Literature Review in Learning with Tangible Technologies

Claire O'Malley, Danae Stanton Fraser

FUTURELAB SERIES

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REPORT 12:

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Claire O'Malley, Learning Sciences Research Institute, School of Psychology, University of Nottingham
Danae Stanton Fraser, Department of Psychology, University of Bath

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FOREWORD

When we think of digital technologies in schools, we tend to think of computers, keyboards, sometimes laptops, and more recently whiteboards and data projectors. These tools are becoming part of the familiar educational landscape. Outside the walls of the classroom, however, there are significant changes in how we think about digital technologies – or, to be more precise, how we **don't** think about them, as they disappear into our clothes, our fridges, our cars and our city streets. This disappearing technology, blended seamlessly into the everyday objects of our lives, has become known as 'ubiquitous computing'. Which leads us to ask the question: what would a school look like in which the technology disappeared seamlessly into the everyday objects and artefacts of the classroom?

This review is an attempt to explore this question. It maps out the recent technological developments in the field, discusses evidence from educational research and psychology, and provides an overview of a wide range of challenging projects that have attempted to use such 'disappearing computers' (or tangible interfaces) in education – from digitally augmented paper, toys that remember the ways in which a child moves them, to playmats that record and play back children's stories. The review challenges us to think differently about our future visions for educational technology, and begins to map out a framework within which we can ask how best we might use these new approaches to computing for learning.

As always, we are keen to hear your comments on this review at research@futurelab.org.uk

Keri Facer
Learning Research Director
Futurelab

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EXECUTIVE SUMMARY

The computer is now a familiar object in most schools in the UK today. However, outside schools different approaches to interacting with digital information and representations are emerging. These can be considered under the term 'tangible interfaces', which attempts to overcome the difference between the ways we input and control information and the ways this information is represented. These 'tangible interfaces' may be of significant benefit to education by enabling, in particular, younger children to play with actual physical objects augmented with computing power. Tangible technologies are part of a wider body of developing technology known as 'ubiquitous computing', in which computing technology is so embedded in the world that it 'disappears'.

Tangible technologies differ in terms of the behaviour of control devices and resulting digital effects. A contrast is made between input devices where the form of user control is arbitrary and has no special behavioural meaning with respect to output (eg using a generic tool like a mouse to interact with the output on a screen), and input devices which have a close correspondence in behavioural meaning between input and output (eg using a stylus to draw a line directly on a tablet or touchscreen). The form of such mappings may result in one-to-many relations between input and output (as in arbitrary relations between a mouse, joystick or trackpad and various digital effects on a screen), or one-to-one relations (as in the use of special purpose transducers where each device has one function). Tangibles also differ in terms of the degree of metaphorical relationship between the physical and digital representation. They can range from being completely analogous, in the case of physical devices resembling their digital counterparts, to having no analogy at all. They also differ in terms of the role of the control device, irrespective of its behaviour and representational mapping. So, for example, a control device might play the role of a container of digital information, a representational token of a digital referent, or a generic tool representing some computational function. Finally, these technologies differ in terms of degree of 'embodiment'. This means the degree of attention paid to the control device as opposed to that which it represents; completely embodied systems are where the user's primary focus is on the object being manipulated rather than the tool being used to manipulate the object. This can be more or less affected by the extent of the metaphor used in mapping between the control device and the resulting effects.

In general there are at least two senses in which tangible user interfaces strive to achieve 'really direct manipulation':

1. In the mappings between the **behaviour** of the tool (physical or digital) which the user uses to engage with the object of interest.
2. In the mappings between the meaning or semantics of the represent**ing** world (eg the control device) and the represent**ed** world (eg the resulting output).

Research from psychology and education suggests that there can be real benefits for learning from tangible interfaces. Such technologies bring physical activity and active manipulation of objects to the forefront of learning. Research has shown that, with careful design of the activities themselves, children (older as well as younger) can solve problems and perform in symbol manipulation tasks with concrete physical objects when they fail to perform as well using more abstract representations. The point is not that the objects are concrete and therefore somehow 'easier' to understand, but that physical activity itself helps to build representational mappings that serve to underpin later more symbolically mediated activity after practise and the resulting 'explicitation' of sensorimotor representations.

However, other research has shown that it is important to build in activities that support children in reflecting upon the representational mappings themselves. This work suggests that focusing children's attention on symbols as **objects** may make it harder for them to reason with symbols as **representations**. Some researchers argue for cycling between what they call 'expressive' and 'exploratory' modes of learning with tangibles.

A number of examples of tangible technologies are presented in this review. These are discussed under four headings: digitally augmented paper, physical objects as icons (phicons), digital manipulatives and sensors/probes. The reason for treating digital paper as a distinct category is to make the point that, rather than ICT replacing paper and book-based learning activities, they can be enhanced by a range of digital activities, from very simple use of cheap barcodes printed on sticky labels and attached to paper, to the much more sophisticated use of video tracing in the augmented reality examples. However, even this latter technology is accessible for current UK schools but without the need for special head-mounted displays to view the augmentation. For example, webcams and projectors can be used with the augmented reality software to overlay videos and animations on top of physical objects.

Although many of the technologies reviewed in the section on 'phicons' involves fairly sophisticated systems, once again, it is possible to imagine quite simple and cheap solutions. For example, bar code tags and tag readers are relatively inexpensive. Tags can be embedded in a variety of objects. The only slightly complex aspect is that some degree of programming is necessary to make use of the data generated by the tag reader.

Finally, implications are drawn for future research, applications and practice. Although there is evidence that, for example, physical action with concrete objects can support learning, its benefits depend on particular relationships between action and prior knowledge. Its benefits also depend on particular forms of representational mapping between physical and digital objects. For example, there is quite strong evidence suggesting that, particularly with young children, if physical objects are made too 'realistic' they can actually prevent children learning about what the objects represent.

Other research reviewed here has also suggested that so-called 'really direct manipulation' may not be ideal for learning applications where often the goal is to encourage the learner to reflect and abstract. This is borne out by research showing that 'transparent' or really easy-to-use interfaces sometimes lead to less effective problem solving. This is not an

children can solve problems with concrete physical objects when they fail using more abstract representations the point is not the sophistication of the technologies but the innovative forms of interactivity they enable

argument that interfaces for learning should be made difficult to use – the point is to channel the learner's attention and effort towards the goal or target of the learning activity, not to allow the interface to get in the way. In the same vein, Papert argued that allowing children to construct their own 'interface' (ie build robots or write programs) focused the child's attention on making their implicit knowledge explicit. Other researchers support this idea and argue that effective learning should involve both expressive activity, where the tangible represents or embodies the learner's behaviour (physically or digitally), and exploratory activity, where the learner explores the model embodied in the tangible interface.

1 INTRODUCTION

1.1 AIMS AND OUTLINE OF THE REVIEW

The aims of this review are to:

- introduce the concept of tangible computing and related concepts such as augmented reality and ubiquitous computing
- contrast tangible interfaces with current graphical user interfaces
- outline the new forms of interactivity made possible by tangible user interfaces
- outline some of the reasons, based on research in psychology and education, why learning with tangible technologies might provide benefits for learning
- present some examples of tangible user interfaces for learning
- use these examples to illustrate claims for the benefits of tangible interfaces for learning
- provide a preliminary evaluation of the benefits and limitations of tangible technologies for learning.

We do not wish to argue that tangible technologies are superior to other current and accepted uses of ICT for learning. We wish to open up the mind of the reader to new possibilities of enhancing teaching and learning with technology. Some of these possibilities are achievable with relatively simple and cheap technologies (eg barcodes). Others are still in the early stages of development and involve more sophisticated uses of video-based image analysis or robotics. The point is not the sophistication of the technologies but the innovative forms of interactivity they enable and, it is hoped, the new possibilities for learning that they provide.

We have tried in this review to outline the interactional capabilities afforded by tangible technology by analysing the properties of forms of action and representation embodied in their use. We have also reviewed some of the relevant research from developmental psychology and education in order to draw out implications for the potential benefits and limitations of these approaches to learning and teaching. Although many of the educational examples given here refer to use by young children, several also involve children of secondary school age. In general we feel that the interactional and educational principles involved can be applied to learning in a wide variety of age groups and contexts.

1.2 BEYOND THE SCHOOL COMPUTER

Few nowadays would disagree that information and communication technology (ICT) is important for learning and teaching, whether the argument is vocational (it's important for young people to become skilled or 'literate' in ICT to prepare them for life beyond school) or 'techno-romantic' (ICT provides powerful learning experiences not easily achieved through other means – see Simon 1987; Underwood and Underwood 1990; Wegerif 2002). There is no doubt that there have been tremendous strides in the take-up and use of ICT in both formal school and informal home settings in recent years, and that there have been many positive impacts on children's learning (see Cox et al 2004a; Cox et al 2004b; Harrison et al 2002). However, developments in the use of ICT in schools tend to lag behind developments in other areas of life (the workplace, home). At the turn of the 21st century, the use of computers in schools largely concerns the use of desktop (increasingly laptop) machines, whilst outside of school the use of computers consists increasingly of personal mobile devices which bear little resemblance to those desktop machines of the 1980s.

Technology is now increasingly embedded in our everyday lives. For example, when we go shopping barcodes are used by supermarkets to calculate the price of our goods. Microchips embedded in our credit cards and magnetic strips embedded in our loyalty cards are used by supermarkets and banks (as well as other agencies we may not know about) to debit our bank accounts, do stock control, predict our spending patterns and so on. Sensors in public places such as the street, stores, our workplace are used to record our activities (eg reading car number plates, detecting our entrance and exit via radio frequency ID tags or pressure or motion sensors in buildings). We communicate by mobile phone and our location can be identified by doing so. We use remote control devices to control our entertainment systems, the opening and closing of our garages or other doors. Our homes are controlled by microcomputers in our washing machines, burglar alarms, lighting, heating and so on.

This is as much true for school-aged children as it is for adults: the average home with teenagers owns an average of 3.5 mobile phones (survey by ukclubculture, reported in The Observer, 17 October 2004); teenagers prefer to buy their music online rather than buying CDs; 80% of teenagers access the internet from

technology is now increasingly embedded in our everyday lives

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'tangible interfaces' try to open up new possibilities for interaction that blend the physical and digital worlds

home. Young people's experience with technology outside of school is far more sophisticated than the grey/beige box on the desk with its monitor, mouse and keyboard.

It is probably safe to say that most schools in the UK (both primary and secondary) now have fairly well-stocked ICT suites or laboratories, where banks of PCs and monitors line the walls or sit on desks in rows. It is less likely that they occupy central stage in the classroom where core subject teaching and learning takes place, but many schools are now adopting laptops and so this may be gradually changing. A few schools may even be experimenting with PDAs. Many schools use interactive whiteboards or 'smartboards'. However, despite the changes in technology, the organisation of teaching and learning practice is relatively unchanged from pre-ICT days – in fact one might be tempted to argue that interactive whiteboards are popular with teachers largely because they can easily incorporate their use into existing practices of face-to-face whole class teaching. The smartboard is the new blackboard, just as the PC/laptop/palmtop is the new slate (or paper). There are occasional examples of innovative uses of technology, but the vast majority of use of technology in learning arguably hasn't changed very much since the early days of the BBC micro in the 1970s and early 1980s.

However, outside schools there has been a growing trend for technology to move beyond the traditional model of the desktop computer. In the field of human-computer interaction (HCI), traditional desktop metaphors are now being supplanted by research into the radically different relationships between real physical environments and digital worlds[1]. Outside the school we are beginning to see the development of what is becoming known as 'tangible' interfaces.

1.3 TANGIBLES: FROM GRAPHICAL USER INTERFACES (GUIs) TO TANGIBLE USER INTERFACES (TUIs)

It's probably useful at this point to introduce a brief history of the term 'tangibles'.

Digital spaces have traditionally been manipulated with simple input devices such as the keyboard and mouse, which are used to control and manipulate (usually visual) representations displayed on output devices such as monitors, whiteboards or head-mounted displays. 'Tangible interfaces' (as they have become known) attempt to remove this input-output distinction and try to open up new possibilities for interaction that blend the physical and digital worlds (Ullmer and Ishii 2000).

When reviewing the background to TUIs most people tend to refer to a paper by Hiroshi Ishii and Brygg Ullmer of MIT Media Lab, published in 1997 (Ishii and Ullmer 1997). They coined the phrase **tangible bits** as:

"...an attempt to bridge the gap between cyberspace and the physical environment by making digital information (bits) tangible." (Ishii and Ullmer 1997 p235)

In using the term 'bits' they are making a deliberate pun – we use the term bits to

1 See for example www.equator.ac.uk

refer to physical things, but in computer science, the term bits refers also to digital 'things' (ie binary digits). The phrase 'tangible bits' therefore attempts to consider both digital and physical things in the same way.

Tangible interfaces emphasise touch and physicality in both input and output. Often tangible interfaces are closely coupled to the physical representation of actual objects (such as buildings in an urban planning application, or bricks in a children's block building task). Applications range from rehabilitation, for example, tangible technologies that enable individuals to practise making a hot drink following a stroke (Edmans et al 2004) to object-based interfaces running over shared distributed spaces, creating the illusion that users are interacting with shared physical objects (Brave et al 1998).

The key issue to bear in mind in terms of the difference between typical desktop computer systems and tangible computing is that in typical desktop computer systems (so-called **graphical user interfaces** or **GUIs**) the mapping between the manipulation of the physical input device (eg the point and click of the mouse) and the resulting digital representation on the output device (the screen) is relatively indirect and loosely coupled. You are making one sort of movement to have a very different movement represented on screen. For example, if I use a mouse to select a menu item in a word processing application, I move the mouse on a horizontal surface (my physical desktop) in 2D in order to control a graphical pointer (the cursor) on the screen. The input is physical but the output is digital. In the case of a desktop computer, the mapping between input and output is fairly obviously decoupled because I have to move the mouse in 2D on a horizontal surface, yet the output appears on a vertical 2D plane. However, even if I use a stylus on a touchscreen (tablet or PDA), there is still a sense of decoupling of input and output because the output is in a different representational form to the input – ie the input is physical but the output is digital.

In contrast, **tangible user interfaces (TUIs)** provide a much closer coupling between the physical and digital – to the extent that the distinction between input and output becomes increasingly blurred. For example, when using an abacus, there is no distinction between 'inputting' information and its representation – this sort of blending is what is envisaged by tangible computing.

1.4 DEFINING SOME KEY CONCEPTS: TANGIBLE COMPUTING, UBIQUITOUS COMPUTING AND AUGMENTED REALITY

Tangible computing is part of a wider concept know as 'ubiquitous computing'. The vision of ubiquitous computing is usually attributed to Mark Weiser, late of Xerox PARC (Palo Alto Research Centre). Weiser published his vision for the future of computing in a pioneering article in Scientific American in 1991 (Weiser 1991). In it he talked about a vision where the digital world blends into the physical world and becomes so much part of the background of our consciousness that it disappears. He draws an analogy with print – text is a form of symbolic representation that is completely ubiquitous and pervasive in our physical environment (eg on

tangible interfaces emphasise touch and physicality in both input and output

billboards, signs, in shop windows etc). As long as we are skilled 'users' of text, it takes no effort at all to scan the environment and process the information. The text just disappears into the background and we engage with the content it represents, effortlessly. Contrast this with the experience of visiting a foreign country where not only do you not know the language, but the alphabet is completely unfamiliar to you – eg an English visitor in China or Saudi Arabia – suddenly the text is not only virtually impossible to decipher, it actually looks very strange to see the world plastered with what seem to you like hieroglyphs (which, of course, for the Chinese or Arabic reader, are 'invisible'). So, the vision of ubiquitous computing is that computing will become so embedded in the world that we don't notice it, it disappears. This has already happened today to some extent. Computers are embedded in light switches, cars, ovens, telephones, doorways, wristwatches.

In Weiser's vision, ubiquitous computing is 'calm technology' (Weiser and Brown 1996). By this, he means that instead of occupying the centre of the user's attention all the time, technology moves seamlessly and without effort on our part between occupying the periphery of our attention and occupying the centre. Ishii and Ullmer (1997) also make a distinction in ubiquitous computing between the foreground or centre of the user's attention and the background or periphery of their attention. They talk about the need to enable users both to 'grasp and manipulate' foreground digital information using physical objects, and to provide peripheral awareness of information available in the ambient environment. The first case is what most people refer to nowadays as tangible computing; the second case is what is generally referred to as 'ambient media' (or ambient intelligence, augmented space and so on). Both are part of the ubiquitous computing vision, but this review will focus only on the first case.

A third related concept in tangible computing is augmented reality (AR). Whereas in virtual reality (VR) the goal is often to immerse the user in a computational world, in AR the physical world is augmented with digital information. Paul Milgram coined the phrase 'mixed reality' to refer to a continuum between the real world and virtual reality (Milgram and Kishino 1994). AR is where, for example, video images of real scenes are overlaid with 3D graphics. In augmented virtuality, displays of a 3D virtual world (possibly immersive) are overlaid with video feeds from the real world.

Fig 1: The continuum of mixed reality environments (from Milgram and Kishino 1994).

As we shall see, many examples of so-called tangible computing have employed AR techniques and there are some interesting educational applications. Generally, the distinction between ubiquitous computing (or 'ubicomp'), tangible technology, augmented reality and 'ambient media' has been blurred or at least the areas overlap considerably. Dourish (2001), for example, refers to them all as tangible computing.

One of the earliest examples of tangible computing was Bricks, a 'graspable user interface' proposed by Fitzmaurice, Ishii and Buxton (Fitzmaurice et al 1995). This consisted of bricks (like LEGO bricks) which could be 'attached' to virtual objects, thus making the virtual objects physically graspable.

Fitzmaurice et al cite the following properties of graspable user interfaces. Amongst other things, these interfaces:

- allow for more parallel input specification by the user, thereby improving the expressiveness or the communication capacity with the computer
- take advantage of well developed, everyday, prehensile skills for physical object manipulations (cf MacKenzie and Iberall 1994) and spatial reasoning
- externalise traditionally internal computer representations
- afford multi-person, collaborative use.

We will return to this list of features of tangible technologies a little later on to consider their benefits or affordances for learning.

The sheer range of applications means it is out of this report's scope to adequately describe all tangible interface examples. In this review, we focus specifically on research in the area of tangible interfaces for learning.

1.5 WHY MIGHT TANGIBLES BE OF BENEFIT FOR LEARNING?

Historically children have played individually and collaboratively with physical items such as building blocks, shape puzzles and jigsaws, and have been encouraged to play with physical objects to learn a variety of skills. Montessori (1912) observed that young children were intensely attracted to sensory development apparatus. She observed that children used materials spontaneously, independently, repeatedly and with deep concentration. Montessori believed that playing with physical objects enabled children to engage in self-directed, purposeful activity. She advocated children's play with physical manipulatives as tools for development[2].

Resnick extended the tangible interface concept for the educational domain in the term 'digital manipulatives' (Resnick et al 1998), which he defined as familiar physical items with added computational power which were aimed at enhancing children's learning. Here we discuss physical and tangible interfaces – physical in that the interaction is based on movement and tangible in that objects are to be touched and grasped.

Figures 2 and 3 show two examples of recent applications of tangible technologies for educational use.

historically children have played with physical objects to learn a variety of skills

2 www.montessori-ami.org/ami.htm

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Fig 2: These images show the MagiPlanet application developed at the Human Interface Technology Laboratory New Zealand[3] (Billinghurst 2002).

Imagine a Year 5 teacher is trying to help her class understand planetary motion. They are standing around in a circle looking down on a table on which are marked nine orbital paths around the Sun. The children have to place cards depicting each of the planets in its correct orbit. As they do, they can see overlaid onto the cards a 3D animation of that planet spinning on its own axis and orbiting around the Sun. They can pick up the card and rotate it to see the surface of the planet in more detail, or its moons.

In Figure 2 the physical table is augmented with overlaid 3D animations that are tied to particular physical locations. These 3D animations provide visualisations appropriate to the meaning of the gestures used by the children to interact with the display. Instead of observing a pre-set animation, or using a mouse to direct an animation, the child's physical gestures themselves control the movement displayed. This example is called MagiPlanet and is one of a range of applications of AR developed by Mark Billinghurst and his group at the Human Interface Technology Laboratory New Zealand (Billinghurst 2002). The application of this technology for learning in UK classrooms is currently being explored by Adrian Woolard and his colleagues at the BBC's Creative R&D, New Media and Technology Unit[4] (Woolard 2004).

Figure 3 illustrates a tangible technology called 'I/O Brush', developed by Kimiko Ryokai, Stefan Marti and Hiroshi Ishii of MIT Media Lab's Tangible Media Group (Ryokai et al 2004). It is showcased at BETT 2005[5] as part of Futurelab's Innovations exhibition.

Tangibles have been reported as having the potential for providing innovative ways for children to play and learn, through novel forms of interacting and discovering and the capacity to bring the playfulness back into learning (Price et al 2003). Dourish (2001) discusses the potential of 'tangible bits', where the digital world of information is coupled with novel arrangements of electronically-embedded physical objects, providing different forms of user interaction and system behaviour, in contrast with the standard desktop.

3 www.hitlabnz.org/index.php?page=proj-magiplanet
4 www.becta.org.uk/etseminars/presentations/presentation.cfm?seminar_id=29&section=7_1&presentation_id=68&id=2608
5 www.bettshow.co.uk

Fig 3: These images show the 'I/O Brush' system developed by Kimiko Ryokai, Stefan Marti and Hiroshi Ishii of MIT Media Lab's Tangible Media Group[6] (Ryokai et al 2004).

Imagine a reception class is creating a story together. Their teacher has been reading from a storybook about Peter Rabbit during literacy hour over the past few weeks. Today they are trying to create an animated version of the story to show in assembly. They are using special paintbrushes which they can sweep over the picture of Peter Rabbit in the storybook. One child wants to draw a picture of Peter Rabbit hopping. He places the brush over the picture of Peter Rabbit and as he does so he makes little hopping motions with his hand. Then he paints the brush over the display screen that the class are working with and as he does a picture of the rabbit appears, hopping with the same movements that the child made when he painted over the storybook. The special paintbrush has 'picked up' the image, with its colours, together with the movements made by the child and transferred these physical attributes to a digital animation.

Familiar objects such as building bricks, balls and puzzles are physically manipulated to make changes in an associated digital world, capitalising on people's familiarity with their way of interacting in the physical world (Ishii and Ullmer 1997). In so doing, it is assumed that more degrees of freedom are provided

6 http://web.media.mit.edu/~kimiko/iobrush/

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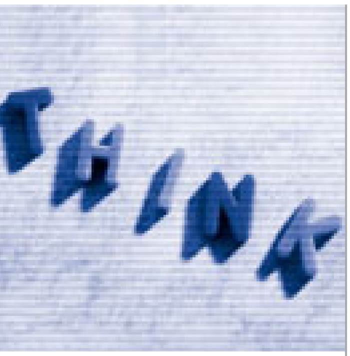

tangibles are thought to provide different kinds of opportunities for reasoning about the world

for exploring, manipulating and reflecting upon the behaviour of artefacts and their effects in the digital world. In relation to learning, such tangibles are thought to provide different kinds of opportunities for reasoning about the world through discovery and participation (Soloway et al 1994; Tapscott 1998). Tangible-mediated learning also has the potential to allow children to combine and recombine the known and familiar in new and unfamiliar ways encouraging creativity and reflection (Price et al 2003).

1.6 SUMMARY

While the computer is now a familiar object in most schools in the UK today, outside schools different approaches to interacting with digital information and representations are emerging. These can be considered under the term 'tangible interfaces' which attempt to overcome the difference between the ways we input and control information and the ways this information is represented. These 'tangible interfaces' may be of significant benefit to education by enabling, in particular, younger children to play with actual physical objects augmented with computing power. Tangible technologies are part of a wider body of developing technology known as 'ubiquitous computing' in which computing technology is so embedded in the world that it 'disappears'. The next section of this review will discuss the key attributes of these technologies in more detail before moving on, in Section 3, to discuss their potential educational applications.

2 TANGIBLE USER INTERFACES: NEW FORMS OF INTERACTIVITY

In this section of the review we offer a discussion of different ways in which researchers in the field have classified different types of tangible user interfaces. Each of the frameworks we describe emphasises slightly different properties of these interfaces, which present some potentially interesting ways to think about the educational possibilities of tangible technologies.

The conceptual frameworks we describe classify and analyse the properties of tangible technologies in terms of the human-computer interface. They share several characteristics in common, but differ in the type and number of dimensions and the degree to which they restrict or relax the space of possible technologies. All of them, albeit in different ways, incorporate a notion of **representational mapping**, ranging from tight coupling (iconic or indexical) to loose coupling (symbolic, arbitrary), whether in terms of the referents of an operation (physical or digital) or in terms of the nature of the referring expression (operation or manipulation) and its effects.

2.1 DIRECT MANIPULATION INTERFACES

Prior to the mid-80s, interaction with computers consisted of typing in special commands on a keyboard which resulted in the output of alphanumeric characters on a teleprinter or monitor, usually restricted to 24 rows of around 80 characters per line. In the mid-80s there was something of a revolution in personal computing. Instead of the previous command-line interfaces and keyboards, technologies were developed which enabled users to interact much more directly via a pointing device (the mouse) and a graphical user interface employing the now familiar desktop system with windows, icons and menus. The earliest example of such systems was the Star office application (Smith et al 1982), the precursor to Microsoft Windows and the Apple Macintosh operating systems.

Researchers in HCI called such systems 'direct manipulation' interfaces (Hutchins et al 1986; Shneiderman 1983). Hutchins et al (1986) analysed the properties of so-called direct manipulation interfaces and argued that there were two components to the impression the user could form about the directness of manipulating the interface: the degree to which input actions map onto output displays in an interactional or articulatory sense (psychologists refer to this as 'stimulus-response compatibility'), and the degree to which it is possible to express one's intentions or goals with the input language (semantic directness).

Articulatory directness refers to the extent to which the behaviour of an input action (eg moving the mouse) maps directly or otherwise onto the effects on the display (eg the cursor moving from one position to another). In other words, a system has articulatory directness to the extent that the form of the manipulation of the input device mirrors the corresponding behaviour on the display. This is a similar concept to stimulus-response compatibility (SRC) in psychology. An example of SRC in the physical world is where the motion of turning a car steering wheel maps onto the physical act of the car turning in the appropriate direction.

Semantic directness in Hutchins et al's analysis referred to the extent to which the meaning of a digital representation (eg an icon representing a wastebasket) mapped onto the physical referent in the real world (ie the referent of a wastebasket).

In terms of tangible user interfaces, similar analyses have been carried out concerning the mapping between (i) the form of physical controls and their effects and (ii) the meaning of representations and the objects to which they refer. We outline these analyses below.

2.2 CONTROL AND REPRESENTATION

In this section we consider the extension of Hutchins et al's analysis of direct manipulation to the design of tangible user interfaces.

As argued earlier, in traditional human-computer interfaces (ie graphical user interfaces or GUIs), a distinction is typically made between input and output. For example, the mouse is an input device and the screen is the output device. In tangible user interfaces this distinction disappears, in two senses:

1. In tangible interfaces the device that **controls** the effects that the user wants to achieve may be at one and the same time both input and output.
2. In GUIs the input is normally physical and the output is normally digital, but in tangible user interfaces there can be a variety of mappings of digital-to-physical **representations**, and vice versa. Ullmer and Ishii explain this by analogy with one of the earliest forms of computer, the abacus:

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"In particular, a key point to note is that the abacus **is not an input device**. The abacus makes no distinction between 'input' and 'output'. Instead, the beads, rods, and frame of the abacus serve as manipulable **physical representations** of abstract numerical values and operations. Simultaneously, these component artefacts also serve as physical controls for directly manipulating their underlying associations." (Ullmer and Ishii 2000)

The term **physical representation** is important here because Ullmer and Ishii wish to argue that it is the representational significance of a tangible device that makes it different to a mouse, for example, which has little representational significance (ie a mouse isn't meant to 'mean' anything). They explain the difference by describing an interface for urban planning where, instead of icons on a screen controlled by a mouse, physical models of buildings are used as physical representations of actual buildings – instead of manipulating digital representations, you are manipulating the models (physical representations) which then also manipulate a digital display (Underkoffler and Ishii 1999).

The key issue here is that instead of there being a distinction between the controlling device (the mouse) and the representation (images of a city on screen), in this sort of interaction the control device (physical models of buildings) is also a physical representation which is tightly coupled with an additional digital representation.

Ullmer and Ishii point out several characteristics of this sort of approach:

- physical representations are coupled to digital information
- physical representations embody mechanisms for interactive control
- physical representations are perceptually coupled to actively mediated digital representations
- the physical state of tangibles embodies key aspects of the digital state of the system.

Koleva et al (2003) develop Ullmer and Ishii's approach a bit further. They distinguish between different types of tangible interfaces in terms of 'degree of coherence' – ie whether the physical and the digital artefacts are seen as one common object that exists in both the physical and digital worlds, or whether they are seen as separate but temporally interlinked objects. The weakest level of coherence in their scheme is seen in general-purpose tools where one physical object may be used to manipulate any number of digital objects. An example is the mouse, which controls several different functions (eg menus, scrollbars, windows, check boxes) at different times. In computer science terms, these are referred to as 'time-multiplexed' devices (Fitzmaurice et al 1995). In contrast, one can have physical objects as input devices where each object is dedicated to performing one and only one function – these are referred to as space-multiplexed devices. An example in tangible computing is the use of physical 'buildings' in the Urp urban planning application of Underkoffler and Ishii (op cit).

Space-multiplexed devices are what one might call 'tightly coupled' in terms of mappings between physical and digital representations, whereas time-multiplexed devices are less tightly coupled. Unless one allows for this range of interface types, there would be a very small class of devices of interfaces that could count as tangible, and, in fact, many examples which claim to employ tangible user interfaces for learning do not lie on the strict, tightly coupled end of this continuum.

The strongest level of coherence (physical-digital coupling) in the scheme of Koleva et al is where there is the illusion that the physical and digital representations are the same object. An example in the world of tangible computing is the Illuminating Clay system (Piper et al 2002), where a piece of 'clay' can be manipulated physically and as a result a display projected onto its surface is altered correspondingly.

A second kind of distinction which Koleva et al make is in the nature (meaning) of the representational mappings between physical and digital. In the case of a **literal** or one-to-one mapping, any actions with the physical devices should correspond exactly to the behaviour of the digital object. In the case of a **transformational** mapping there is no such direct correspondence (eg placing a digital object on a particular location might trigger an animation).

2.3 CONTAINERS, TOKENS AND TOOLS

Another classification of tangible technologies is provided by Holmquist et al (1999). They distinguish between **containers**, **tokens**, and **tools**. They define **containers** as generic objects that can be associated with any types of digital information. For example, Rekimoto demonstrated how a pen could be used as a container to 'pick-and-drop' digital information between computers, analogous to the 'drag-and-drop' facility for a single computer screen (Rekimoto 1997). However, even though containers have some physical analogy in their functionality, they do not necessarily reflect physically that function nor their use – they lack natural 'affordances' in the Gibsonian sense (Gibson 1979; Norman 1988, 1999).

In contrast, **tokens** are objects that physically resemble the information they represent in some way. For example, in the metaDESK system (Ullmer and Ishii 1997)[7], a set of objects were designed to physically resemble buildings on a digital map. By moving the physical buildings around on the physical desktop, relevant portions of the map were displayed.

Finally, in Holmquist et al's analysis, **tools** are defined as physical objects which are used as representations of computational functions. Examples include the Bricks system referred to at the beginning of this review (Fitzmaurice et al 1995), where the bricks are used as 'handles' to manipulate digital information. Another example is the use of torches or flashlights to interact with digital displays as in the Storytent system[8] (Green et al 2002), described in more detail in Section 4.

2.4 EMBODIMENT AND METAPHOR

Fishkin (2004) provides a two-dimensional classification involving the dimensions 'embodiment' and 'metaphor'. By

7 http://tangible.media.mit.edu/projects/metaDESK/metaDESK.html
8 http://machen.mrl.nott.ac.uk/Challenges/Devices/torches.htm

embodiment Fishkin means the extent to which the users are attending to an object while they manipulate it. In terms of Weiser's notion of ubiquitous computing discussed previously (Weiser and Brown 1996), this is the dimension of central-peripheral attentional focus. At one extreme of Fishkin's dimension of embodiment, the output device is the same as the input device – examples include the Tribble system[9] (Lifton et al 2003) which consists of a 'sensate skin' which can react to being touched or stroked by changing lights on its surface, vibrating, etc. Another similar example is 'Super Cilia Skin'[10] (Raffle et al 2003). It consists of computer-controlled actuators that are attached to an elastic membrane. The actuators change their physical orientation to represent information in a visual and tactile form. Just like clay will deform if pressed, these surfaces act both as input and output devices.

Slightly less tight coupling between input and output in Fishkin's taxonomy is seen in cases where the output takes place **proximal** or near to the input device. Examples include the Bricks system (Fitzmaurice et al 1995) and a system called I/O Brush[11] (Ryokai et al 2004) referred to in the introduction to this review. This consists of a paintbrush which has various sensors for bristles which allow the user, amongst other things, to 'pick up' the properties of an object (eg its colour) and 'paint' them onto a surface.

In the third case of embodiment the output is 'around' the user (eg in the form of audio output) – what Ullmer and Ishii refer to as 'non-graspable' or ambient (Ullmer and Ishii 2000). Finally, the output can be **distant** from the input (eg on another screen).

Fishkin argues that as embodiment increases, the 'cognitive distance' between input and output increases. He suggests that if it is important to maintain a 'cognitive dissimilarity' between input and output 'objects' then the degree of embodiment should be decreased. This may be important in learning applications, for example if the aim is to encourage the learner to reflect on the relationships between the two.

The second dimension in Fishkin's framework is **metaphor**. In terms of tangible interfaces this means the extent to which the user's actions are analogous to the real-world effect of similar actions. At one end of this continuum the tangible manipulation has **no analogy** to the resulting effect – an extreme example is a command-line interface. An example they cite from tangible interfaces is the Bit Ball system (Resnick et al 1998) where squeezing a ball alters audio output.

In other systems an analogy is made to the physical appearance (visual, auditory, tactile) of the device and its corresponding appearance in the real world. In terms of GUIs this corresponds to the appearance of icons representing physical documents, for example. However, the actions performed on/with such icons have no analogy with the real world (eg crumpling paper). In terms of TUIs examples are where physical cubes are used as input devices where the particular picture on a face of a cube determines an operation (Camarata et al 2002).

9 http://web.media.mit.edu/~lifton/Tribble/
10 http://tangible.media.mit.edu/projects/Super_Cilia_Skin/Super_Cilia_Skin.htm
11 http://tangible.media.mit.edu/projects/iobrush/iobrush.htm

In contrast, other systems have analogies between **manipulations** of the tangible device and the resulting operations (as opposed to operands). Yet other systems combine analogies between the referents in the physical and digital worlds and the referring expressions or manipulations. For example, in GUIs the 'drag-and-drop' interface (eg dragging a document icon into the wastebasket) involves analogies concerning both the appearance of the objects (document, wastebasket) and the physical operation of dragging and dropping an object from the desktop into the wastebasket. An example in terms of TUIs is the Urp system described earlier (Underkoffler and Ishii 1999) where physical input devices resembling buildings are used to move buildings around a map in the virtual world.

Finally, Fishkin describes the other extreme of this continuum, where the digital system maps completely onto the physical system metaphorically. He refers to this as '**really direct manipulation**' (Fishkin et al 2000). An example from GUIs is the use of a stylus or light pen to interact with a touchscreen or tablet (pen-tablet interfaces), where writing on the screen results in altering the document directly. An example from TUIs that he gives is the Illuminating Clay system (Piper et al op cit).

2.5 SUMMARY

The dimensions highlighted in these frameworks are:

- **The behaviour of the control devices and the resulting effects:** a contrast is made between input devices where the form of user control is arbitrary and has no special behavioural meaning with respect to output (eg using a generic tool like a mouse to interact with the output on a screen), and input devices which have a close correspondence in behavioural meaning between input and output (eg using a stylus to draw a line directly on a tablet or touchscreen). This is what Hutchins et al (1986) refer to as articulatory correspondence. The form of such mappings may result in one-to-many relations between input and output (as in arbitrary relations between a mouse, joystick or trackpad and various digital effects on a screen), or one-to-one relations (as in the use of special purpose transducers where each device has one function).
- **The semantics of the physical-digital representational mappings:** this refers to the degree of metaphor between the physical and digital representation. It can range from being a complete analogy, in the case of physical devices resembling their digital counterparts, to no analogy at all.
- **The role of the control device:** this refers to the general properties of the control device, irrespective of its behaviour and representational mapping. So, for example, a control device might play the role of a container of digital information, a representational token of a digital referent, or a generic tool representing some computational function.
- **The degree of attention paid to the control device as opposed to that which it represents:** completely embodied systems are where the user's primary focus is on the object being manipulated rather than the tool being used to manipulate the object. This can be more or less affected by the extent of the metaphor used in mapping between the control device and the resulting effects.

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it is commonly believed that physical action is important in learning

Of course none of these dimensions or analytic frameworks are entirely independent, nor are they complete. The point is that there are at least two senses in which tangible user interfaces strive to achieve 'really direct manipulation':

1. In the mappings between the **behaviour** of the tool (physical or digital) which the user uses to engage with the object of interest.
2. In the mappings between the meaning or semantics of the represent**ing** world (eg the control device) and the represent**ed** world (eg the resulting output).

3 WHY MIGHT TANGIBLE TECHNOLOGIES BENEFIT LEARNING?

In this section we consider some of the research evidence from developmental psychology and education which might inform the design and use of tangibles as new forms of control systems, and in terms of the learning possibilities implied by the physical-digital representational mappings we have discussed in the previous section.

3.1 THE ROLE OF PHYSICAL ACTION IN LEARNING

It is commonly believed that physical action is important in learning, and there is a good deal of research evidence in psychology to support this. Piaget and Bruner showed that children can often solve problems when given concrete materials to work with before they can solve them symbolically – for example, pouring water back and forth between wide and narrow containers eventually helps young children discover that volume is conserved (Bruner et al 1966; Martin and Schwartz in press; Piaget 1953). Physical movement can enhance thinking and learning – for example Rieser (Rieser et al 1994) has shown how locomotion supports children in categorisation and recall in tasks of perspective taking and spatial imagery, even when they typically fail to perform in symbolic versions of such tasks.

So evidence suggests that young children (and indeed adults) can in some senses 'know' things without being able to express their understanding through verbal language or without being able to reflect on what they know in an explicit sense.

This is supported by research by Goldin-Meadow (2003), who has shown over an extensive set of studies how gesture supports thinking and learning. Church and Goldin-Meadow (1986) studied 5-8 year-olds' explanations of Piagetian conservation tasks and showed that some children's gestures were mismatched with their verbal explanations. For example, they might say that a tall thin container has a large volume because it's taller, but their gesture would indicate the width of the container. Children who produced these kinds of gestures tended to be those who benefited most from instruction or experimentation. The argument is that their gestures reflected an implicit or tacit understanding which wasn't open to being expressed in language. Goldin-Meadow also argues that gestures accompanying speech can, in some circumstances, reduce the cognitive load on the part of the language producer and, in other circumstances, facilitate parallel processing of information (Goldin-Meadow 2003).

Research has also shown that touching objects helps young children in learning to count – not just in order to keep track of what they are counting, but in developing one-to-one correspondences between number words and item tags (Alibali and DiRusso 1999). Martin and Schwartz (in press) studied 9 and 10 year-olds learning to solve fraction problems using physical manipulatives (pie wedges). They found that children could solve fraction problems by moving physical materials, even though they often couldn't solve the same problems in their heads, even when shown a picture of the materials. However, action itself was not enough – its benefits depended on particular relationships between action and prior knowledge.

Recent neuroscientific research suggests that some kinds of visuo-spatial transformations (eg mental rotation tasks, object recognition, imagery) are interconnected with motor processes and possibly driven by the motor system (Wexler 2002). Neuroscientific research also suggests that the neural areas activated during finger-counting, which is a developmental strategy for learning calculation skills, eventually come to underpin numerical manipulation skills in adults (Goswami 2004).

gesture supports thinking and learning

3.2 THE USE OF PHYSICAL MANIPULATIVES IN TEACHING AND LEARNING

There is a long history of the use of manipulatives (physical objects) in teaching, especially in mathematics and especially in early years education (eg Dienes 1964; Montessori 1917). There are several arguments concerning why manipulation of concrete objects helps in learning abstract mathematics concepts. One is what Chao et al (2000) call the 'mental tool view' – the idea that the benefit of physical materials comes from using the mental images formed during exposure to the materials. Such mental images of the physical manipulations can then guide and constrain problem solving (Stigler 1984).

An alternative view is what Chao et al call the 'abstraction view' – the idea that the value of physical materials lies in learners' abilities to abstract the relation of interest from a variety of concrete instances (Bruner 1966; Dienes 1964). However, the findings concerning the effectiveness of manipulatives over traditional methods of instruction are inconsistent, and where

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they are seen to be effective it is usually after extensive instruction and practice (Uttal et al 1997).

Uttal et al (op cit) are critical of the simple argument that manipulatives make dealing with abstractions easier because they are concrete, familiar and non-symbolic. They argue that at least part of the difficulty children may have with using manipulatives stems from the need to interpret the manipulative as a representation of something else. Children need to see and understand the relations between the manipulatives and other forms of mathematical expression – in other words, children need to see that the manipulative can have a symbolic function, that it can stand for something.

Understanding symbolic functions is not an all-or-nothing accomplishment developmentally. Children as young as 18 months to 2 years can be said to understand that a concrete object can have some symbolic function as seen, for example, in their use of pretence (eg Leslie 1987). However the ability to reason with systems of symbolic relations in order to understand particular mathematical ideas (eg to use Dienes blocks in solving mathematical problems) requires a good deal of training and experience. DeLoache has carried out extensive research on the development of 'symbol-mindedness' in young children (DeLoache 2004) and has shown that it develops gradually between around 10 months of age and 3 years, that even when children might be able to distinguish between an object as a symbol (eg a photograph, a miniature toy chair) and its referent (that which the photograph depicts, a real chair), they sometimes make bizarre errors such as trying to grasp the photograph in the book (DeLoache et al 1998; Pierroutsakos and DeLoache 2003) or trying to sit in the chair (DeLoache et al 2004).

understanding symbolic functions is not an all-or-nothing accomplishment developmentally

3.3 REPRESENTATIONAL MAPPINGS

In Section 2 we outlined Ullmer and Ishii's analysis of the mappings between physical representations and digital information. They introduced a concept they call 'phicons' (physical icons). In using this term they are careful to emphasise the representational properties of icons and distinguish them from symbols. In HCI usage generally the term icon has come to stand for any kind of pictorial representation on a screen. Ullmer and Ishii use the term phicon to refer to an icon in the Peircean sense. The philosopher Peirce distinguished between indices, icons and symbols (Project 1998), where an icon shares representational properties in common with the object it represents, a symbol has an arbitrary relationship to that which it signifies, and an index represents not by virtue of sharing representational properties but literally by standing for or pointing to, in a real sense, that which it signifies (eg a proper name is an index in this sense).

This is an interesting distinction to make in terms of the affordances of tangible interfaces for learning. Bruner made the distinction between 'enactive', 'iconic' and 'symbolic' forms of representation in his theory of learning (1966). He argued that children move through this sequence of forms of representation in learning concepts in a given domain. For example, a child might start by being able to group objects together according to a number of dimensions (eg size, colour, shape) – they are enacting their understanding of classification. If they can draw pictures of these groupings they are displaying an iconic understanding. If they can use verbal labels to represent the categories they are displaying a symbolic understanding. Iconic representations have a **one-to-one correspondence** with their objects they represent and they have some **resemblance** (in representational terms) to that which they represent. They serve as bridging analogies (cf Brown and Clement 1989) between an implicit sensorimotor representation (in Piagetian terms) and an explicit or articulated symbolic representation.

Piaget's developmental theory involved the transformation of initially sensorimotor representations (from simple reflexes to more and more controlled repetition of sensorimotor actions to achieve effects in the world), to symbolic manipulations (ranging from simple single operations to coordinated multiple operations, but operating on concrete external representations), to fully-fledged formal operations (involving cognitive manipulation of complex symbol systems, as in hypothetico-deductive reasoning). Each transition through Piagetian stages of cognitive development involved increasing explicitation of representations, gradually rendering them more and more open to conscious, reflective cognitive manipulation. Similarly, Bruner's theory of development (1966) also involved transitions from implicit or sensorimotor representations (which he terms 'enactive') to gradually more explicit and symbolic representations. The distinction, however, between Piaget's and Bruner's theories lies in the degree to which such changes are domain-general (for Piaget they were, for Bruner each new domain of learning involved transitions through these stages) and age-related or independent.

More recent theories from cognitive development also involve progressive 'explicitation' of representational systems – for example, Karmiloff-Smith's theory of representational re-description (1992) describes transitions in children's representations from implicit to more explicit forms. In her theory children start out learning in a domain (eg drawing, mathematics) by operating on solely external representations (similar to Bruner's enactive phase). At this level they have learned highly specific procedures that are not open to revision, conscious inspection or verbal report and are triggered by specified environmental conditions. Gradually these representations become more flexible and can be changed internally (for example, children gradually learn to generalise procedures and appear to operate with internal rules for producing behaviour). Finally the child is able to reflect upon his or her representations and is able, for example, to transfer rules or procedures across domains or modes of representation.

The representational transformations described by Piaget, Bruner and Karmiloff-Smith are also mirrored in another highly influential theory of learning – that of John Anderson – but in the reverse sequence. Anderson's theory of skill acquisition (Anderson 1993; Anderson and Lebiere 1998) describes the transitions from initial explicit or declarative representations that involve conscious awareness and control (learning facts or condition-action rules) to procedures which become more automated and implicit with practice. An example is in learning to drive, where rules of behaviour (eg depressing the clutch and moving the gear lever into position) are initially, for the novice driver, a matter of effortful recall and control and where it is

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a child is asked to explore the creation of the shape by moving her body

difficult to carry out several actions in parallel, to the almost unconscious carrying out of highly routine procedures in the expert driver (who can now move into gear, steer the car, carry on a conversation with a passenger and monitor other traffic).

The analysis of systems of representational mapping presented in the previous section on tangible interfaces has, at least on the face of it, some parallel with the analysis of representational transformations in theories of cognitive development and learning. It is interesting to try and draw some inferences for the design of tangible technologies for learning. One of the most influential educational researchers to attempt this is Seymour Papert.

3.4 MAPPING FROM PHYSICAL TO DIGITAL REPRESENTATIONS: THE ARGUMENT FOR LEARNING

Papert's theory of learning with technology was heavily influenced by his mentor, Jean Piaget. Papert is famous for the development of the Logo programming environment for children, which launched a whole paradigm of educational computing referred to, in his term, as 'constructionism' (Papert 1980)[12]. Papert's observation was that young children have a deep and implicit spatial knowledge based on their own personal sensorimotor experience of moving through a three-dimensional world. He argued that by giving children a spatial metaphor by manipulating another body (a physical robot or an on-screen cursor), they might gradually develop increasingly more explicit representations of control structures for achieving effects such as creating graphical representations on a screen. The Logo programming environment gave children a simple language and control structure for operating a 'turtle' (the name given to the on-screen cursor or physical robot). For example, the Logo command sequence:

```
TO SQUARE   :STEPS
REPEAT 4    [FORWARD  :STEPS
            RIGHT 90]
END
```

results either in a cursor tracing out a square on-screen or a robot moving around in a square on the floor (McNerney 2004). The idea was that this body-centred or 'turtle geometry' (Abelson and diSessa 1981) would enable children to learn geometric concepts more easily than previous more abstract teaching methods. McInerney puts it as follows:

"...rather than immediately asking a child to describe how she might instruct the turtle to draw a square shape, she is asked to explore the creation of the shape by moving her body; that is, actually 'walking the square'. Through trial and error, the child soon learns that walking a few steps, turning right 90°, and repeating this four times makes a square. In the process, she might be asked to notice whether she ended up about where she started. After this exercise, the child is better prepared to program the turtle to do the same thing... In the end, the child is rewarded by watching the turtle move around the floor in the same way as she acted out the procedure before." (McNerney 2004)

[12] The term 'constructionism' is based on Piaget's approach of 'constructivism' – the idea being that children develop knowledge through action in the world (rather than, in terms of the preceding behaviourist learning theories, through more passive response to external stimuli). By emphasising the construction of knowledge, Papert was stating that children learn effectively by literally constructing knowledge for themselves through physical manipulation of the environment.

Papert outlined a number of principles for learning through such activities. These included the idea that otherwise implicit reasoning could be made explicit (ie the child's own sensorimotor representations of moving themselves through space had to be translated into explicit conscious and verbalisable instructions for moving another body through space), that the child's own reasoning and its consequences were therefore rendered visible to themselves and others, that this fostered planning and problem solving skills, that therefore errors in the child's reasoning (literally, 'bugs' in programming terms) were made explicit and the means for 'debugging' such errors were made available, all leading to the development of metacognitive skills.

In earlier sections of this review we saw how various frameworks offered for understanding tangible computing referred to close coupling of physical and digital representations – the ideal case being 'really direct manipulation' where the user feels as if they are interacting directly with the object of interest rather than some symbolic representation of the object (Fishkin et al 2000). Papert's vision also involves close coupling of the physical and digital. However, crucial to Papert's arguments about the advantages of Logo, turtle geometry and 'body-centered geometry' (McNerney 2004) is the notion of reflection by the learner. The point about turtle geometry is not just that it is 'natural' for the learner to draw upon their own experience of moving their body through space, but that the act of instructing another body (whether it is a robot or a screen-based turtle) to produce the same behaviour renders the learner's knowledge explicit.

So 'really direct manipulation' may not be the best for learning. For learning, the goal of interface design may not always be to render the interface 'transparent' – sometimes 'opacity' may be desirable if it makes the learner reflect upon their actions (O'Malley 1992). There are at least three layers of representational mapping to be considered in learning environments:

- the representation of the learning domain (eg symbol systems representing mathematical concepts)
- the representation of the learning activity (eg manipulating Dienes blocks on a screen)
- the representation embodied in the tools themselves (eg the use of a mouse to manipulate on-screen blocks versus physically moving blocks around in the real world).

When designing interfaces for learning the main goal may not be the speed and ease of creation of a product – when the educational activity is embedded within the task one may not want to minimise the cognitive load involved. Research by Golightly and Gilmore (1997) found that a more complex interface produced more effective problem solving compared to an easier-to-use interface. They argue that, for learning and problem solving, the rules of transparent direct manipulation interface design may need to be broken. However, designs should reduce the learner's cognitive load for performing non-content related tasks in order to enable learners to allocate cognitive resources to understanding the educational content of the learning task. A similar point is made by Marshall et al (2003) in their analysis of tangible interfaces for learning.

the act of instructing another body to produce the same behaviour renders the learner's knowledge explicit

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effective learning involves being able to reflect upon, objectify and reason about the domain, not just to act within it

Marshall et al discuss two forms of tangible technologies for learning: **expressive** and **exploratory**. They draw upon a concept from the philosopher Heidegger, termed 'readiness-to-hand' (Heidegger 1996) later applied to human-computer interface design by Winograd and Flores (1986) and more recently to tangible interfaces by Dourish (2001). The concept refers to the way that when we are working with a tool (eg a hammer) we focus not on the tool itself but on the task for which we are using the tool (ie hammering in a nail). The contrast to 'readiness-to-hand' is 'present-at-hand' – ie focusing on the tool itself. Building on Ackermann's work (1996, 1999), they argue that effective learning involves being able to reflect upon, objectify and reason about the domain, not just to act within it. Marshall et al's notion of 'expressive' tangible systems refers to technologies which enable learners to create their own external representations – as in Resnick's 'digital manipulatives' (Resnick et al 1998), derived from the tradition of Papert and Logo programming. They argue that by making their own understanding of a topic explicit, learners can make visible clear inconsistencies, conflicting beliefs and incorrect assumptions.

Marshall et al contrast these expressive forms of technologies with exploratory tangible systems where learners focus on the way in which the system works rather than on the external representations they are building. Again, this is in keeping with Papert's arguments about the value of 'debugging' for learning. When their program doesn't run or the robot doesn't work in the way in which they expected, learners are forced to step back and reflect upon the program itself or the technology itself to try and understand why errors or bugs have occurred. In so doing, they become more reflective about the technology they are using. This line of argument is also in keeping with a situated learning perspective, where opportunities for learning occur when there are 'breakdowns' in 'readiness-to-hand' (Lave and Wenger 1991).

Marshall et al suggest that effective learning stems from cycling between the two modes of 'ready-to-hand' (ie using the system to accomplish some task) and 'present-to-hand' (ie focusing on the system itself). They also suggest two kinds of activity for using tangibles in learning; expressive activity is where the tangible represents or embodies the learner's behaviour (physically or digitally), and exploratory activity is where the learner explores the model embodied in the tangible interface that is provided by the designer (rather than themselves). The latter can be carried out either in some practical sense (eg figuring out how the technology works, such as the physical robot in LEGO/Logo – Martin and Resnick 1993), or in what they call a theoretical sense (eg reasoning about the representational system embodied in the model, such as the programming language in the case of systems like Logo).

A study by Sedig et al (2001) provides some support for the claims made by Marshall et al. The study examined the role of interface manipulation style on reflective cognition and concept learning. Three versions of a tangrams puzzle (geometrically shaped pieces that must be arranged to fit a target outline) were designed:

- Direct Object Manipulation (DOM) interface in which the user manipulates the visual representation of the objects

- Direct Concept Manipulation (DCM) interface in which the user manipulates the visual representation of the transformation being applied to the objects
- Reflective Direct Concept Manipulation (RDCM) interface in which the DCM approach is used with scaffolding.

Results from 44 11 and 12 year-olds showed that the RDCM group learned significantly more than the DCM group, who in turn learned significantly more than the DOM group.

Finally, research by Judy DeLoache and colleagues on the development of children's understanding of and reasoning with symbols provides another note of caution in drawing implications for learning from the physical-digital representational mappings in tangibles. Deloache et al (1998) argue that it cannot be assumed that even the most 'obvious' or iconic of symbols will automatically be interpreted by children as a representation of something other than itself. We might be tempted to assume that little learning is required for highly realistic models or photographs – ie symbols that closely resemble their referents. Even very young infants can recognise information from pictures. However, DeLoache et al argue that perceiving similarity between a picture and a referent is not the same as understanding the nature of the picture. She and her colleagues have shown over a number of years of research that problems in understanding symbols continue well beyond infancy and into childhood.

For example, young children (2.5 years) have problems understanding the use of a miniature scale model of a room as a model. They understand perfectly well that it is a model and can find objects hidden in the miniature room. However they have great difficulty in using this model as a clue to finding a corresponding real object hidden in an identical real room (DeLoache 1987). DeLoache argues that the problem stems from the dual nature of representations in such tasks. While the models serve as representations of another space, they are also objects in themselves – ie a miniature room in which things can be hidden. Young children find it difficult, she argues, to simultaneously reason about the model as a representation and as an interesting object partly because it is highly salient and attractive as an object in its own right (DeLoache et al op cit). She tested this theory by having children use photographs of the real room rather than the scale model and showed that children found that task much easier. This and other research leads DeLoache and colleagues to issue caution in assuming that highly realistic representations somehow make the task of mapping from the symbol to the referent easier. In fact, they argue, it can have the opposite effect to that which is desired. They argue that the task for young children in learning to use symbols is to realise that the properties of the symbols themselves are less important than what they represent. So making symbols into highly salient concrete objects may make their meaning less, not more, clear to young children.

Such cautions may also apply to the use of manipulatives with older children. For example, Hughes (1986) found that 5 – 7 year-olds had difficulties using small blocks to represent a single number or the simple addition problems. The difficulties the children had suggested that they didn't really understand how the blocks were

physical activity itself helps to build representational mappings

supposed to relate to the numbers and the problem. DeLoache et al (op cit) make a very interesting comment on the difference between the ways in which manipulatives are used in mathematics teaching in Japan and in North America:

"In Japan, where students excel in mathematics, a single, small set of manipulatives is used throughout the elementary school years. Because the objects are used repeatedly in various contexts, they presumably become less interesting as things in themselves. Moreover, children become accustomed to using the manipulatives to represent different kinds of mathematics problems. For these reasons, they are not faced with the necessity of treating an object simultaneously as something interesting in its own right and a representation of something else. In contrast, American teachers use a variety of objects in a variety of contexts. This practice may have the unexpected consequence of focusing children's attention on the objects rather than on what the objects represent." (Deloache et al 1998)

3.5 SUMMARY

In this section we have reviewed research from psychology and education that suggests that there can be real benefits for learning from tangible interfaces. Such technologies bring physical activity and active manipulation of objects to the forefront of learning. Research has shown that, with careful design of the activities themselves, children (older as well as younger) can solve problems and perform in symbol manipulation tasks with concrete physical objects when they fail to perform as well using more abstract representations. The point is not that the objects are concrete and therefore somehow 'easier' to understand, but that physical activity itself helps to build representational mappings that serve to underpin later more symbolically mediated activity after practise and the resulting 'explicitation' of sensorimotor representations.

However, other research has shown that it is important to build in activities that support children in reflecting upon the representational mappings themselves. DeLoache's work suggests that focusing children's attention on symbols as objects may make it harder for them to reason with symbols as representations. Marshall et al (2003) argue for cycling between what they call 'expressive' and 'exploratory' modes of learning with tangibles.

4 CASE STUDIES OF LEARNING WITH TANGIBLES

In this section we present case studies of educational applications of tangible technologies. We summarise the projects by highlighting the tangibility of the application and its educational potential. Where the technology has been evaluated, we report the outcomes. The studies presented here do not give complete coverage to the field but rather indicate current directions in the full range of applications.

4.1 DIGITALLY AUGMENTED PAPER AND BOOKS

In some examples of educational applications of tangibles, 'everyday technology' such as paper, books and other physical displays have been augmented digitally.

For example, Listen Reader (Back et al 2001) is an interactive children's storybook, which has a soundtrack triggered by moving one's hands over the book. The book has RFID tags embedded within it which sense which page is open, and additional sensors (capacitive field sensors) which measure an individual's position in relation to the book and adjust the sound accordingly.

A more familiar, commercially available system, is LeapPad®[13], which is also a digitally augmented book. Provided with the book is a pen that enables words and letters to be read out when a child touches the surface of each page. The book can also be placed in writing mode and children can write at their own pace. A whole library of activities and stories are available for various domains including reading, vocabulary, mathematics and science. The company claims that the educational programs available for this system are based on research findings in education. For example, their Language First! Program was designed based on findings from language acquisition research.

A recent EU-funded research and development project called Paper++[14] was aimed at providing digital augmentation of paper with multimedia effects. The project used real paper together with special transparent and conductive inks that could be detected with a special sensing device (a 'wand'). This made the whole surface of the paper active, without involving complex technology embedded in the paper itself. The project focused on the use of paper in educational settings and developed technologies to support applications such as children's books, materials for students, brochures and guides. Naturalistic studies were conducted of children in classrooms working with paper in which the researchers examined how subtle actions involving paper form an integral part of the process of collaboration between children. The researchers also compared the behaviour of children working with a CD-Rom, an ordinary book, and an augmented paper prototype, to examine how the different media affected children's working practices. They found that the paper enabled a more fluid and balanced sharing of tasks between the children (Luff et al 2003).

'everyday technology' such as paper, books and other physical displays have been augmented digitally

13 www.leapfrog.com
14 www.paperplusplus.net

CASE STUDIES OF LEARNING WITH TANGIBLES

as the user turns the page to reveal the marker they see an image overlaid onto the page of the book

In the KidStory project[15] we developed various tangible technologies aimed at supporting young children's storytelling (O'Malley and Stanton 2002; Stanton et al 2002; Stanton et al 2001b). For example, children's physical drawings on paper were tagged with barcodes which enabled them to use a barcode reader to physically navigate between episodes in their virtual story displayed on a large screen, using the KidPad storytelling software (Druin et al 1997).

In the Shape project a mixed reality experience was developed to aid children to discover, reason and reflect about historical places and events (Stanton et al 2003). An experience was developed which involved a paper-based 'history hunt' around Nottingham Castle searching for clues about historical events which took place there. The clues involved children making drawings or rubbings on paper at a variety of locations. The paper was then electronically tagged and used to interact with a virtual reality projection on a display called the Storytent (see Fig 4). A Radio Frequency ID (RFID) tag reader was positioned embedded in a turntable inside the tent. When placed on the turntable, each paper clue revealed an historic 3D environment of the castle from the location at which the clue was found. Additionally, 'secret writing' revealed the story of a character at this location by the use of an ultra-violet light placed over the turntable. The aim was to help visitors learn about the historical significance of particular locations in and around the medieval castle (no longer visible because it was burned down) by explicitly linking their physical exploration of the castle (using the paper clues) with a virtual reality simulation of the castle as it was in medieval times.

Fig 4: Child and adult in the Storytent with close-up of turntable (inset).

A final example of augmented paper is Billinghurst's MagicBook[16] (Billinghurst 2002; Billinghurst and Kato 2002). This employs augmented reality techniques to project a 3D visual display as the user turns the page. The system involves the user wearing a pseudo see-through head-mounted display (eg glasses). The MagicBook contains special symbols called 'fiducial markers' which provide a registration identity and spatial transformation derived using a small video camera mounted on the display. As the user turns the page to reveal the marker they see an image overlaid onto the page of the book. The system also enables collaboration with another user wearing identical equipment. The same technology was used in the MagiPlanet application illustrated at the beginning of this review.

15 www.sics.se/kidstory
16 www.hitl.washington.edu/magicbook/

4.2 PHICONS: THE USE OF PHYSICAL OBJECTS AS DIGITAL ICONS

The previous section gave examples of the use of paper and books which were augmented by a range of technologies (eg barcodes, RFID tags, video-based augmented reality) to trigger digital effects. In this section we review examples of the use of other physical objects such as toys, blocks and physical tags, to trigger digital effects.

In recent years a range of digital toys have been designed aimed at very young children. One example is the suite of Microsoft ActiMates™, starting in 1997 with Barney™ the purple dinosaur. The CACHET project (Luckin et al 2003) explored the use of these types of interactive toys (in this case, DW™ and Arthur™) in supporting collaboration. The toys are aimed at 4-7 year-olds and contain embedded sensors that are activated by children manipulating parts of the toy. The toys can also be linked to a PC and interact with game software to give help within the game. Luckin et al compared the use of the software with help on-screen versus help from the tangible interface and found that the presence of the toy increased the children's interactions with one another and with the facilitator.

Storymat (Ryokai and Cassell 1999) is a soft interactive play mat that records and replays children stories. The aim is to support collaborative storytelling even in the absence of other children. The space is designed to encourage children to tell stories using soft toys. These stories are then replayed whereby a moving projection of the toy is projected over the mat, accompanied by the associated audio. Thus children can activate stories other children have told and also edit them and create their own stories.

In the KidStory project referred to earlier, RFID tags were embedded in toys as story characters. When the props were moved near to the tag reader it triggered corresponding events involving the characters on the screen (Fig 5).

Fig 5: RFID tags were embedded in physical story props and characters and used to navigate digital stories in the KidStory project.

The Tangible Viewpoints system (Mazalek et al 2002) uses physical objects to navigate through a multiple viewpoint story. When an object (shaped like a chess pawn) is placed on the interaction surface, the story segments associated with its character's point of view are projected around it in the form of images or text.

Chromarium is a mixed reality activity space that uses tangibles to help children aged 5-7 years experiment and learn about colour mixing (Rogers et al 2002)[17].

[17] www.equator.ac.uk/Projects/Digitalplay/Chromarium.htm

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interactions with a digital image triggered a physical movement on an adjacent toy windmill

A number of different ways of mixing colour were explored, using a variety of physical and digital tools. For example, one activity allowed them to combine colours using physical blocks, with different colours on each face. By placing two blocks together children could elicit the combined colour and digital animations on an adjacent screen. Children were intuitively able to interact with the coloured cubes combining and recombining colours with immediate visual feedback. Another activity enabled children to use software tools, disguised as paintbrushes, on a digital interactive surface. Here children could drag and drop different coloured digital discs and see the resultant mixes. A third activity again allowed children to use the digital interactive surface, but this time their interactions with a digital image triggered a physical movement on an adjacent toy windmill. In their comparison of different types of these mappings between digital and physical representations, Rogers et al (2002) found the coupling of a familiar physical action with an unfamiliar digital effect to be effective in causing children to talk about and reflect upon their experience. The activities that enabled reversibility of colour mixing and immediate feedback were found to support more reflective activity, in particular the physical blocks provided a wider variety of physical manipulation and encouraged children to explore.

4.3 DIGITAL MANIPULATIVES

The examples in the previous sections involved the use of physical objects to trigger digital augmentations. In this section we focus on a number of examples of the use of physical devices which have computational properties embedded in them.

Resnick's group at MIT's Media Lab have built on Papert's pioneering work with Logo to develop a suite of tangible technologies dubbed 'digital manipulatives' (Resnick et al 1998). The aim was to enable children to explore mathematical and scientific concepts through direct manipulation of physical objects. Digital manipulatives are computationally enhanced versions of toys enabling dynamics and systems to be explored. This work began with a collaboration with the LEGO toy company to create the LEGO/Logo robotics construction kit (Resnick 1993) by which children can create Logo programs to control LEGO assemblies. The kit consists of motors and sensors and children use Logo programs to control the items they build.

The next generation of these digital manipulatives was Programmable Bricks (P-Bricks) (Resnick et al 1996). These bricks contain output ports for controlling motors and lights, and input ports for receiving information from sensors (eg light, touch, temperature). As with LEGO/Logo, programs are written in Logo and downloaded to the P-Brick, which then contains the program and is autonomous. These approaches are commercially available under the LEGO Mindstorms brand[18].

Crickets (Resnick et al 1998) were another extension but this time much smaller and with more powerful processors and a two-way infrared capability. These Crickets have been used, together with an accelerometer and coloured LEDs to

[18] http://mindstorms.lego.com

create the BitBall – a transparent rubbery ball. BitBalls have been used in scientific investigations with undergraduates and children in learning kinematics. For example, BitBalls can be thrown up into the air and can store acceleration data which can then be viewed graphically on a screen. Children as young as 10 years old used programmable bricks and Crickets to build and program robots to exhibit chosen behaviours. Crickets have been used by children to create their own scientific instruments to carry out investigations (Resnick et al 2000). For example, one girl built a bird feeder with a sensor attached so that when the bird landed to feed, the sensor triggered a photo of the bird to be taken. The girl could then see all the birds that had visited the feeder while she was away.

Curlybot (Frei et al 2000) is a palm-sized dome-shaped two-wheel toy that can record and replay physical motion. A child presses a button to record the movement of Curlybot and then presses a button to indicate recording has finished. The replay facility then enables the child to replay the motion and Curlybot repeats the action at the same speed and with the same pauses and motion. Curlybot can also be used with a pen attached to leave a trail as it moves. The authors highlight Curlybot as an educational tool encompassing geometric design, gesture and narrative.

More recently, Raffle et al produced Topobo (Raffle et al 2004), a 3D 'constructive assembly system' which is aimed at helping children to understand behaviours of complex systems. Topobo is embedded with kinetic memory – the ability to record and play back physical motion. By snapping together a combination of static and motorised components, children can assemble dynamic biomorphic figures, such as animals, and animate them by pushing, pulling and twisting them, and observe the system play back those motions. The designers argue that Topobo can be used to help children learn about dynamic systems.

The Telltale system[19] is a technology-enhanced language toy which is said to aid children in literacy development (Ananny 2002). It consists of a caterpillar-like structure and children can record a short audio clip in each segment of the body and can rearrange each segment to alter the story. Annany found that Telltale's segmented interface enabled children to produce longer and more linguistically elaborate stories than with a non-segmented interface.

StoryBeads (Barry et al 2000) are tangible/wearable computing elements designed to enable the construction of stories by allowing users to trade stories through pieces of images and text. The beads communicate by infrared and can beam items from bead to bead or can be traded in order to construct and share narratives.

Triangles (Gorbet et al 1998) were used as a tangible interface for exploring stories in a non-linear manner. Triangles are interconnecting physical shapes with magnetic edges. Each triangle contains a microprocessor which can identify when it is connected to another. Triangles have been used for a range of applications including storytelling. Audio, video and still images can be captured and stored within the triangles. The three-sided nature of

BitBalls can be thrown up into the air and can store acceleration data which can then be viewed graphically on a screen

[19] http://web.media.mit.edu/~ananny/thesis.html

triangles allows the user to take different paths through the story space. The software records users' interactions and enables the triggering of time sensitive events.

Thinking Tags (Borovoy et al 1996; Colella 2000; Resnick and Wilensky 1997) are electronic badges which employ similar technology to communicate data between themselves via infrared. They have been used to create participatory simulations of the spread of a virus (Colella 2000). The technology has also been used to create genetics simulations for understanding inheritance (MacKinnon et al 2002).

The Ambient Wood (Price et al 2003; Rogers et al in press; Rogers et al 2002a; Rogers et al 2002b) project consisted of groups of children using mobile technologies outdoors. The aim was to create a novel learning experience to support scientific enquiry about the biological processes taking place in a wood. Pairs of children explored a woodland area using two styles of mobile device that presented digital information triggered by the immediate surrounding environment, and allowed further data to be captured according to the children's exploration. Children then used a tangible interface consisting of tokens made from the images they had received within the wood, in order to reflect on their findings. Within a den in the woodland, physical tokens were used as a reflection tool. The combination of these tokens caused digital reactions on screen concerning the relationships within the habitat. At a later date, back in the classroom, children used these tokens to build a food web based on the items and relationships they had learned about in the wood (see Fig 6).

Fig 6: Using RFID tags as tokens representing flora and fauna found in the Ambient Wood being used to interact with a table-top display back in the classroom.

Another example of using tangibles for storytelling was a project called Hunting the Snark – a collaborative adventure game designed within the Equator project[20]. The Snark was based on the elusive fictitious creature in Lewis Carroll's poem (Carroll 1962/1876). In this game children were given different technologies to try to discover something about the Snark's appearance, personality and preferences. In one example children were given toy food made from coloured clay, in which were embedded RFID tags. When they dropped these tags into a 'well' (a physical chute containing a tag reader) the display at the bottom of the well showed a short video clip of the Snark's smile or grimace (depending on whether it liked the food or not) and they heard a corresponding sound of laughter or disgust. The aim was for children to collect instances of the Snark's preferences in order to build up categories of its feeding behaviour. Another tangible technology used in the game involved a PDA and ultra-sonic tracking to create a Snooper.

20 www.equator.ac.uk

As the children moved the Snooper around the room they could discover hidden food tokens which they could then try out in the well. The PDA displayed an image of the food token on the display as it was moved near to the location of the hidden tag. These and other technologies were evaluated with 6 and 7 year-olds hunting the Snark in pairs (Price et al 2003).

4.4 SENSORS AND DIGITAL PROBES

This section describes a range of tangible devices which are based on physical tools which act as sensors or probes of the environment (eg light, colour, moisture).

A device for tangible storytelling involves the use of ordinary flashlights or torches to interact with a display. For example the Storytent (Green et al 2002) used flashlights to manipulate objects on a tent which had a 3D virtual world displayed on it. The same technology was used in a different application within the Shape project mentioned earlier to trigger audio clips on the wall of the underground caves in Nottingham Castle, enabling users to play sequences of such audio clips to hear about the history of the caves as it happened at the very location where they shone the flashlight (Ghali et al 2003)[21]. A third example of the use of flashlights as tangible technologies was to interact with a digital Sandpit – a floor projection showing virtual 'sand'. As users collaboratively shone their flashlights on the sand it burned a virtual hole through the surface to reveal images beneath, telling the history of Nottingham Castle (Fraser et al 2003).

Fig 7: A torch being used to interact with a display in the Shape project.

Another example of using physical tools to interact with digital objects comes from the KidStory project mentioned earlier, in which pressure pads on the floor were used to create a 'magic carpet' for children to navigate collaboratively through their story in the 3D virtual world (Stanton et al 2001a).

I/O Brush (Ryokai et al 2004) is a drawing tool for young children aged 4 and over. The I/O Brush is modelled on a physical paintbrush but in addition has a small video camera with lights and touch sensors embedded inside it. The aim is to get the children thinking about colours and textures in the way an artist might.

a device for tangible storytelling involves the use of ordinary flashlights or torches to interact with a display

21 www.equator.ac.uk/Challenges/Devices/torches.htm

children can move the brush over any physical surface and pick up colours and textures and then draw with them on canvas

Children can move the brush over any physical surface and pick up colours and textures and then draw with them on canvas. The authors found that when the I/O brush was used in a kindergarten class, children talked explicitly about patterns and features available in their environment.

The SENSE project (Tallyn et al 2004) has been exploring the potential of sensor technologies to support a hands-on approach to learning science in the school classroom. Children at two participating schools designed and used their own pollution sensors within their local environment. The technology consisted of a PDA and carbon monoxide pollution sensor. The sensor was coloured differently on each side so that the direction in which the sensor was facing would be evident when children later inspected video data of the sensor in use. Children captured their own sensor data using this device, which was downloaded to additional visualisation technologies to help them analyse their data and to understand it in the context of similar data gathered by scientists carrying out related research (Equator Environmental e-Science project[22]).

In the Ambient Wood project mentioned earlier (Price et al 2003; Rogers et al in press; Rogers et al 2002a; Rogers et al 2002b) groups of children used mobile technologies (PDAs) outdoors to support scientific enquiry about the biological processes taking place in a wood. One of the devices used (a probe tool) contained sensors enabling measurement of the light and moisture levels within the wood. A small screen was also provided which displayed the readings using graphical visualisations. Analysis of the patterns of interaction amongst the children showed that the technologies encouraged active exploration, the generation of ideas and the testing of hypotheses about the ecology of the woodland.

[22] www.equator.ac.uk

4.5 SUMMARY

We have very briefly reviewed a number of examples of tangible technologies which have been designed to support learning activities. We have discussed these under four headings: digitally augmented paper, physical objects as icons (phicons), digital manipulatives and sensors/probes.

The reason for treating digital paper as a distinct category is to make the point that, rather than ICT replacing paper and book-based learning activities, they can be enhanced by a range of digital activities, from very simple use of cheap barcodes printed on sticky labels and attached to paper, to the much more sophisticated use of video tracing in the augmented reality examples. However, as Adrian Woolard and his team at the BBC have shown, real classrooms can use AR technology very effectively, without the need for special head-mounted displays to view the augmentation. He and his team have worked with teachers using webcams and projectors to overlay videos and animations on top of physical objects. Even something as simple as projecting a display on top of paper, or on a tabletop with physical objects, could be used as an effective technique for getting children to see the relationships between objects and representations they create and manipulate in the physical world, and what happens in the computational world.

SUMMARY AND IMPLICATIONS FOR FUTURE RESEARCH, APPLICATIONS, POLICY AND PRACTICE

Although many of the technologies reviewed in the section on 'phicons' involved fairly sophisticated systems, once again, it's possible to imagine quite simple and cheap solutions. For example, barcode tags and tag readers are relatively inexpensive. Tags can be embedded in a variety of objects – we have even experimented with baking them in clay for the Equator Snark project – they still worked! The only slightly complex aspect is some programming to make use of the data generated by the tag reader.

Digital manipulatives have been used over a number of years in classrooms in the form of Logo and Roamer, for example. The more advanced toolkits available with such systems as the Mindstorms robotics kits, with their various kinds of sensors, could be used in teaching and learning with older age groups and across the curriculum.

Finally, sensors and digital probes have also had a long history of use in UK classrooms, especially in science, in the form of data-logging systems. The increasing accessibility of PDAs and technologies such as GPS make it feasible to consider more mobile and ubiquitous use of sensor-based systems. Teachers could even think about using children's own mobile phones as 'probes' to log information and share it in the classroom, especially with the availability of camera phones.

5 SUMMARY AND IMPLICATIONS FOR FUTURE RESEARCH, APPLICATIONS, POLICY AND PRACTICE

In Section 1 of this review we introduced the concepts of tangible interfaces, ubiquitous computing and augmented reality. We also provided a couple of specific examples of two forms of tangibles technology: the MagiPlanet system, which uses augmented reality to overlay video on physical objects, and the I/O Brush system which uses a physical object to 'pick up' properties of the world and interact with digital representations of them.

We then considered in more detail in Section 2 the various interactional properties of tangible technology for control of representations and for mappings between forms of representations (physical and digital). Although researchers have used different terminologies and structured the design space in different ways, each of the frameworks presented in Section 2 (Ullmer and Ishii's concepts of control and representation, Holmquist et al's concepts of containers, tokens and tools, Fishkin's concepts of embodiment and metaphor) is an attempt to deal explicitly with the interaction metaphors embodied in (i) the manipulation (operation) of tangible devices and (ii) the mappings between forms (appearance) of physical and digital representations.

In Section 3 we reviewed some of the research evidence from psychology and education concerning claims made for physical manipulatives. For example, people have argued that physical manipulatives are beneficial for learning because:

the increasing accessibility of PDAs make it feasible to consider more mobile and ubiquitous use of sensor-based systems

SUMMARY AND IMPLICATIONS FOR FUTURE RESEARCH, APPLICATIONS, POLICY AND PRACTICE

- physical action is important in learning – children can demonstrate knowledge in their physical actions (eg gesture) even though they cannot talk about that knowledge
- concrete objects are important in learning – eg children can often solve problems when given concrete materials to work with even though they cannot solve them symbolically or even when they cannot solve them 'in their heads'
- physical materials give rise to mental images which can then guide and constrain future problem solving in the absence of the physical materials
- learners can abstract symbolic relations from a variety of concrete instances
- physical objects that are familiar are more easily understood by children than more symbolic entities.

In addition, the following claims have been made for tangible interfaces and digital manipulatives:

- they allow for parallel input (eg two hands) improving the expressiveness or the communication capacity with the computer
- they take advantage of well developed motor skills for physical object manipulations and spatial reasoning
- they externalise traditionally internal computer representations
- they afford multi-person, collaborative use
- physical representations embody a greater variety of mechanisms for interactive control
- physical representations are perceptually coupled to actively mediated digital representations
- the physical state of the tangible embodies key aspects of the digital state of the system.

> if physical objects are made too 'realistic' they can actually prevent children learning about what the objects represent

5.1 IMPLICATIONS FOR DESIGN AND USE

Although there is evidence that, for example, physical action with concrete objects can support learning, its benefits depend on particular relationships between action and prior knowledge. Its benefits also depend on particular forms of representational mapping between physical and digital objects. For example, there is quite strong evidence suggesting that, particularly with young children, if physical objects are made too 'realistic' they can actually prevent children learning about what the objects represent.

Other research reviewed here has also suggested that so-called 'really direct manipulation' (Fishkin et al 2000) may not be ideal for learning applications where often the goal is to encourage the learner to reflect and abstract. This is borne out by research showing that 'transparent' or really easy-to-use interfaces sometimes lead to less effective problem solving. Sometimes more effort is required for learning to occur, not less. However, it would be wrong to conclude that interfaces for learning should be made difficult to use – the point is to channel the learner's attention and effort towards the goal or target of the learning activity, not to allow the interface to get in the way. In the same vein, Papert argued that allowing children to construct their own 'interface' (ie build robots or write programs) focused the child's attention on making their implicit knowledge explicit. Others (Marshall et al 2003) support this idea and argue that effective learning should involve both expressive activity, where the tangible represents or embodies the learner's behaviour (physically or digitally), and exploratory activity, where the learner explores the model embodied in the tangible interface.

Finally, some implications for design and use of tangibles could be drawn from research on multiple representations in cognitive science. Ainsworth (Ainsworth 1999; Ainsworth et al 2002; Ainsworth and VanLabeke 2004) has carried out research on the use of multiple representations (eg text, graphics, animations) across a number of domains. She argues that the use of more than one representation can support learning in several different ways. For example, multiple representations can present complementary information, or they can constrain interpretations of each other, or they can support the identification of invariant aspects common to all representations and support abstraction. The research on the design of tangibles for learning has not so far drawn on research on multiple representations, but it is clearly potentially relevant and important.

5.2 IMPLICATIONS FOR POLICY AND PRACTICE

Many of the technologies reviewed here are still in early prototype form and not readily available for the classroom. However some of them are – Logo and Roamer have been used for many years now in primary classrooms – and some of them are potentially available now with a bit of programming effort (eg barcodes, RFID tags). Even the augmented reality software is available as a public domain toolkit[23] and can be used together with ordinary cameras or webcams and projectors to create effective augmented reality demonstrations for children – as seen in the innovative work by Adrian Woolard and colleagues at the BBC Creative R&D. Data-logging and sensors have been used for many years in secondary school science. New portable technologies such as PDAs extend the flexibility of such systems to create potentially powerful mobile learning environments for use outside of the classroom.

Even if the technologies aren't yet available, the pedagogy underlying these approaches can be used as a source for ideas in thinking about using ICT in teaching and learning various subjects. Especially in early years there is a need to recognise that younger children may not understand the representational significance of the objects they are asked to work with in learning activities (whether computer-based or not). They need scaffolding in reasoning about the relationship between the properties of an object (or symbol on the screen) and the more abstract properties they represent.

It is hoped that teachers might also take inspiration from the whole idea of technology-enhanced learning moving beyond the desktop or classroom computer by, for example, making links between ICT-based activities and other more physical activities. For example, interactive whiteboards are appealing because teachers can use them in familiar ways for whole class teaching. But they

[23] www.hitl.washington.edu/research/shared_space/download/

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new forms of assessment are needed to reflect the potential of these new technologies for learning

have much more potential than just being slightly enhanced versions of PowerPoint. Children could be encouraged to interact actively with whiteboard sessions by collecting their own data for presentation (eg via mobile phones, digital cameras). Physical displays around the classroom might be linked to digital displays by, for example, camera phones or digital cameras. Children could be encouraged to simulate screen-based activities with physical models, either on paper or using 3D objects. Digital displays could be projected in more imaginative ways than just the traditional vertical screen. For example, projecting onto the floor would enable children to sit in a circle around the shared screen. The display could be combined with the use of physical objects and, using some 'wizardry', teachers might make some changes to the display by manipulating the mouse or keyboard 'behind-the-scenes'. Displays could also be projected onto tabletops, over, say, paper which children are working with. Such arrangements not only enable the links between computer-based and non computer-based representations to be made more explicit for children, but the social or collaborative arrangement also changes in interesting ways.

In terms of policy, ICT is already integrated into teaching across the curriculum, but more encouragement might be given to teachers in terms of incorporating everyday technologies (eg mobile phones) into classroom-based ICT activities (rather than seeing them as competing with school-based activities). The importance of physical (kinaesthetic) and multisensory activities is also increasingly recognised, especially in primary years. However this development is happening without regard to the use of ICT. This review provides some suggestions, it is hoped, for seeing how physical and digital activities could be more integrated.

More research is needed on the benefits of tangibles for learning – so far the evaluation of these technologies has been rather scarce. More effort is also needed to translate some of the research prototypes into technologies and toolkits that teachers can use without too much technical knowledge. Teachers also need training in the use of non-traditional forms of ICT and how to incorporate them into teaching across the curriculum. And finally, new forms of assessment are needed to reflect the potential of these new technologies for learning.

GLOSSARY

Affordance a term first introduced by JJ Gibson, who took an ecological approach to the study of perception. The basic concept is that certain physical properties of objects (eg the surface of a table) 'naturally' suggest what they can be used for (eg supporting objects placed upon them)

Ambient intelligence a term often used to refer to computation that is embedded in the world around us. When the term 'intelligent' is used, it usually means automatic. An example is the use of light, heat or motion sensors in a room that may control heating or lighting depending on who is in the room or what they are doing

Ambient media similar to ambient intelligence, this refers to a range of media (eg sound, light) that can be used to automatically detect changes in the environment and alter other aspects of the environment accordingly

AR (Augmented Reality) this term refers to the use of digital information to augment physical interaction. An example is the projection of video displays onto 3D physical objects

Articulatory directness a concept from an analysis of 'direct manipulation' interfaces by Hutchins, Hollan and Norman (1986) which refers to the degree of directness between the behaviour of an input device and the resulting output

Augmented spaces this term refers to the digital augmentation (eg by video or audio projections) of physical environments (eg a physical desktop)

Augmented virtuality the use of, for example, video projections of physical spaces into 3D virtual environments

Barcode reader a device used to detect a barcode symbol

Body-centred geometry a concept from Papert's vision of Logo where children are taught to reason about geometry from their own actions in the physical world (eg turning in a circle)

Breakdown a concept borrowed from Heidegger referring to a break between paying attention to the object of a tool (eg the nail one is hammering) and the tool itself (eg the hammer)

Bridging analogy the use of an analogy to bridge between one representation and another, especially where the mapping between the two representations is not obvious to the learner – from Brown and Clement (1989)

Bug an error in a computer program

Calm technology a concept from Mark Weiser (1991) referring to the idea of technology disappearing into the background of the user's attentional focus

Command-line interface a term used to refer to computer systems where a programming language is needed to interact with the system – usually used to refer to systems before the advent of graphical user interfaces

Constructionism a term usually attributed to Seymour Papert referring to the educational benefits of the learner constructing a physical representation of an abstract concept, as in the Logo programming environment (see also constructivism)

Constructivism a concept usually attributed to Jean Piaget referring to the idea that learners actively construct their own knowledge (as opposed to passively assimilating knowledge from another)

GLOSSARY

Container in the context of tangible user interfaces this means the use of a control device to 'contain' some digital properties, as in 'pick-and-drop' interfaces.

Debugging the process of discovering and eradicating errors in computer programs (see 'bug')

Declarative representation usually refers to the way in which factual knowledge (knowing that) is stored in human memory. Used in contrast to procedural knowledge (knowing how)

Digital manipulative a term coined by Mitchell Resnick and colleagues (1998) to refer to the digital augmentation of physical manipulatives such as Dienes blocks

Digital toys physical toys that can be manipulated to produce digital effects (eg make sounds, trigger animations on a computer screen)

Direct manipulation a concept coined in the mid-80s by Ben Schneiderman and others to refer to the use of physical input devices such as mice to interact with graphical displays. Also refers to a theory concerning direct physical-digital mappings in human-computer interaction (Hutchins et al 1986)

Drag-and-drop a term used to refer to an interface technique where one uses an input device (usually a mouse) to select and 'drag' a screen-based object from one location to another

Embodiment a term used in tangible computing to refer to the degree to which an interaction technique (eg manipulation of a digital object) carries with it an impression of being a physical (as opposed to digital) activity

Enactive a term used by Jerome Bruner to refer to a sensorimotor representation – eg a child who is physically counting out from an array of objects is said to be enacting the process of counting

Explicitation a term used to refer to the transformation of an implicit or tacit representation (eg procedural knowledge of counting) to one that is open to verbalisation and reflection

Fiducial markers special graphical symbols overlaid on physical displays (eg paper) that are used by vision-based systems to register location and identity in order to project augmented reality displays

GUI Graphical User Interface

HCI Human-Computer Interaction – an interdisciplinary research field focused on the design and evaluation of ICT systems

Head-mounted display a projection system worn by a user – can be a helmet that completely immerses the user or a see-through display (eg glasses) that allows the user to see both the real world and the projected world at the same time

ICT Information and Communication Technology

Input device A physical device used to interact with a computer system

Interactive whiteboard a display that uses a touchscreen for direct input with a stylus or other pointing device (also referred to as a 'smartboard')

LED Light Emitting Device (eg display on a digital watch)

Manipulative a term used to refer to the use of physical objects such as Dienes blocks in teaching mathematics

Mixed reality A term used to refer to the merging of physical and digital representations

Output device usually refers to a screen or monitor in traditional graphical user interfaces, but can also refer to audio speakers, force-feedback devices, tactile displays

Palmtop a small hand-held device usually with a touchcreen display that can be manipulated with a stylus (see PDA)

PDA Personal Digital Assistant (eg Palm, iPaq)

Pick-and-drop an interaction technique where information from one computer system is 'picked up' by a device (eg a pen or stylus) and 'dropped onto' another computer system – by analogy with 'drag-and-drop' techniques

Prehensile skills grasping skills needed to hold and manipulate objects with the hands

Present-at-hand a term borrowed from the philosopher Heidegger to refer to an attentional focus on the tool itself (eg a hammer) rather than the object of interest (eg the nail)

Readiness-to-hand a term borrowed from the philosopher Heidegger to refer to an attentional focus on the object of interest (eg the nail) rather than the tool being used (eg a hammer) (see 'present-at-hand')

RFID tags Radio Frequency Identification tags – eg security tags on store goods

Semantic directness a term used by Hutchins, Hollan and Norman (1986) to refer to the degree to which an interface metaphor (eg a wastebasket icon) resembles the operation the user has in mind (eg deleting a document)

Sensorimotor representation a term derived from Piaget's theory of intellectual development referring to a non-symbolic cognitive representation based in low-level perception and action rather than 'higher-level' cognition

Space-multiplexed with space-multiplexed input, each function to be controlled has a dedicated transducer, each occupying its own space. For example, a car has a brake, clutch, accelerator, steering wheel, and gear stick which are distinct, dedicated transducers controlling a single specific task (see 'time-multiplexed')

Stimulus-response compatibility the extent to which what people perceive is consistent with the actions they need to take – eg the extent to which the arrangement of 'up' and 'down' arrow keys on a keyboard is spatially compatible with their meaning or effects on the screen rather than being side-by-side

Tangible bits a term used to refer to tangible (physical, graspable) digital information

Tangible computing a term used to refer to tangible (physical, graspable) computing

Tangible media a term used to refer to tangible (physical, graspable) media

Techno-romantic the view that some uses of ICT can transform learning in ways not possible without technology

Time-multiplexed time-multiplexing input uses one device to control different functions at different points in time. For instance, the mouse uses time-multiplexing as it controls functions as diverse as menu selection, navigation using the scroll widgets, pointing, and activating 'buttons' (see 'space-multiplexed')

Token a term used in tangible user interfaces to refer to a physical representation (instantiation) of a digital object

Touchscreen a screen which can detect physical contact (eg the touch of a finger) with its surface

Transducer something that transforms one form of information into another

Transparent interface used to refer to interfaces that are so easy to use they are 'obvious' – usually contrasted with 'opaque' or hard-to-use interfaces

TUI Tangible User Interface (see 'GUI – Graphical User Interface')

Turtle a term used in Logo programming to refer to a (usually screen-based) cursor that the learner 'programs' to move around. It can also be a physical robot, as in the Roamer system

Turtle geometry the use of Logo to create (and teach about) geometric shapes

Ubiquitous computing a term used to refer to technology that has become so embedded in the everyday world it 'disappears' – usually contrasted with desktop computing

Ultra-sonic tracking the use of ultra-sound to track the position of objects

Virtual reality 3D graphical animations usually running in a completely seamless 3D 'world' or 'environment'. VR systems can be desktop-based or immersive. Immersive VR may involve the wearing of a head-mounted display or the user may be within a physical 'cave' where the 3D virtual world is projected onto the walls, floor and ceiling

Wearable computing technology (eg RFID tags) that is worn on the person or sewn into the fabric of clothing

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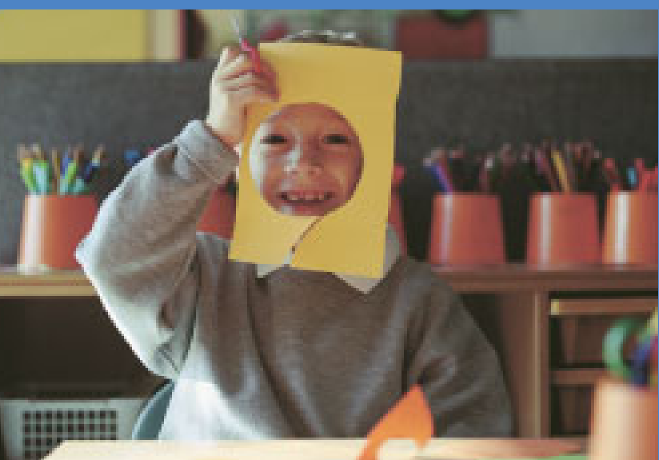
Futurelab
1 Canons Road
Harbourside
Bristol BS1 5UH
United Kingdom

tel +44 (0)117 915 8200
fax +44 (0)117 915 8201
info@futurelab.org.uk

www.futurelab.org.uk

Registered charity 1113051



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