Let's get physical: The learning benefits of interacting in digitally augmented physical spaces

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Abstract

The advent of wireless and pervasive technologies offers many opportunities for designing learning experiences that encourage children to explore, initiate and reflect. Novel forms of interactions can be developed, that exploit the 'physical' and the 'digital' in a diversity of ways that move beyond the 'desktop' genre of interactions. In this paper, we describe an approach for developing digitally augmented physical spaces. Our claim is that getting children to interact with the physical world, resulting in relevant augmented digital information appearing and which can subsequently be interacted with, is what can facilitate active learning. We describe three case studies where we developed such novel learning experiences, and explain how we were able to promote active and playful learning.
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1. Introduction

It is well known that interacting with one another and the environment underpins our learning and development. Active involvement in learning, in the sense of being engaged, interacting and taking part, is central to its effectiveness. To this end, a variety of computer-based activities have been developed with the aim of augmenting and extending active learning (e.g., Papert, 1980). However, the use of ICT in classrooms is often quite different and, if anything, tends to support more passive forms of learning. Many learning applications used in schools are based on a model of learner interaction that is primarily from an 'onlookers' perspective rather than a participant's

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one (Morris, 1999). Educational software, in particular, can be predictable and exercise-driven, with the focus of the learning being to complete modules or levels. Alternatively, how might we realize the potential of the novel pervasive technologies that are now becoming available to stretch children's minds and, in so doing, support and extend active learning?

One approach we are exploring is to bring 'physicality' into 'brains-on' learning. By this we mean combining physical movements, such as, manipulation with real world objects, gestures, and bodily posture changes, with higher order cognitive activities, like thinking, reasoning and reflecting. Our rationale for bringing together body and brain in this sense is based on fundamental developmental theory; effective learning takes place when meaning is taken from experience with the world, when children through their own experience discover what is "going on in their own heads" (Bruner, 1973, p. 72). Physical engagement with something creates an involvement and activeness in learning that passive listening or watching does not. This, in part, increases levels of motivation and an interest in the activity or learning context. High levels of engagement can in turn affect the cognitive interaction of the learner, in terms of their attention, inquisitiveness and reflection.

Our approach is to consider how physical actions can become more an integral part of cognitive activities, through using the process of digital augmentation, and in so doing, promoting learning activities that provoke children to reflect. Digital augmentation involves children interacting with the physical world in a variety of ways causing digital events to occur. We have been experimenting with a variety of new technologies, namely pervasive environments, handheld devices and wireless networking to create a series of 'digitally augmented physical spaces'. We have found that this new genre of technologies provides greater degrees of freedom than a PC and single monitor to design physical–digital interactions – quite different from the screen-based interactions imposed by a mouse button or key click (Hall, 1994).

To interact with and in digitally augmented physical spaces, involves children moving around them and/or exploring them, using a variety of tools and body movements. They can be created to be both indoors and outdoors – the key is to develop such spaces that exploit physicality in interaction, and which trigger various digital representations at appropriate and pertinent times, points and places, stimulating the children to decide what to do next in the learning activity, while also encouraging them to think and reflect. Thus, children are encouraged to drive their own learning and understanding, through the novel physical–digital couplings. For this to work, however, requires designing open-ended and provocative learning or play activities, in the sense that it is not necessarily obvious to the children as to what to do or what to expect. Indeed, part of the active learning challenge is for them to have to discover for themselves what to do and what is possible through their physical interactions.

In this paper, we describe in more detail what we mean by digitally augmented physical spaces, showing how physicality can promote active learning and in particular, reflection in play and learning. We being with an overview of the relevant literature on 'physicality', then present our framework which we used to guide the design of our spaces, followed by a description of three different ones that we developed. The first space provides children with various ways of exploring and experimenting with mixing colour, for example, paint or light can be mixed to make different colour combinations using physical, or digital tools or a combination of both. The second is an adventure game, where children have to collaboratively discover as much as they can about a virtual imaginary creature, through interacting with various devices and aspects of the environ-

ments. The third space provides a woodland field trip for children learning about ecology, enhanced by combining physical and digital information.

2. Background

A critical aspect of learning is for learner's to build their own understanding from what they already know, and taking from the world, new information with which they can expand their current knowledge, and reach more complex levels of understanding in ways which make sense to them. This construction of knowledge is based on an interaction between subject and object, through perpetual exchanges of thought and different kinds of experimental interaction (Piaget, cited in Holzer, 1998). In addition, cultural background and social interaction is an inherent part of this knowledge construction, as a person's understanding and knowledge is grounded in their experience of the world, and is developed through social interaction and mediation of that grounding (Vygotsky, 1978). The concept of active learning, therefore, has several aspects, including, experienced-based learning; actively engaging in meaningful activities in the real world; collaboration, taking part by talking about what is being learned, and making it an active social interaction (Chickering & Gamson, 1987); reflection, to make the learning process itself an active process, learners need to experience, construct, test, and revise knowledge (Thompson & Jorgensen, 1989). They need also to interpret and transform it (Schomberg, 1986), understand the content in context and create a personal meaning (Peterson, Morrison, Cram, & Misanchuk, 1996). This involves reflecting in various ways in their activities. Furthermore, enabling explorative play within the 'real' world stimulates independent discovery, and in so doing, facilitates both the acquisition of information about, and experience with, the environment. In addition, exploration of different combinations of information can enhance creativity (e.g., Bruner, 1985, cited in Clements, 1995; Dansky & Silverman, 1973).

While educational software, developed to be interacted with on desktop computers, can support some of these active learning processes, they can also be quite constraining, often not living up to the expectation that multimedia capabilities enhance educational value (e.g., Hoogeveen, 1997; Large, Beheshti, Breuleux, & Renaud, 1994; Rogers & Scaife, 1997). The advent of ubiquitous computing and pervasive environments offers greater scope for supporting the various aspects of active learning. In particular, it offers opportunities for bringing 'physicality' into learning enabling authentic interaction with the real world. In so doing, they can potentially enable a different kind of engagement with objects and the environment from that of desktop computing, enabling learners to explore their world more concretely. Physical interaction can, not only take place with the environment itself but also with the tools available in that environment. In turn, these tools can mediate interaction with the physical environment, changing the kinds of learning interactions that can take place.

In moving interaction away from the desktop, pervasive technologies not only allow a more active, physical engagement with the environment, but also provide the opportunity to digitally augment interaction in novel ways. One benefit of doing so is to provide different ways of thinking about the world than interacting solely with digital representations or solely with the physical world. Digital augmentation also provides the facility to convey information or experiences not possible in the physical world, for example, making the invisible visible. In turn, this can provide

opportunities to encourage or even enhance further exploration, discovery, reflection and collaboration.

To support such claims, Resnick, Berg, and Eisenberg (2000), Resnick et al. (1998), and Resnick, Martin, Sargent, and Silverman (1996) have begun to show the learning benefits of children interacting with a range of technologies that communicate with the physical world. Here, familiar physical manipulative toys, such as bricks, beads, balls are computationally augmented and designed to enable children to explore additional concepts, such as, those relating to dynamical systems. For example, 'Programmable Bricks' enable children to explore concepts of feedback and control, and 'Thinking Tags' support a new kind of participatory simulation for students learning about systems related concepts. Embedding physical artefacts with digital information has also been found to provide a number of opportunities for reasoning about the world through discovery and participation (e.g., Forrester & Jantzie, 2000; Soloway, Guzdial, & Hay, 1994; Tapscott, 1998). The digital world of information when coupled with familiar and novel arrangements of electronically embedded physical objects has also been found to provide different forms of user-interaction (e.g., Ananny & Cassell, 2001; Underkoffler & Ishii, 1998). Everyday actions and artefacts 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, 1998). When physically engaged with physical objects in this way, children and students have been found to build up highly complex (subconscious) models of physical behaviour (Piper, Ratti, & Ishii, 2002). An early prototype that was built was the Illuminating Light, which was designed to allow students to learn about lasers and holography by manipulating models of optical elements using physical objects that were coupled with various forms of digital augmentation in the form of light patterns (Underkoffler & Ishii, 1998). Another benefit of combining physical interactions with digital augmentation is the extent to which it allows children to combine and recombine the known and familiar in new and unfamiliar ways, providing a further motor for creativity (Hoyles & Noss, 1999). The combining of familiarity with unfamiliarity has also been found to promote reflection in children (Rogers et al., 2002; Scaife, 2002), which is critical in stimulating awareness and enhancing learning (e.g., Ackerman, 1996; Piaget & Inhelder, 1967).

In the next section, we explore in more detail the relationship between the physical and the digital, providing a general framework from which to consider how to design digitally augmented physical spaces that can promote these kinds of active learning experiences.

3. A framework for digitally augmented physical spaces

Designing computer-based learning and playing experiences to be more physical requires us to initially find out what kinds of interactions children carry out in their physical environment, what kind of actions they perform and how they interact with different kinds of artefacts. This provides us with a basis from which to consider what kinds of physical actions and interactions maybe most amenable and appropriate for digital augmentation. It can also provide us with a starting point by which to conceptually understand how physical–digital couplings can aid exploration and reflection in ways that are different from desktop software interactions. There are many kinds of physical actions and interactions and we do not wish to provide an exhaustive list here. Instead, we broadly categorize physicality into three main types, for the purpose of investigating how to

support them digitally: (i) interaction with physical tools, (ii) physical movements, and (iii) combining artefacts with each other.

3.1. (i) Interaction with physical tools

These include actions like drawing or writing with a pen, chalk, or paintbrush and are highly familiar actions that children learn to do to and which 'externalize' their cognition. A key question is how extending children's cognitive actions with physical tools can be further augmented through being coupled with new forms of digital content. A child may also use various tools (e.g., hammers, spades, wands) to cause certain effects, which can also be coupled with digital content.

3.2. (ii) Physical movements

There are various kinds of movement children readily explore and engage in as part of their development. These include crawling, rolling around, dancing, walking and gesturing. Here, we are interested in how these can be used to pervasively trigger various digital events (e.g., sounds, animations) in a way that becomes an integral part of a learning experience.

3.3. (iii) Combining artefacts with each other

A common kind of physical activity is placing one object besides, inside or on top of another (e.g., bricks) and inserting one inside another. A key question is how these highly familiar activities can be augmented with digital content in unexpected ways.

We report here on three physically augmented digital environments we developed to explore how the three broad categories of physicality can be brought into the playing and learning experience. The first is the Chromarium, which explores primarily the first and third categories of physicality, augmenting the highly familiar activity of mixing colour with various physical–digital couplings. The second is the Hunting of the Snark, which focuses mainly on the first and second categories of physicality, investigating novel couplings between familiar actions and unfamiliar digital responses. The third is Ambient Wood, which explores all three categories of physicality, using a range of digital–physical couplings to support learning and reflection.

4. Space 1: Chromarium

Chromarium was developed as a mixed reality environment to enable young children, aged between 4 and 7 years, to explore different ways of mixing colour, using various physical and digital actions and combinations of the two (see Rogers, Scaife, Gabrielli, Smith, & Harris, 2003). Colour mixing with paint is a highly familiar physical activity. In addition to using this as the default condition, we transformed the physical activity of colour mixing using a variety of alternative physical–digital couplings, varying in their degree of physicality. One coupling with high physicality was mixing colour through combining two physical coloured blocks. Each block has six sides, each with a different colour displayed on it. Each face is embedded with an RF tag; when one block is faced onto a table it is read by an RF tag reader triggering a digital animation of the

colour of the face currently showing on the top of the block to appear on an adjacent display. When both blocks are placed on the table, an animation is triggered showing the two colours of the sides that are currently face-up being blended on the display. Thus physically turning the blocks and placing them onto the table results in another digital colour being mixed – quite a different experience to mixing colour using wet paints. An important difference is that colours can be rapidly and easily mixed and unmixed using the physical–digital coupling afforded by the blocks, which is not possible with wet paint.

We also provided a 'low' physical condition; where colour mixing is done using a screen-based digital painting or digital lighting application. Different coloured disks are moved onto each other, by using a touch screen, to mix the colours. The blended colour that results is shown appearing on the screen overlaying the combined digital disks. Un-mixing and remixing is also relatively easy to achieve by dragging a disk away and replacing it with another one.

Another form of physical–digital coupling, we provided was to mix colours by using digital paint, resulting in a physical action. Here, the physicality is provided as an effect of a digital action. The digital–physical coupling is achieved through a digital image of a windmill, having alternative coloured sails being combined with a physical counterpart. When the digital sails are turned by touching them on the screen, the physical windmill sails are simultaneously rotated, creating the illusion of the physical sails changing colour (e.g., when yellow and blue sails are mixed in this way the illusion of green appears). We also provided children with torches that had coloured lights to mix colours. Owing to the different properties of light and paint, the result of mixing certain colours can be different. For example, mixing red, green and yellow results in the colour white appearing on a screen, when using lights, and brown when using paints.

Thus, a number of digital and physical couplings were provided as a means of enabling children to mix colour in novel ways, varying in degree of physicality either in the action or the resultant effect (see Table 1). The ways of mixing colour also varies along other dimensions, including the nature of the coupling, the ability to reverse actions easily and the scope of mixing afforded by the set-up. For example, the constraints of the digital–physical set-up meant that only limited colours can be mixed, based on the colours of the sails, in the physical windmill connected to the digital windmill display. One of the key questions we were interested in was whether high physicality has a different effect on the children's level and kind of exploration and reflection, compared with low physicality. As predicted, a main finding was that pairs of children explored, experimented and reflected much more with the physical blocks than they did with the equivalent digital representations. They rapidly combined and recombined colour, appreciating the reversible and im-

Table 1
Types of colour mixing in terms of different levels of physicality, couplings between cause and effect, extent of reversibility of actions and scope of possible exploratory actions

Type	Physicality	Coupling (cause-effect)	Reversible	Mixing
Wet paint mixing	High	Physical–physical	No	High
Torch light mixing	High	Physical–digital	Yes	Low
Digital painting	Low	Digital–digital	Yes	High
Digital lights	Low	Digital–digital	Yes	High
Blocks and animation	High	Physical–digital	Yes	High
Windmill	Medium	Digital–physical	No	Low

mediate feedback provided by this physical–digital coupling. The children were also quite inventive and collaborative, sometimes piling the blocks on top of each other on the table and pressing them down hard to see if such actions changed the way the colours were mixed from the default setting. They also placed them side by side in the air to see if this had a different effect. A couple of the children placed their faces and hands onto the table to see if these would cause an effect and their colour to be mixed. With the digital–physical coupling (the windmill condition) the children marvelled at the physical effect they created and spontaneously came up with everyday theories of how this was caused.

In contrast, in the digital–digital conditions the children tended to work alone when using the digital disks to mix colour. One child would drag the disks on top of each other while the other looked on. After trying a few combinations they would stop and wait for the next task to be given them by the facilitator. Thus, they were much less adventurous and exploratory in their actions. They were also less communicative and engaged with the task. In sum, the Chromarium study showed that the high physicality condition resulted in more active interaction, in the sense that more experimenting, spontaneity and glee were witnessed, coupled with explicit reflection on the why, how and what-if behind the children's actions. This suggests to us therefore, that physicality provided by tool manipulation offers the potential for more engagement and exploration, more opportunities for communication between children and more sharing and joint activity.

5. Space 2: The Hunting of the Snark

The Hunting of the Snark was designed as a digitally augmented adventure game for slightly older children, aged between 7 and 9 years (Rogers et al., 2002). A number of activity spaces were developed, where different kinds and levels of physicality were designed to be a central part of the children's interactions in the game. In particular, various physical–digital couplings were designed to engage the children in novel ways. The goal of the game is to find and discover as much as possible about an elusive virtual creature, called the Snark, which is hidden in virtual space and appears digitally in a variety of physical places (e.g., the air, water, land). To do this, pairs of children have to interact with the virtual Snark, by walking around in a cave where it is sleeping, feeding it in a well where it is swimming, and flying with it in the air.

To begin the game, the children have to collect a number of physical tokens that will allow them to interact with the virtual Snark. The function of the physical tokens is to provide an explicit mechanism for triggering a physical–digital event. To collect the tokens, the children use a specially designed 'Snooper' tool, which is a PDA hooked up with ultrasonic indoor positioning sensors that can detect hidden virtual objects (Randell & Muller, 2001). The children have to move around a physical space, using the Snooper tool to find them. When in close proximity of a hidden token, a digital representation of the token appears on the PDA screen, enabling the children to then find a physical counterpart. The various tokens consist of food objects (to feed the Snark), musical stones (to enter the cave) and a key (to enter a clothes box).

Feeding animals (e.g., ducks, fish) in water is a very familiar activity that the game capitalised on. The children readily took to this physical action by placing the physical food tokens into a feeding chute adjacent to the virtual well. Depending on the type of food token (e.g., sweets, meat,

vegetable) the Snark shows a digital emotional response of disgust or delight on the water's surface. The Snark itself does not appear, just its response in the form of a simple animation.

To find out more about the Snark's personality (e.g., shy, cheeky) the children have to explore a darkened cave. By walking around the floor, their foot movements are detected by a series of pressure sensitive pads. Depending on which part of the cave floor they stand on different types and levels of sounds (e.g., forest sounds) are played; the Snark responds accordingly via emitting its own sounds. Thus, a high level of physicality is involved in this interaction, involving whole body movement to elicit a digital response from the Snark.

To find out more about the emotional state of the Snark, the children fly with the Snark, flapping their arms in front of a screen, with the expectation that the Snark will come out from hiding and virtually fly with them in the digital sky. To enable this to happen, a pair of wearable 'flying' jackets were built, embedded with multiple detection sensors and accelerometers, that gathered data on pairs of children's arm movements (Randell & Muller, 2000). Again, physical body movements (this time arm movements) were required of the children to trigger a digital visual representation of the Snark to appear; the type of emotional response (e.g., sadness, excitement) being determined by the way the children coordinated their arm movements. In sum, the way physicality was instantiated in the Snark game, was through getting the children to interact with the Snark, through a number of physical movements (manipulation, gestural, positional), using a variety of digitally enhanced objects, devices or clothing. In so doing, the children discover different things about the Snark, such as its likes and dislikes and its personality, and use this information to reflect and create their own understanding of the novel physical–digital couplings – which is very different from how they might do so if reading a story about the Snark in a book or interacting with a software adventure game.

The findings from a number of pairs of children playing the Snark game (Price, Rogers, Scaife, Stanton, & Neale, 2003) were indicative of a highly engrossing and engaging experience. The children were never quite sure what would happen next and what the nature of the next physical–digital coupling might be. Similar to the high physicality condition in the Chromarium, the children spontaneously generated theories about the unfamiliar couplings, especially when the effects of their familiar physical actions were contrary to their expectations. This led them to creatively experiment and explore other ways of interacting with the Snark, and, in turn to collaborate much more with each other.

6. Space 3: Ambient Wood

The Ambient Wood was designed as a learning experience in the form of a field trip for pupils aged 10–12 years studying ecology. Digitally enhanced tools were developed, using wireless networking with mobile and handheld technologies, to enable children to explore and learn about the habitats in a physical woodland, through 'being there' and 'being apart'. By the former we mean the actual experience of being in the wood through exploring and by the latter we mean reflecting on this experience in a different setting from that where it was experienced. In this case it was a makeshift classroom ('the den') that was placed in the wood. Digital augmentation was also provided through more pervasive means; the children's physical movement and location were used to trigger sounds from various parts of the wood and images to appear on a handheld PDA screen

Table 2
Types of physicality experimented with in the Ambient Wood, showing method/device used, the nature of the coupling between the cause-effect of an action and the form of digital augmentation

Type of physicality	Method/device	Coupling (cause-effect)	Digital media
(i) Physical movements	Naked eye and ear	Physical–physical	None
(ii) Interaction with physical tool	Probing device	Physical–digital	Dynamic visualisation
(iii) Interaction with physical tool	Computer display	Physical–digital	Holistic visualisation
(iv) Physical movements	Pinged digital information	Physical–digital	Images, sounds
(v) Combining artefacts	Tagged objects	Physical–digital	Animations

at particular locations in the wood. The forms of physicality provided in the learning experience are shown in Table 2. They involve the children walking around the wood and discovering things about the habitats they come across, using their naked eyes and ears, together with various tools and through the use of pervasive technologies, that provide contextually relevant digital information to their ongoing exploratory activities. These include sounds, images and animations of animal and plant behaviour and at a higher level various biological processes – that are normally invisible to the naked eye or ear.

6.1. (i) Physical movements in the wood

In the physical wood, the children can explore the woodland habitats, themselves, by observing different things in the real world, by seeing, touching, hearing and smelling what is around them. Exploring the physical environment in this way provides much physical engagement. The children can perceive the aspects of the habitat and start building up a picture of what thrives where.

Additionally, in the 'ambient' wood, the children can physically interact with the physical wood in a variety of ways, resulting in a number of physical–digital couplings being triggered. The goal of augmenting the wood in this fashion was to encourage the children to integrate their physical discoveries of the environment (e.g., spotting a caterpillar on a thistle) with the more abstract knowledge they have learned in the classroom, together with the digital representations collected and observed through the digital augmentation (e.g., the interdependency between a caterpillar and a thistle in a wood).

6.2. (ii) and (iii) Interaction with physical tools

One of the tools provided for the children to explore their environment, at a more abstract level, was a probing tool. This was developed to collect light and moisture readings from the environment. The tool is a simple to use and lightweight device, with a light sensor and moisture detector prongs attached to it, enabling alternate readings of light and moisture. The readings can be taken anywhere and immediate feedback is provided on an attached PDA device. Abstract representations in the form of relative levels of the two variables are displayed on the PDA screen each time a child takes a probe reading.

The children's probe readings are also tracked, using GPS, and recorded and then re-represented to them in the form of an agglomerate dynamic information visualisation, that can be

examined in more detail in a classroom setting. In this more conventional learning environment, a PC is considered to be an appropriate tool to use by the children to interact with and hypothesize about their different sets of collected data. The purpose of providing this kind of digital representation is again to provide a link between the abstract data and the physical activity of collecting it, but to set it up in a way that enables the children to reflect (i.e., to stand apart from the physical activity) on how the different patterns of light and moisture they have collected, affects what lives where and why in a part of a habitat. The visualisations also provide a sense of ownership and a personal relationship with the data, that can facilitate their ability to recall where they were in the wood for the various projected data points and what they saw, found and heard there. Having a more intimate relationship with the abstract data, in the sense of knowing how they were physically created, thus can trigger strong associated memories. Furthermore, by having a richly built-up picture ready-to-hand, a better grounding can be available by which to understand the higher order interdependencies that arise in the physical habitats. In so doing, it can provide better leverage by which to think about how and why such visualisations can be useful in performing more abstract and complex tasks on the data.

A main function of this physical–digital augmentation, therefore, is to provide strong *dynamic links* over time, representation and physical activity that can aid the complex learning activity of reasoning about the interdependencies in a given habitat. First, it provides *immediate feedback* for the ongoing physical activity of probing the wood, providing a representation of light or moisture levels on the handheld PDA. Second, it provides *delayed feedback*, re-representing the information in a more abstract form, that can be discussed and reflected upon later in a classroom setting. Third, it provides *cumulative feedback*, enabling children to perceive more holistically and abstractly the combinatorial distribution of their collected data from their probing. Each of these builds on the other, providing an integrated set of representations that the children can use to build up and integrate with their own understanding of how the physical world works.

6.3. (iv) Physical movements

Another form of physical–digital interaction that we capitalised on in the ambient wood was the provision of contextually relevant digital information (e.g., a thistle dying, a bird singing, a caterpillar eating). Children's movements in proximity to where such physical events might occur triggered sounds to be emitted in the wood via wireless speakers hidden in the trees and/or images with sound to appear on their PDA. In creating a digital event to occur in this ambient way, our goal was to prime the children to pertinent aspects of the wood, according to their location in the wood, such that they might see for themselves the physical agent of the digital event (e.g., a thistle, a caterpillar) and reflect upon its behaviour and underlying processes in the habitat.

This mode of physicality is similar in many ways to that experimented with in the Hunting of the Snark game. A difference, however, is that the unconstrained space of the wood means that the children never know when or what body movements will trigger something to happen. In the Hunting of the Snark game, the indoors space was much more constrained, and so the children quickly worked out that flapping their arms or walking over the confined space in the cave would cause various digital events to happen. In contrast, in the ambient wood, the children need to walk in the proximity of a pinger (a movement sensing device) to trigger a digital event and then it is short-lived. A number of pingers were strategically hidden in 'key' parts of the wood, being

geographically spread out. For most of the time, therefore, their walking movements remain undetected. Thus, serendipity and surprise play a much greater role for how the ambient information is discovered. Minimising the amount of pervasive information available was a deliberate design decision, as we did not want the children to be too focussed on locating the hidden pingers in the wood – otherwise it could have turned the activity more into a treasure hunt. In so doing, the children can instead orient to the physical activities of looking, testing and listening, observing the life in the physical habitat while receiving the occasional pervasive ping of digital information.

6.4. (v) Combining artefacts

Another form of physical–digital interaction we used was tagged objects. After exploring the wood, and discussing their findings, the children are required to make predictions about what would happen to various processes in the habitats if certain alien organisms were placed in the various habitats. Two alien RF tagged objects were provided for this purpose, presented in Petri dishes; a lifelike plastic spider and some fungi. The children have to predict what organisms will survive and what will die, if, either or both are added to the part of the woodland they have explored. To determine if their hypotheses are correct they test them back in the woodland, through using a special periscope device that has attached to it a receptacle (a disguised RF tag reader) which the Petri dishes, containing the organisms, are placed in (Wilde, Harris, Rogers, & Randell, 2003). A digital animation is played on the viewer of the periscope for the three different outcomes, depending on which of the organisms (or both) are placed in the receptacle.

Another way of combining artefacts that was exploited was the provision of physical tokens, in the form of RF-tagged paper cut-outs of organisms in the wood. The goal was to get the children to think about their experiences when apart from the physical activity in a classroom setting and to reconstruct their findings in the form of a pictorial representation for the different seasons than the one they had explored the wood. In so doing, a key task was for them to externalise the relational links between the kind of habitats and the organisms they supported. Various kinds of digital feedback were provided at different stages of this task, providing hints as to what works and the provision of resultant animations of combining the tokens in certain ways (Marshall, Price, & Rogers, 2003, in press).

Findings from a study of different pairs of children exploring the ambient wood were like the, Hunting of the Snark game, indicative of a highly engaging experience, that the children readily took to (Price et al., 2003). Moreover, our deliberate decision to let the activity be 'physically led' by the children, rather than task-based, provided many opportunities for discovery and exploration. Never quite knowing what to expect next had the effect of captivating the children and maintaining high levels of concentration and motivation. When 'being there' exploring the wood, they frequently generated ideas and chatted with each other about how to find out about the habitat and why certain things lived where they did. When 'being apart' in the classroom setting, the children were not at all self-conscious and talked openly and freely about their data collections. Using the various digital visualisations and animations provided, they also reflected on why certain parts of the habitats had different readings and what the implications of this were for the organisms living in that part of the habitat. Thus, it appears that the provision of a medley of physical–digital couplings, varying in kind of physicality, offered much scope for bridging the gap between physical experiences and the learning and reasoning about abstract processes – in ways,

we would argue, that goes beyond what has been possible to achieve through the provision of desktop educational software.

7. Discussion and conclusions

Our research has shown how digitally augmented physical spaces can be designed to exploit the interactional capabilities, enabled by wireless networks and pervasive technologies, to support learning in quite different ways than has traditionally been the case with desktop-based PC interactions. Most significantly, the spaces provide opportunities for a new genre of physical–digital interactions, that can support active learning, and in particular exploration, initiation and reflection. A key question these series of claims raise, however, is how do the two core aspects that underlie the design of these spaces – physicality and digital augmentation – actually promote active learning? In what ways does moving through a physical space, manipulating physical objects or combining them – causing various digital events to occur – get children to think more about what they are experiencing, doing and importantly, how this relates to what they know and what they do not know; and what the significance of the coupling they have experienced is to what's happening around them and their previous experiences? In particular, how do the children make sense of and integrate the series of physical–digital encounters they have within the physical environment they are in while also abstracting relevant knowledge from them?

We suggest that one of the key aspects of interacting in digitally enhanced physical spaces is to raise the *awareness* of the children as to what they are doing in them. Another core aspect is that they provide a richer *experience* (compared with PC virtual worlds), allowing children to make explicit bridges between their various perspectives and understandings of the physical and digital worlds. Other features are the *anticipation* and contemplation that are triggered when experiencing couplings between highly familiar physical actions and unfamiliar effects. The degree of *authenticity* of the learning experience and the amount of *collaboration* that results can also be greater – both of which are considered in the literature to be important aspects of active learning. Below we briefly describe each of these aspects.

Awareness. Physical interaction in the spaces enables awareness at different levels: first, awareness of the objects being manipulated and their functionality, focussing attention on the activity or task at hand; second, awareness at a multiple perceptual level, enabling access to more information through different senses, providing a richer basis for reflection about the 'world' and third, focusing attention on contextually relevant information at a given time, drawing attention to 'highlighted' aspects of a physical world in particular locations.

Experience. The experience of interacting in the spaces is more than just visual or multimedia (as is largely the case with desktop interaction). It can entail all senses. Experiencing the digital–physical couplings through more varied modalities, simultaneously or separately, offers a greater diversity of perceptual information on which to reflect about the experience, the environment, or the discoveries that are being made.

Anticipation. Many of our physical–digital couplings were designed based on familiar physical actions and unexpected effects. For example, walking passed a plant (e.g., a thistle) results in an ambient sound being played, and in so doing making an invisible behaviour in a habitat visible (e.g., butterfly sipping nectar). The juxtaposition of the familiar with the unfamiliar provokes

children in ways in which normally taken-for-granted couplings (between familiar action and familiar effect) are often overlooked, causing them to reason how and why such links are possible.

Exploration. The spaces allow for high levels of exploration and discovery. Many of them can be designed to enable a number of different combinations of actions and interactions to be experimented with and in so doing allowing for creative exploration.

Authenticity. Another aspect of digitally augmented physical spaces is that they can provide children with the means by which to interact with the physical environment, that is personally meaningful for them, allowing them to reflect on their own experience in relation to the learning experience. This form of interaction was most evident in the Ambient Wood learning experience, where children had the opportunity to physically collect data that was then re-represented digitally to them and which they could manipulate and hypothesize from in more abstract ways.

Collaboration. Compared with static screen collaboration, digitally augmented physical spaces can support more diverse forms of collaboration, between children and others. The interactions are very much part of the ongoing learning or playing experience and as such can be commented or questioned as part of the ongoing activity. More collaboration involves more verbal engagement, promoting a greater exchange of ideas and suggestions.

In conclusion, our research has shown how designing computer-based interactions to be an integral part of digitally augmented physical spaces provides much scope for supporting active learning. A core consideration is to get children to be more physical in their interactions with the physical environment. Instead of just pressing buttons or selecting options by mouse clicking in front of a PC to obtain and view digital content, we propose that the repertoire of computer-based learning activities be extended to encourage children to engage in a range of familiar and pervasive physical actions and interactions, where digital information is triggered, obtained or made present as part of the ongoing learning or playing activity in hand. In so doing, children can become much more highly engaged and creative participants in the learning experience.

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