Designing for physical-digital correspondence in tangible learning environments

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ABSTRACT

In tangible learning environments the potential to exploit different physical-digital links increases representational power but also broadens the complexity of design. This paper presents studies that illustrate the effect of physical correspondence design choices on learners' interpretations, particularly regarding meaning making and conceptual mappings between objects and representations, and learners' ability to generalize. Pre-conceptions and associations with familiar real settings were found to have a significant level of interference in children's perception, interpretation and comprehension of the concepts.

Categories and Subject Descriptors

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General Terms

Human Factors

Keywords

Tangible, interactive surfaces, physical correspondence, children, design, learning.

1. INTRODUCTION

Tangible environments and shared interactive surfaces offer new ways for children to interact with information and with one another. Physical objects coupled with digital effects offer greater representational power and allow access to more or different information than is normally available in the immediate physical environment [9]. At the same time the number and complexity of design decisions increases. This highlights the need to understand the effect of different design mappings and choices on children's interaction and interpretation within the learning domain.

Our earlier work describes a conceptual framework for investigating how different ways of linking digital information with physical artefacts influence interaction and cognition [9]. One strand of the framework focuses on 'correspondence', which "refers to the metaphorical mappings between objects, representations and action and the learning concept" [9: 360]. The two components of the 'correspondence' strand relevant for this paper are: (i) *physical correspondence*, which refers to the degree to which the physical properties of the objects are mapped to the learning concepts, and how this influences inferences and conceptual understanding. A 'symbolic' physical correspondence defines objects that act as common signifiers, and which may have little or no characteristics of the entity it represents. A 'literal' physical correspondence defines objects whose physical properties closely map to the metaphor of the represented domain. *(ii) Representational correspondence,* which refers to the design considerations of the representations themselves and their metaphorical mapping within the learning domain.

Based on the design of an interactive tangible environment for supporting children learning about the physics of light, this paper discusses preliminary work, which illustrates the effect of the physical and representational correspondence design choices on children's interpretations. It identifies and discusses the issues surrounding the design choices that need to be made for both physical objects and associated digital representations, and the mappings between them.

2. BACKGROUND

Assuming that perception and cognition are closely interlinked, the form and nature of representations have an impact on knowledge construction [6]. For every representation with which learners are presented, they must come to understand how information is encoded and how it relates to the domain [1]. Concrete representations are said to help reasoning because they can be explicitly designed to promote inferences from rich perceptual representations to abstract principles [4]. Concrete representations are usually easier to remember, engaging and connected to real-world situations [4], and provide hands-on problem solving [3]. According to Piaget, manipulation of concrete physical objects supports and develops thinking [7]. On the other hand, by focusing on the critical essence of phenomena, abstract representations are less tied to specific contexts and therefore more transferable to other domains.

Research shows that it may be difficult for children to understand an object as both a physical thing and a symbol representing something else [11]. Concrete objects have salient physical properties that decrease their ability to serve as symbolic representations. Symbolic interpretations might therefore be more likely to be attained through abstract representations, which are less influenced by physical constraints [4]. In general, idealized, low-fidelity artefacts encourage people to see them as referents, while concrete, high-fidelity materials make people reason about the artefact itself and hence employ solution processes that have real-world analogs [4].

In tangible learning environments, both physical and digital representations must be carefully designed in terms of the mappings and affordances they offer for interaction and comprehension [2]. Concrete and digital representations can be linked in terms of their appearance (perceptual mappings) and/or behaviour (how things respond within the system), among others [2].

3. THE TABLETOP ENVIRONMENT

A tangible environment was designed to illustrate concepts relating to the physical processes of light, including absorption, reflection and transmission related to colour and different physical materials e.g. rough or smooth objects. Two key design considerations included the physical artefacts that served as interaction devices and the digital representations that illustrated light behaviour accordingly. The choice of digital representation is not straightforward. Light behaviour can be explained in terms of wave or particle models depending on the phenomenon, this duality introducing extra complexity. At school level, light is usually represented by straight lines and diagrams indicating directions and angles. Our design decisions were based on data collected through informal interviews with teachers, advice from experts and pilot studies of different designs with children and adults, taking into account the technical limitations of tangible environments.

As the aim was to promote understanding of light behaviour on real world objects, a literal physical correspondence metaphor was adopted in the design of the environment, i.e. objects acted as themselves: the torch represented a torch and the blocks behaved according to their 'real' physical properties (colour, opacity, shape and texture). We chose Newton's colour spectrum among other models as it is usually adopted for basic explanations about light and colour (being illustrated through experiments with prisms). Thus, the physical artefacts in the environment consisted of: a set of plastic blocks comprising the colours of Newton's spectrum plus white and black blocks (Figure 1, center); transparent blocks (to illustrate transmission and refraction); rough and smooth textures (to illustrate differences in reflection) (Figure 1, left); and a real torch (for the source of light). Children could interact with the system by placing and moving the torch and the blocks on the surface of the table.

Figure 1. Blocks used in the environment

Digital representation designs included showing absorbed colours inside (Figure 2, left) or next to the object which shows the light beam as white or as the spectrum of colours; and illustrating reflection through ripples, arrows (Figure 2, right), or straight lines (Figure 2, left).

Figure 2. Digital representations

Object recognition was implemented using ReacTIVision technology [5] requiring the objects to be tagged with fiducials (Figure 1). This imposed constraints on the size and shape of the objects as well as on the related representations. For instance, it was not feasible to show refraction through transparent blocks or colours being absorbed inside opaque objects (e.g. by providing a hole to 'see' inside) because the fiducial had to be attached to the bottom of the blocks. Such limitations meant that: refraction could only be inferred from the table-top display by noticing that the light beam entered and then exited the object at a different angle; and absorption was illustrated using a different object with an elongated shape to accommodate a hole (Figure 1, right), through which children could see the absorbed colours (Figure 2, left).

3.1 Studies

Studies were undertaken with 21 children, aged 11–12 years, with little formal knowledge about the physics of light. In sessions of about thirty minutes, groups of three pupils were invited to explore the interface. The system was designed to support exploratory interaction to support knowledge construction of the domain, rather than to complete a fixed task with a final answer. Thus, children were asked to freely explore the interface to find out about light behaviour. The environment was very intuitive and children were able to use and interact with it easily. During the interaction, a researcher facilitator occasionally prompted the group with general questions like *"what's happening here?"* and *"why do you think this is happening?"*, to elicit children's ongoing thinking and understanding. At the end of the session, a basic assessment activity was performed, which consisted of asking pupils to discover the colour of specific transparent objects programmed to behave like coloured ones. Groups were informally interviewed after the session, when they were asked how they liked the interaction, how they thought the system worked and what they remembered about light and the activities performed. All sessions with the tabletop were video-recorded and post interviews were audio recorded. Qualitative analysis was undertaken, collectively based on data from video, interviews and the post session activity.

4. DISCUSSION

A number of findings about 'correspondence' emerged from the studies that inform design considerations in the context of tangible learning environments. Primarily these include how pupils interpreted physical and digital representations to build concepts; the effect of swapping between literal and symbolic scenarios; and the value of understanding something about how the system works.

4.1 Symbolic Interpretation from Literal Correspondence

In this environment a literal physical correspondence design was adopted for the artefacts. The behavioural mappings in the environment were of a tight coupling design [2], and children had little difficulty in understanding the cause-effect relationships (i.e. physical action input and digital output). However, children's interpretation and use of the artefacts varied according to their interpretation of other physical-digital mappings and the perceived affordances of the different objects, as well as their pre-conceptions based on familiar everyday concepts related to the objects and digital representations.

4.1.1 Physical Objects

The mapping between physical objects and their meaning and function within the environment was not always literally interpreted by children, who sometimes perceived objects to have a symbolic correspondence. The torch, being an object taken directly from the 'real world' with familiar affordances of interaction, was intuitively manipulated within a 3D space (lifting, switching on), rather than within the constraints of the 2D surface. However, such technical constraints were rapidly accommodated and the meaning (source of light) and purpose (shining light on objects) of the torch in the environment were unambiguous and comprehensible. On the other hand, the coloured blocks (although representing themselves) were perceived as being representative of something else, giving rise to a variety of interpretations. For example, the spectrum of absorbed colours shown inside the objects evoked the common experiment of decomposing white light through a prism, and induced the perception that the block represented a prism. Furthermore, the notion of reflection, being mostly associated with concepts of optics, led to the interpretation of blocks as mirrors or lenses and never as regular opaque objects.

The difference in attributing a literal versus symbolic interpretation may relate to issues of semantic mapping [2], where the notion of 'semantic' is extended to include the functionality of objects. The semantic mapping of the (real world) torch was closely coupled with its intended meaning or function in the tangible environment, whereas the semantic mapping of blocks was more ambiguous. In this environment the 'coloured blocks' per se carried no fundamental functional meaning (as they might in an environment where they are used to build towers or create different patterns). In other words, although the blocks were designed to be instances of common, real objects, they did not semantically map to objects with which children interact in their everyday lives. Consequently, children did not transfer the conclusions drawn from the interaction of the blocks with light in the environment to the interaction of opaque objects with light in real settings. Thus, using such purpose-made blocks did not contribute to the generalization of the concept that we 'see' objects in the world because they reflect some colours and absorb others (e.g., by working with a blue block in the system, realize that, say, a chair looks blue because it is reflecting blue).

4.1.2 Digital Representations

Interpretations of the digital effects were also affected by real world experience and familiar representations. For instance, the representation of absorbed colours as a colour spectrum was immediately associated with a rainbow (Figure 2, left). Although children were excited by the representation, the representation itself did not appear to facilitate their understanding of the phenomenon of absorption. In fact, children described it as light going through (the object) in the form of a rainbow, the word rainbow being often repeated, which was not the intention of the design. This raises issues about using representations that evoke a distinct familiar phenomenon, with other purposes, and again about the ability of children to transfer across domains. In previous studies [8], children preferred having abstract sounds to represent light phenomena rather than sounds associated with real world situations (e.g. doorbells and clapping). Interference of familiar representations must therefore be carefully taken into account during design.

4.2 Swapping Between Literal and Symbolic

One proposed benefit of tangible environments is the flexible linking of objects and representations, the design of which can define the boundaries that exist between what is meant to be 'real' (i.e. meaning within the system literally corresponds to meaning in 'real' contexts) and what is meant to be 'artificial' (i.e. symbolically representative). In the studies presented here, the implications of swapping between what was literal and what was symbolic within the environment were illustrated with our use of clear objects to assess whether children had understood the concept of colour and reflection at the end of their interaction. To do this, clear objects were programmed to behave as if they were coloured, i.e. reflected a coloured beam. Children were expected to infer the 'invisible' colour of the object from the colour of the beam. However, throughout the interaction children had acquired, as expected, the concept that a certain coloured object reflected that same colour. Taking advantage of the technology to create symbolic scenarios in order to assess understanding resulted in introducing some level of confusion when children saw clear objects reflecting coloured light beams. Children did not understand how the block could reflect a coloured beam if it was not that colour, 'physically' speaking. In fact, they had internalized the correct concept, but 'believed' so much in that model of reality that they were unable to integrate the potential of the 'artificially' created to be modified for different purposes. In line with other findings [10], such unexpected effects prompted children to think more about the concepts, e.g. seeing a clear block reflect green led children to try to find reasons for the fact based on the concepts they had learned. Although, such inconsistency brought about interesting cognitive conflict, it also introduced doubt in children's minds regarding the just-learned concepts.

When adopting a literal physical correspondence design, the idea is to provide a simulation of how the objects behave and interact in real settings. In this sense, children are expected to believe the system and 'trust' it to be showing a correct model. However, when rules are changed and a transparent object reflects a coloured ray, children might feel that anything is possible and discard beliefs built during the interaction. Given that tangible systems do not just exploit the physicality of the real world but also aggregate digital modules enabling access to phenomena 'invisible' in everyday interaction and manipulation of symbolic models, a key issue is how to effectively mesh together an accurate model of reality with artificial scenarios, which do not necessarily correspond to reality but serve a different purpose within the system.

4.3 Understanding Technology

Other considerations emerged from the approaches pupils took to the environment, particularly the value of understanding the technology. Children displayed the common propensity to inquire about and find out how the system worked. They oscillated between reflecting on the concepts and wondering how the digital effects were produced. At some stage, they were able to grasp an understanding that everything was artificially controlled and modeled to represent the concepts. Acquiring this comprehension is an enriching experience for children, and may be a key component in engendering effective understanding about the learning domain. One question is how and when such technical issues should be integrated into the learning experience. When asking a question like "why is it reflecting green?", the expected answer is "because it's a green object", and not "because there is a fiducial at the bottom of it telling the system to display a green ray". In other words, the aim is that children will be immersed in the simulation and take it as the '(scientific) truth'. The main goal is not for them to be thinking in terms of the technical implementation, but to reflect about the concepts the interface illustrates. However, understanding the technology may be empowering. For example, when illustrating reflection off rough surfaces, the scattered beams did not reflect when encountering a second object, due to technical constraints. Although the children's understanding that the beams should reflect was correct, even when told this was a problem of the system, children kept trying to get the rays reflected and seemed to find it hard to believe the system was 'wrong'. In such cases, having some notion of what happens behind the scenes allows children to abstract technical limitations and move to a higher level of comprehension.

5. CONCLUSIONS AND FUTURE WORK

Tangible environments offer the potential to exploit pertinent features of both physical and virtual environments. This paper presented issues that arise when designing using a physical correspondence metaphor in tangible learning environments. Findings suggest that children's interpretation of scientific phenomena results from an interaction between different design choices for physical objects and associated representations, pre-conceptions and previous real-world experience. We can design with literal and symbolic correspondences, but learners do not necessarily infer the same correspondence metaphor. This also raises issues about how to design tangibles to effectively exploit the 'physicality' of the real world. Despite using real objects children did not tend to extend or generalize their models of understanding to real contexts. Furthermore, boundaries between literal and symbolically representative were not always clear for children, and raised issues about and trade offs between using mixed models of real and virtual to create cognitive conflict, and undermining children's understanding.

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