 1997). Shaer and Hornecker's (2010: 4) definition offers a useful description for the purposes of this chapter: 'Interfaces that are concerned with providing tangible representations to digital information and controls, allowing users to quite literally grasp data with their hands' and thus physically manipulate associated representations. There are three key categories of systems that sit under this umbrella term: constructive assembly kits, token and constraint systems and interactive surfaces.

Interaction with tangibles depends on the manipulation of physical artefacts and/or physical forms of action, offering the opportunity to build on our everyday interaction and experience with the world, exploiting senses of touch and physicality. A key feature of these technologies is the high level of flexibility in design and the degree to which the design space is extended. This applies to the objects themselves – for example, their shape, size, colour, weight and texture; to the actions that can be placed upon them – for example, they can be impactive, requiring physical contact with an artefact (e.g. grasp and grip) or non-impactive (e.g. gesture); and to the associated digital information. Digital information, in the form of sound, narration, images, text or animation, can be flexibly combined with artefacts (e.g. Zuckerman et al., 2006), the environment (e.g. Klopfer and Squire, 2007; Price at al., 2010) or action (e.g. Price and Rogers, 2003; Raffle et al., 2006) to provide contextually relevant information based on abstract concepts or on enhancing key components of the task or concept with which the user is engaging. This potential to link to a wide variety and mix of representational media offers new possibilities and challenges for designing information artefacts and representations for learning. At the same time it demands particular considerations when researching these technologies, environments and interaction with them.

In terms of research methods they offer a complex domain for research. One key factor is the number of variables to take into consideration when studying tangible environments. Another is the choice of research approach, given the unique, novel and *not* off-the-shelf technology that it entails, and the different disciplinary perspectives involved, including computer science, art and design, psychology and social science more broadly. This chapter aims to outline these challenges for research design and evaluation, its focus being on research in the context of tangible learning environments and learning interaction (which might inform design of user interfaces), but not on the building or development process of tangible interfaces. It begins with a review of related research and an introduction to key research approaches in the field. This provides the context for an illustrative research example investigating the use of tangibles in an education context. Through this example, the chapter will explore some key research issues – for example, notions of physical–digital mappings, concepts of engagement, the effect of different design parameters. Finally, the chapter will outline critical future research directions and related challenges.

LITERATURE REVIEW

This section offers a review of how these technologies have been used in research to date and provides the context for an illustrative research example investigating the use of tangibles in a science-learning context. Research with tangible technologies can involve a number of different aspects, including the design and building of the system or environment (which often takes an iterative participant design approach); observing and analysing user interaction (in the wild or in the lab); measuring specific features of interaction that are of interest to the research question, such as the design of physical–digital mappings, learning outcomes, engagement. Tangibles have been designed for use in a variety of contexts, from museum exhibits (e.g. Horn et al., 2008; Wall and Wang, 2009) and interactive music installations (e.g. Jorda, 2003), to tools that support planning and decision-making (e.g. Underkoffler and Ishii, 1999). A number of tangible technology-based projects specifically explore applications in the learning domain, with emphasis on various aspects of interaction, from how design influences interaction, the learning process and social interaction to engagement and edutainment, together with a strand of work that focuses on special needs learners. A number of tangible systems for learning in different contexts have been developed during the last decade. Studies of such systems primarily inform us about levels of engagement and enjoyment, the technical achievements of mapping to learning activities that may be promoted through tangible interfaces, but with increasing insights into collaborative forms of interaction and a developing interest in the role of embodied forms of interaction through digital environments for learning.

Early examples of tangibles used popular, familiar toys, such as balls and blocks, digitally embedding them with, for example, light-emitting diodes (LEDs) or accelerometers. Bitball is a transparent sphere that records and transmits information about its own movement through the use of accelerometers (Resnick et al, 1996); Stackables and Programmable Beads comprise assembling blocks that allow children to explore

Figure 20.1 From left to right: Bitball and Programmable Beads (© Mitch Resnick MIT).

dynamic behaviour patterns (Resnick et al., 1998; see Figure 20.1); while SystemBlocks and FlowBlocks generate visual representations of behaviour according to the way the objects are combined (Resnick et al., 1998; Zuckerman et al., 2006; see Figure 20.2). In other work blocks are used as tangible programming elements to ease programming tasks for children by arranging blocks with different functions (e.g. Wyeth and Purchase, 2002; Schweikardt and Gross, 2008).

Other kinds of assembly or constructive kits allow children to build their own, personalized models, stimulating their creativity and imagination. For example, Topobo (Raffle et al., 2004) enables children to build creatures out of digitally embedded pieces that can record and play back physical motion to facilitate children's learning about movement and locomotion (Figure 20.3). This process of creating models is thought to foster a greater understanding of the functioning of things (Klopfer and Squire, 2007) and provide opportunities for children to produce knowledge by expressing themselves through the representations they create (Marshall et al., 2003) – that is, the artefact embodies the children's activity and thoughts.

While familiarity may engage children, the linking to ambiguous or less familiar representations in tangible systems has been shown to promote curiosity and exploration (Rogers et al., 2002). Chromarium, a system to explore colour mixing through physical and digital tools, suggested that children engaged in more experimentation and reflection when objects were linked to less familiar (digital) representations. Subsequent work also suggested that some level of ambiguity provokes children's interest, curiosity and reflection (Price et al., 2003; Randell et al., 2004). In contrast to Topobo, knowledge here is produced through exploration (leading to conclusions), rather than expressivity. There is less space for creativity,

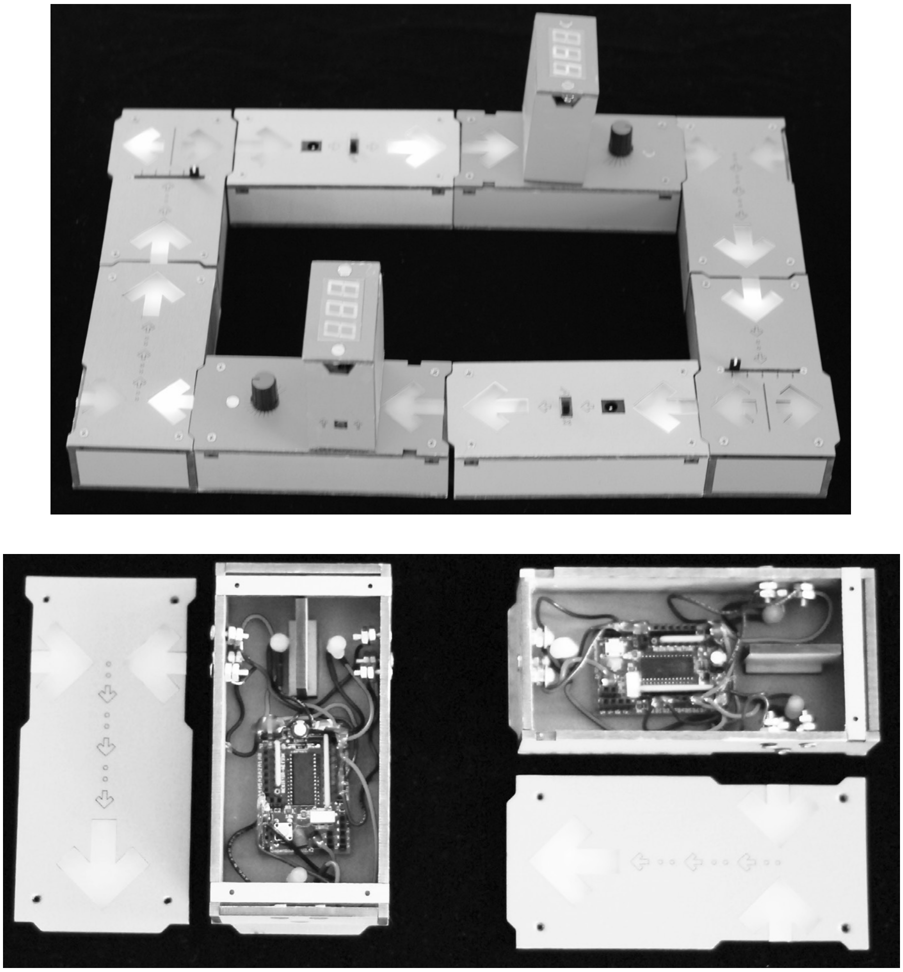

Figure 20.2 FlowBlocks (designed and developed by Oren Zuckerman during his PhD at MIT Media Lab).

suggesting expressive and exploratory systems lend themselves to different learning activities and processes.

Tangible environments have also been shown to encourage collaborative interaction. Tangibles combined with tabletop environments (e.g. Reactable: Jordà, 2003; Sensetable: Patten et al., 2001; LightTable: Price and Pontual Falcão, 2009) show increased collaboration through features of shareable interfaces that accommodate face-to-face interaction and multiple, simultaneous users, thus encouraging communication. Recent work illustrates how these interactive properties support productive collaborative knowledge-building (e.g. Fleck et al., 2009; Pontual Falcão and Price, 2010).

Another strand of work centres around the physically active nature of interaction with tangibles. Antle and colleagues have explored this through notions of metaphor in tangible environments, especially those that relate to 'embodied' interaction (e.g. Antle, 2009; Macaranas et al., 2012) – in particular, understanding how the design of metaphorical mappings between schematic action and

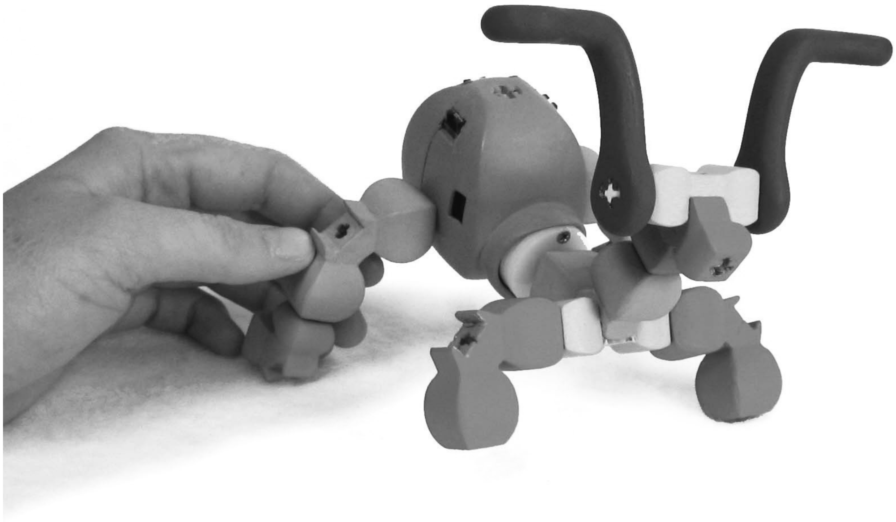

Figure 20.3 Topobo (Hayes Raffle, MIT).

system response improves learning performance. For example, with Springboard, learners explore abstract concepts of 'balance', such as 'social justice', through varying degrees of their own physical bodily balance that triggers visual displays of balance related to a number of social justice issues (Antle et al., 2011).

Other empirical work on tangibles and learning investigates their value in supporting children with special educational needs. Early work suggests that tangible systems positively encourage social activity, fostering social interaction and skill development. A tangible application developed for one- to four-year-olds was found to offer more opportunities for facial, gestural and verbal interaction, as well as slowing down interaction, which was thought to allow more control over the interface (Hengeveld et al., 2009). Research with children on the autistic spectrum found that using Topobo engendered more onlooking, cooperative and parallel play than traditional Lego (Farr et al., 2010a). Furthermore, a digitally enhanced Playmobil set, the Augmented Knights Castle, was found to encourage more collaborative play and less solitary play in the same community of children (Farr et al., 2010b). Current work is investigating how tangible environments might foster more independent exploration in children with learning disabilities (e.g. Pontual Falcão and Price, 2012). This work currently seeks to inform educators about features of tangibles that may be useful for students with learning disabilities and to inform design of artefacts that are accessible across different learning communities. Findings to date suggest important design factors include immediate system feedback (as soon as action is performed); clear mappings between action and effect, both at a physical and a conceptual level; and the use of visual representations and spatial configurations, which are more effective than audio (Pontual Falcão and Price, 2012).

Collectively, this work is beginning to indicate the value of different designs for different kinds of learning processes, learning activities and learning outcomes, as well as for different learner communities, providing the grounding for continued research.

APPROACHES TO RESEARCH

Since the nature of the research field draws on various academic fields, such as computer science, education and design, a single research approach is not usually taken, but often combined motivations underpin the research. While this chapter is centrally concerned with perspectives from social science (psychology, education, design), it begins by emphasizing the primarily interdisciplinary nature of tangible interaction research. It then outlines the central theoretical and conceptual approaches that commonly underpin the research and discusses both technology-driven and non-technology-driven research approaches.

Interdisciplinary Approaches

Tangible interaction research is often driven from different disciplinary perspectives and theoretical bases: computer science, where developments in new techniques in computing and technologies are of central concern; design, where understanding design processes and practices is of central interest; psychology, where research commonly looks at aspects of interaction related to cognition (e.g. perception, action, reasoning, social interaction); and education, where interest lies in how new technologies can support different aspects of learning (process or outcome). The importance of the interaction between these disciplines, or a subset of them, has resulted in a large body of interdisciplinary research, which intersects with and sits under the umbrella of HCI, a community comprising experts from these disciplines that typically work together.

Interdisciplinarity is central to research on tangibles in general, but for specific communities like education, it also demands domain experts, such as teachers or educators. Since tangible technologies are not 'off-the-shelf' they require new design and development. This means that computer science plays an important role in informing the development of the technical application (both what is currently possible and researching new ways of developing devices that work in desired ways); psychologists and education theorists are important in informing design that supports effective learning strategies; designers are central to designing and developing digital media that is linked to the tangible artefacts; and domain experts are instrumental in focusing the tangible as a tool to be effective for the learning domain or in the educational community. Such interdisciplinary teams, therefore, aim to deliver research that would be implausible for a single discipline alone and work towards being culturally embedded, that is, taking a broader, more real-world perspective.

This interdisciplinary nature of the work can be both creative and challenging. Bringing together teams of researchers demands the integration of different research perspectives, requiring the establishment of common ground, particularly around shared understanding (e.g. terminology, perspectives) and fulfilment of research agendas or directions. However, collective perspectives offer a broader range of ideas, commonly pushing and extending the boundaries of research and development.

Theoretical Approaches

Theories of learning and cognition offer a compelling rationale for the value of tangible interaction for supporting learning (e.g. see also O'Malley and Stanton Fraser, 2004), being compatible with constructivist theoretical concepts including hands-on engagement (e.g. Tobin, 1990); experiential and discovery theories of learning (Bruner, 1973); construction of models (e.g. Papert, 1980; Resnick et al., 1996); collaborative activity, transformative communication (Cohen, 1994; Pea, 1994; Webb and Palinscar, 1996) and embodied forms of interaction (Antle, 2009). Increasingly work draws on theoretical ideas around embodiment – a much-debated term that broadly refers to relationships between the body and mind, how bodily interactive processes, such as perception and action, aid, enhance or constrain social and cultural development Several research projects draw on these theoretical notions, but focus on different aspects of learning activity – for example, narrative construction (Annany and Cassell, 2001), exploration and construction (e.g. Raffle et al., 2006), models of phenomena (Moher et al., 2005; Price et al, 2009), pattern-based interaction (Yonemoto et al., 2006), collaboration (e.g. Farr and Yuill, 2010); and metaphorical concepts (e.g. Antle et al., 2011).

Conceptual Approaches

Other approaches that shape research are offered through the development of frameworks, which may focus on descriptive taxonomies, research guidance or analytical perspectives (also see Mazalek and Hoven, 2009). Early frameworks provide descriptive taxonomies, which specify technical configurations of different systems, but say little about the relative strengths and weaknesses of different designs in terms of interaction (e.g. Ullmer and Ishii, 2001; Koleva et al., 2003; Fishkin, 2004). More recent frameworks focus on human interaction and the relationship between design and interaction experience. For example, Hornecker and Burr's (2006) framework encompasses analytical approaches to design, interaction and bodily movement, highlighting the need to design physical tools and their interrelations as well as digital representations.

Other frameworks provide the basis for informing design, for example, Antle (2007), drawing on literature from cognitive psychology, identifies five properties of tangible systems for designers to consider. These primarily concern physical–digital mappings: perceptual (the mapping between the perceptual (often appearance) properties of the physical and digital aspects of the system), behavioral (the mapping between the input behaviors and output effect of the physical and digital aspects of the system) and semantic mappings (the mapping between the information carried in the physical and digital aspects of the system); but also specify designing 'space for action' (space for control through physical action) and 'space for friends' (the ways in which the system supports collaboration).

Frameworks specifying the importance of empirical research approaches for learning (e.g. Marshall, 2007; Price et al, 2008) have also been proposed. Marshall (2007) proposes an analytical framework with six perspectives intended to guide tangible interface empirical research and development. The perspectives draw on a research review and focus on properties or dimensions of tangible systems that relate to learning: learning activity; learning domains; learning benefits; integration of representations; concreteness and sensoridirectness; and effects of physicality. Price's (Price et al., 2008) framework specifies the artefact–action–representation relationships in tangible systems with a view to framing empirical research around the representational properties of tangible environments. The framework has four primary parameters: location, dynamics, correspondence and modality (detailed in the section 'Example research study' below).

Frameworks, such as these, provide a structure for designing and framing research or offer perspectives for analysing research and can be used in conjunction with other theoretical approaches to learning, cognition and interaction.

Technology and Non-technology-driven Approaches

Some research studies into tangibles for learning take a technology-driven approach, while others are driven initially from a non-technology perspective. Technology-driven – or 'technology- inspired' (Rogers et al., 2002) – approaches are claimed to be effective where interactive experiences with unknown (or novel) technologies are largely unexplored: 'a mix of serendipity and invention where creative experimentation is what drives the research' (Rogers et al., 2002: 373). In contrast, work that takes a 'non-technology' approach is equally informative. For example Manches and O'Malley (2012) investigated the effect of physical manipulation on children's reasoning to inform design and evaluation of novel forms of interaction like tangible interaction.

However, much research combines elements of these two approaches to consider the technological opportunities in conjunction with our understanding of learning and cognition and current educational practice. While these approaches might help to steer the research, the majority of work in this area has been exploratory, in the sense of not being systematic or context-dependent. While this is very fruitful in gaining some insight into tangible interaction, and particularly in identifying important areas for future research, the need for systematic and focused research remains.

EXAMPLE RESEARCH STUDY

This section provides an illustrative example of how 'tangible technology' research has been undertaken, identifying the particular features of the technology for the research questions and outlining the research approaches, methods and findings.

Motivation for Research: Representation Framework

Tangible technologies that enable physical, hands-on forms of interaction and flexible linking of digital representations to physical objects offer opportunities for engaging with invisible scientific phenomena in new ways. While this may be assumed to offer learning benefits, the specific advantages and limitations for learning need to be demonstrated. Since research in this area is complex, not least because of the number of variables to take into consideration (e.g. hands-on learning interaction; physical–digital combinations; representation design), the need for more structured research is apparent. To address this, a research framework was developed that focuses on one of the unique properties of tangible environments – the facility to flexibly link artefacts with digital representation, promising greater representational power. The flexibility of such coupling brings an exponential number of parameters for linking together representation, object or environment and action. The proposed research framework therefore focuses on the relationship between different artefact–representation combinations and the role that they play in shaping cognition.

The framework (Price et al., 2008) has four primary parameters, which specify different dimensions for empirical research with respect to learning interactions.

1. *Location* refers to the different spatial locations of digital representations in relation to the object or action triggering the effect. For example in a 'discrete' design, input and output are located separately – that is, a manipulated object triggers a digital representation on an adjacent, but separate, screen (e.g. Chromarium used an adjacent digital display to show the effects of mixing colours on cubes embedded with RFID technology; Gabrielli et al., 2001); in a 'co-located' design, input and output are contiguous–that is, the digital effect is directly adjacent to the artefact (e.g. Urp, a model urban planning environment, displays shadows or wind patterns of architectural structures on a surrounding horizontal table surface ;Underkoffler and Ishii, 1999); an 'embedded' design comprises a digital effect within an object (e.g. FlowBlocks are sensor-embedded blocks that when connected together send light signals through the blocks to help children explore different causal structures ;Zuckerman et al., 2006).
2. *Dynamics* is concerned with the flow of information during interaction. For example, digital effects or feedback can be immediate or delayed or may be dependent on multiple objects or interactions to be triggered. The resultant causal relationships can be quite complex, requiring better understanding of the impact of such flow of information on cognition.
3. *Correspondence* refers to the metaphors involved in the nature of representations of artefacts and the actions placed upon them. 'Physical correspondence' refers to the degree to which the physical properties of the objects are closely mapped to the learning concepts, the emphasis

being on the degree of correspondence to the metaphor of the learning domain. 'Symbolic correspondence' defines objects that act as common signifiers – for example, blocks used to represent various entities, where the object may have few or no characteristics of the entity it represents. For example, a block could represent a book or abstract entities, like chromosomes or circuit components. 'Literal correspondence' defines objects the physical properties of which are closely mapped to the metaphor of the domain it is representing. For example, a rigid block representing chromosomes reveals none of the fragility or separation that is inherent in the process of genetic changes, whereas loosely magnetically connected 'strips' could convey underlying 'fragile' features of the learning concept.

4. *Representational correspondence* encompasses design considerations of the representations themselves and how this corresponds to the artefact and action within the context or subject domain of use. Meaning mappings between physical and digital representations can be designed with different levels of association (direct to ambiguous) between symbol and symbolized according to the concept being displayed or indeed the desired interaction/reflection. For example, research suggests that ambiguous mappings between sound and environment engender different levels of reflection about meaning in context than direct mappings (Randell et al., 2004).
5. *Modality* of representation impacts on different aspects of the whole interaction and can be considered in parallel to all other categories. Although the visual mode is often a predominant form of representation, the potential for audio and tactile modes in tangible computing requires a broader understanding of their role for learning.

While a framework approach offers the basis for structuring research, and the potential for examining different design parameters, there are a number of limitations. It requires a substantial amount of different studies to provide a comprehensive view of learning with tangibles together with specification of the design and development of the tangible environments that enable this level of detailed investigation. Also, issues of systematic, reductionist approaches to research versus in-the-wild studies are raised.

Context of the Research

This example is situated within a science-learning context, the learning experience being designed to fit within the UK science curriculum. Specifically, a tangible environment was designed to investigate the role of tangible technologies in supporting learning about the behaviour of light, particularly basic concepts of reflection, transmission, absorption and refraction of light, and derived concepts of colour. These phenomena are invisible, hard to show in a classroom context (beyond visual illustration) and exploit the physical properties of objects. Of particular interest here was, first, to understand how the physical properties of objects that are central to the scientific idea, and their linking to digital representations, might shape interpretation. For example, green reflects green, while red reflects red; rough objects reflect in a diffuse manner, while smooth ones do not. Second, we wanted to examine the differential effects of representation location on interaction and cognition; and third to explore the role of hands-on manipulation in shaping action and contributing to scientific understanding.

The Environment

A purpose-built tangible tabletop environment was developed. The system consisted of a table with a frosted glass surface, which was illuminated from underneath by infrared LEDs. This enabled an infrared camera under the table to track objects placed on the table surface, using reacTIVision software for object recognition (Kaltenbrunner and Bencina, 2007). In order for the camera to track the objects, each object was tagged with a paper marker called a 'fiducial'. Thus, each object could be individually identified, together with its location and orientation. When distinct objects were recognized by the system, different digital effects were projected on to the tabletop (see Sheridan et al., 2009 for more technical details) and (Figure 20.4).

The digital effects were designed to illustrate light behaviour. Thus, a torch acted as a

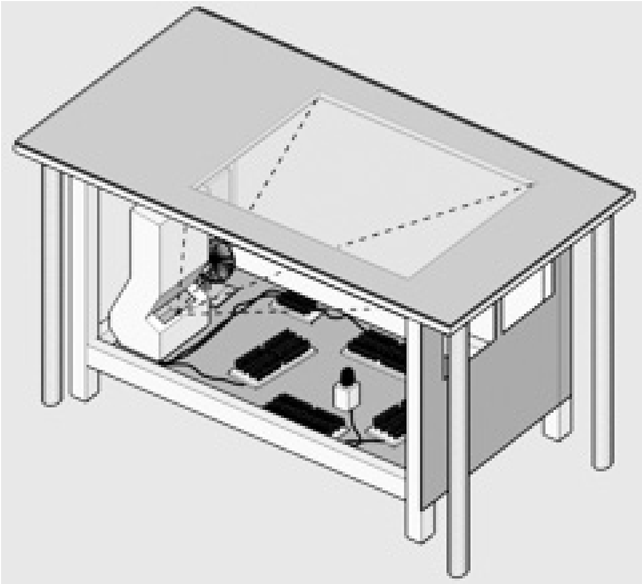

Figure 20.4 Schematic illustration of tangible lighttable.

light source (causing a digital white light beam to be displayed when placed on the surface) and objects that were placed in the beam reflected, refracted and/or absorbed the digital light beams, according to their physical properties (shape, material and colour). For example, pointing the torch at a green block caused a green beam to be reflected (Figure 20.5 left).

The torch, when placed on the surface, was 'always on', while the other objects only produced digital effects if they were placed in the pathway of the digital light beam. The digital effects changed when someone directly manipulated the objects – either by taking them off the table or altering their position on the table – which caused the light beam to be interrupted or redirected.

Scenario Design

Designing scenarios for purpose-built systems offers another research challenge. The physically based nature of the environment that uses real-world objects requires consideration in terms of design, particularly where levels of realism (i.e. objects) are combined with schematic ideas (digital representation). Initially distinct phases for learning about each concept (reflection, refraction and absorption) were proposed. However, as the scientific concepts being explored are interrelated, sequencing removed important overall coherence of the phenomena. In addition, rather than leading children towards solving well-defined tasks, one aim of the application was to encourage free collective exploration and promote discovery learning. By experimenting with the different types of objects and the torch, children would have the opportunity to explore how light behaved with different combinations of objects and draw conclusions about the different phenomena involving light. The elements of the system were designed to encourage children's reasoning and thinking about light behaviour and the expected outcomes of the interactive sessions were dialogues between the children about the learning topic and collective knowledge building through conceptual conclusions drawn from their interaction with the interface.

The design and choice of the kind of digital representations to be used when learning

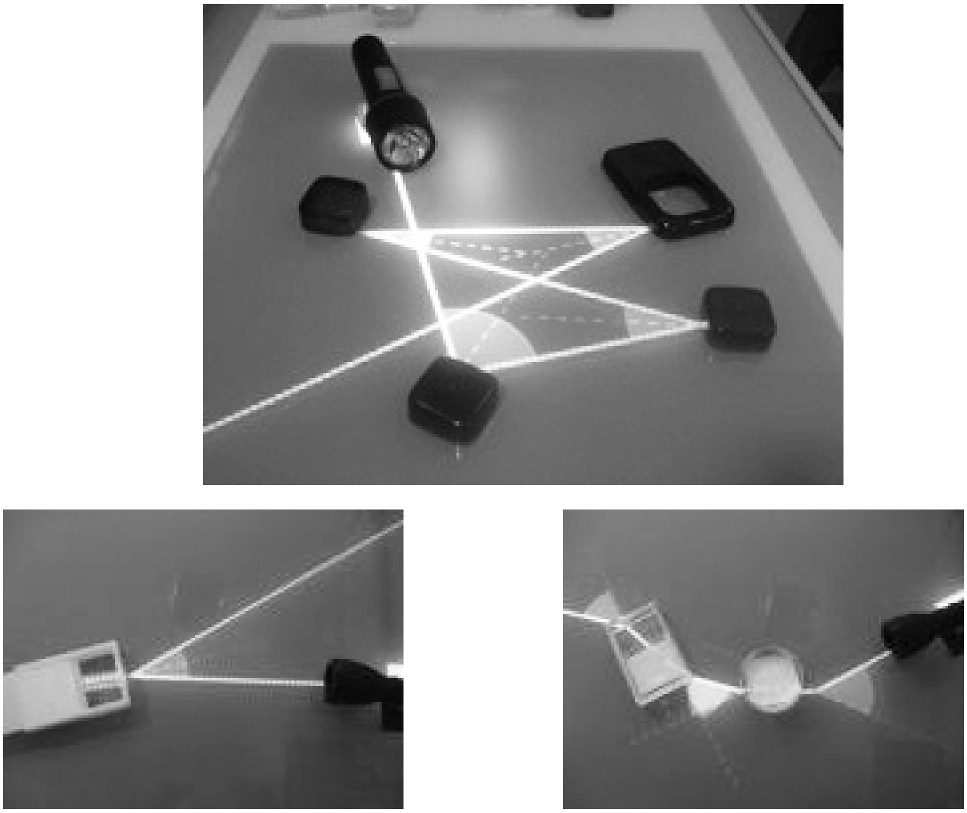

Figure 20.5 Reflection, refraction and absorption displayed on tangible lighttable.

about light in a tangible environment was also complex, with technical limitations having to be taken into account. Informal interviews with the teachers, the piloting of different designs with children and adults and input from domain experts and different academic disciplines were all instrumental in informing the design. Choices included showing absorbed colours inside or next to the object that shows the light beam as white or as the spectrum of colours and illustrating reflection through ripples, arrows or straight lines.

Study Design

A number of challenges around study design emerged. First, an appropriate task needs to be designed. Here an explorative task was chosen in order to study interaction at a general level – to see what children intuitively did and intuitively inferred through their interaction. Other work might choose well-defined tasks to study particular learning concepts or particular forms of physical interaction.

Second, the location of studies needs to be considered – for example lab-based or 'in the wild'. In this work, lab-based studies were the only realistic option, since moving the table and situating it in a school or museum proved impractical. This creates subsequent challenges of bringing groups of students into the lab and has implications for analytical interpretation, particularly if this focuses on learning outcomes or teacher interaction. Since the focus of these studies was to examine aspects of representation design and related interaction and interpretation, a lab-based environment sufficed.

Figure 20.6 Discrete and co-located arrangements.

For the studies discussed here, 21 children from Year 7, aged 11–12 years (11 female and 10 male), and 22 children from Year 9 (10 female and 12 male) aged 13–14 years, from two schools in the UK took part. Children worked with the tangible table in groups of three and were selected by the teacher on the basis of being able to work well together. One study focused on comparing interaction and interpretation in a 'discrete' representation design with a 'co-located' design (Figure 20.6).

Each session lasted 35–45 minutes. Children were asked to freely explore the interface (by moving the objects on the tabletop) to find out about light behaviour. During the interaction, a researcher facilitator prompted the group with general questions like 'What's happening here?' and 'Why do you think this is happening?' to guide students through the exploration of the concepts towards making inferences and drawing conclusions. All sessions were video recorded. After engaging with the tangible system, children were interviewed in their groups to obtain information on their understanding of key concepts of light behaviour, feedback on the system as a whole and their general experience.

Analytical Approaches

A thematic analysis approach was taken with all video data, the specific themes being related to aspects of the framework and to different studies undertaken. To develop coding schemes based on themes, group and paired analysis with researchers took place. One challenge here was selecting video focus – on the tabletop surface providing detailed views of manipulation and hands-on interaction or taking more global views of the 'whole' view of interaction. In this example, data were analysed from a tabletop focus of interaction, together with verbal interaction, which enabled examination of key aspects of the representation framework. In contrast, more recent work looking at 'embodied' forms of interaction took multiple video data views of interaction to access aspects of gaze and body posture as well as manipulation data.

Summary of Findings

Collectively the studies generated a number of key research findings, which feed into the research framework and offer insights into design, as well as indicating important future directions of research.

Representation Location (Discrete v. Co-located)

Findings indicate that interaction differences in the two location modes have some key implications for learning. First, they were found to have different attention demands. In the discrete mode learners tended to look at the screen, in similar ways to mouse-based interaction, using the objects as input devices, following the effect of their actions on a separate screen. Here the collaborative focus becomes the screen. On the other hand, when learners' attention was directed to the table surface, they could see each other's actions while looking at the table surface for the system's feedback. The opportunity this provides for learners to give opinions on others' actions and events changes the nature of the collaboration: explicit awareness of others' hand actions facilitated exploration and increased collaborative forms of construction and interpretation. When looking at a separate screen, users may more easily lose track of each other and tended to work by themselves.

Second, the co-located approach fostered more rapid dynamic interaction, which enabled access to increased exemplary instances of scientific phenomena and enhanced explorative activity. On the other hand, slower interaction in the discrete mode allowed more 'time' for thinking. This raises questions about the value and realization of different forms of reflection – reflection in action and reflection on action – for learning with co-located shared interfaces and highlights the need to specifically design learning activities that slow down interaction and promote opportunities for reflection to occur during 'calm' periods at various points in the learning task. Overall these findings build on previous work (Sensetable: Patten et al., 2001) showing that users preferred information displayed on the sensing surface rather than on a separate screen, precluding the need to divide their attention between the input (sensing surface) and the output (separate screen display), by illustrating the interactive and cognitive effect of such different designs.

Physical Digital Mappings

The behavioural mappings in the environment were of a tight coupling design (Antle, 2007) and children had little difficulty in understanding the cause and effect relationships (i.e. physical action input and digital output). As well as the design of representations themselves, a key factor that underlies interpretation in tangible environments is the design of the physical–digital mappings. However, findings here suggest that children's interpretation of scientific phenomena resulted from an interaction between different design choices for physical objects and associated representations, preconceptions and previous real-world experience.

In terms of physical correspondence, issues were raised around mappings of real-world objects to virtual, artificial environments, in which the object behaves as itself. Although the torch was actually representing a torch, it could not be turned on or used in the 3D space in the same way as in the real world. Thus, the system constraints on objects or actions do not always map to familiar interaction in the real world. This highlights issues around the design of tangible interfaces and the potential impact on learning of mixed metaphors or requirements to shift from one metaphor to another The mapping between physical objects and their meaning and function within the environment was not always literally interpreted by children, who sometimes perceived objects to have a symbolic correspondence. The torch, being an object taken directly from the 'real world' with familiar affordances of interaction, was intuitively manipulated within a 3D space (lifting, switching on), rather than within the constraints of the 2D surface. However, such technical constraints were rapidly accommodated and the meaning (source of light) and purpose (shining light on objects) of the torch in the environment were unambiguous and comprehensible. On the other hand, the coloured blocks (although representing themselves) were perceived as being representative of something else, giving rise to a variety of interpretations. For example, the spectrum of absorbed colours shown inside the objects evoked the common experiment of decomposing white light through a prism and induced the perception that the block represented a prism. Furthermore, the notion of reflection, being mostly associated with concepts of optics, led to the interpretation of blocks as mirrors or lenses and never as regular opaque objects (Price and Pontual Falcão, 2009).

Interpretations of the digital effects were also affected by real-world experience and familiar representations. For instance, the representation of absorbed colours as a colour spectrum was immediately associated with a rainbow (Figure 20.5, centre). Although children were excited by the representation, the representation itself did not appear to facilitate their understanding of the phenomenon of absorption. In fact, children described it as light going through (the object) in the form of a rainbow, the word rainbow being often repeated, which was not the intention of the design. This raises issues about using representations that evoke a distinct familiar phenomenon, with other purposes, and again about the ability of children to transfer across domains (Price and Pontual Falcão, 2009).

Findings here suggest that while designers may have underlying rationales for choices of literal or symbolic correspondences (see 'Motivation for research: representation framework' earlier this chapter), learners do not necessarily infer the same correspondence metaphor. Using physical blocks or real blocks in conjunction with theoretical scientific models, which are represented symbolically, blurs the boundaries between what is real and what is symbolic. Studies here suggest that this may have an impact on at least two things, but warrants further research. First, interpretation of phenomena in relation to objects was intuitively based on previous experience (e.g. seeing blocks as mirrors rather than as opaque blocks), hindering their tendency to attend to, for example, the physical properties of the blocks, and constraining any extension to their reasoning. Second, despite using real objects, their ability to generalize to other objects was limited.

Given that tangible systems do not just exploit the physicality of the real world but also aggregate digital models enabling access to phenomena 'invisible' in everyday interaction and manipulation of symbolic models, a key issue is how to effectively mesh together an accurate model of reality with artificial scenarios.

With physical environments the constraints of forms of representation may impact on the utility of certain illustrations of phenomena. Let's take the concept of absorption and ways of illustrating absorption of the different light waves in combination with reflection. On the one hand, with a physical object (red), a digital representation depicting a red beam being reflected off the object makes an effective combination for physical–digital representation of invisible phenomena. On the other hand, depicting absorption of the remaining light waves (thus making us 'see' red) is not so easy in the physical object itself. In the studies described here, such absorption was shown 'inside' the object – but as a 'fixed' representation rather than, for example, illustrating a dynamic process of the absorption taking place. This may have contributed to students' classification of this as a 'rainbow', thus distracting them from the key point of the representation. Now let's think about this in a purely digitally represented environment, where an object is illustrated on a screen, a light source is shone on the object and a red beam reflects off the object, while at the same time a dynamic depiction of the other light waves gradually being absorbed in the object is illustrated. The point here is that the constraints of the physical object used in the tangible system must be taken into account when considering the most effective form of illustrating invisible phenomena. It could be argued that this is a technical constraint and in the future technology will have advanced to a point that would enable the depiction of such absorption processes inside the physical objects themselves.

Collaboration

Overall the studies provided insight into the role of tangibles and interactive surfaces in collaborative interaction (Pontual Falcão and Price, 2009, 2010). First, the co-located design promoted a high level of awareness of others and of action–effect relationships and provided a common and unique focus of attention. Everyone's actions and the consequent digital effects were visible to all participants on the shared surface, which facilitated collective exploration and collaborative knowledge construction. In contrast, with the discrete mode, the physically separated input–output coupling made the action–effect relationships less clear and being aware of others' actions harder.

Second, the design invited parallel actions and the dynamics provoked rapid changes in configurations. This sparked unexpected events in the dynamic display, which in turn aroused curiosity, drew attention to relevant instances of the phenomena, engendered further exploratory and enquiry activity and promoted the need for verbal negotiation (about what was happening) and synchronization of actions to 'build' a particular configuration. More interestingly, the parallel actions and rapid dynamic changes resulted in many instances where one child's actions 'interfered' with another's current, or planned, configurations. High levels of (accidental or intentional) interference were highly successful in provoking curiosity, drawing attention to relevant instances of the phenomena, engendering exploratory and enquiry activity and promoting verbal negotiation and synchronization of actions. Overall this facilitated effective forms of collaborative interaction.

Shared Resources and Representations

Third, the shared resources within the tangible environment were fundamental in promoting interference and fostering particular ways of sharing. The potential for interference was dependent on the children actively sharing some kind of resource that allowed them some control or influence on the physical or digital resource – this could be objects/artefacts or digital representation. The design meant that although the digital effect from the torch was key to interaction, it did not preclude others from controlling the interaction. Several blocks enabled simultaneous possession of objects for manipulating the configuration and even shy children could gain access to the digital light beam using the objects they were manipulating and, in so doing, were forced to get involved with the group activity. Thus, this design was useful in encouraging all children to be actively included in the collaborative activity.

Awareness of others' actions enabled sharing of resources through gesture or 'physical asking' and they were shared through an implicit protocol of handing resources over. The physicality and availability of the devices contributed to balanced levels of participation. The digital representations were collective – that is, everyone's input fed into the same common digital representation, which contributed to collective knowledge building.

Along with this work, a growing body of evidence suggests the key role that tangible technologies may play in supporting collaborative interaction and exploratory forms of interaction (e.g. Ha et al., 2006; Hornecker et al., 2008; Do-Lenh et al., 2009; Fleck et al., 2009). In learning contexts this is of significant interest, with a general trend to promote both a collaborative nature of learning and student-led learning – or at the very least more student-centred learning.

FUTURE RESEARCH: CHALLENGES/ DIRECTIONS

In this section a number of key research challenges and important research directions are outlined.

Research Challenges

One significant challenge is accounting for rapid changes in technical development and the availability of off-the-shelf technologies. Developments in technology generate increasingly new ways of interaction. Designing studies that can continue to inform such developments is challenging, but fundamental to their sustained value. One advantage of adopting a framework approach based on key properties of the environments, such as representation, is that it offers insight into design implications across technologies.

Another technology-related challenge is choosing whether to develop purpose-built systems to test particular design features or to employ off-the-shelf technology. Such decisions are commonly driven by the research question and research aims. For example, designing for deployment in current educational contexts would likely involve readily available technology; whereas examining theoretical possibilities would likely involve developing purposely designed applications.

A second consideration is whether to carry out research with tangibles *in situ*, for example in a school classroom or museum or the informal contexts of home, or undertake lab-based studies.

A third issue is that of novelty: technology environments such as these are inherently novel to learners, impacting on interaction, and generally heightening engagement and enjoyment. Novelty factors demand longitudinal data, with larger sample sizes. Yet this is problematic when emergent technologies are not yet commonplace or embedded into classroom practice.

Last, but not least, approaches to evaluation, specifically in relation to learning, remains under-researched. Much evaluation focuses on 'usability' and ensuring that learners can easily master the interface (designing for intuitiveness) and on engagement in terms of levels of fun and enjoyment.

Research Directions

Two key research directions are worthy of note here. First, research with tangible learning environments has begun to move from more open-ended exploratory research to more in-depth research on specific forms of interaction. In particular, interest in the role of tangible technologies in fostering collaboration is growing and investigation into the role of embodied interaction in learning and its relationship with tangible learning environments is developing (e.g. Antle et al, 2011; Price and Jewitt, 2013). Current work is developing notions of what embodiment means for learning in digital environments (MODE, n.d.). Digital technologies provide new opportunities to explore and study how the body and embodiment contribute to communication and learning. The mainstreaming of tangible, mobile and sensor-based technologies places embodiment well beyond a question of physical–digital augmentation and opens up new research directions to gain insight into the role of 'embodiment' in technology-learning environments – for example, how the body mediates interaction and experiences and the relationships between context and situatedness and environment–interaction–cognition.

A further significant area of research is tackling the challenge of how to foster the embedding of technologies into classroom education. While research has established the learning opportunities tangibles may provide for students, for such technologies and their accompanying applications to be successfully integrated into educational contexts also requires a focus on teachers and teachers' use of technology. Previous work highlights a number of concerns, including that technology does not reflect pedagogic approaches (Major, 1995), there is a lack of training or familiarity with computers and the time involved in learning a new tool (Mueller et al., 2008). Brown and Green (2008) suggest the need to consider new ways for teachers to use technologies that support modification, creativity and tailoring to student age, ability and subject domain. Such a move requires tools that enable teachers and educators to design and customize their own learning activities with these tools with relative ease. In addition, changing teachers' beliefs about the value of their students learning with technology is a major catalyst for the adoption of new forms of teaching. A critical approach here is engaging them in the design and development of new technologies and approaches to teaching.

ACKNOWLEDGEMENTS

This work was supported by the EPSRC: EP/F018436. Thanks to George Roussos, Taciana Pontual Falcão and Jennifer Sheridan, for their invaluable contributions to the project, and students and teachers from Woodlands and Sweyne Park schools for their participation in the research studies.

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