Action and Representation in Tangible Systems: Implications for Design of Learning Interactions

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ABSTRACT
In tangible learning systems, the facility to promote physically active engagement highlights the need to understand how different designs impact on action and interaction, and the subsequent implications for learning. This paper draws on studies involving two tangible learning systems to analyse the effect of design choices on the kinds of (inter)actions engendered and how they create, shape and constrain different learning opportunities. Main findings suggest the need to promote and allow for different kinds of opportunities for conceptual reflection within the collective physical interaction; the importance of balancing collective representations and individual action-effect links; and the need to enhance appropriate awareness when dealing with several loci of attention.

Author Keywords
Tangible systems, design, action, interaction, learning opportunities.

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General Terms
Human Factors, Design

INTRODUCTION

Tangible systems offer opportunities for promoting new kinds of physical interaction. This is of particular interest in learning communities, where the potential to promote hands-on and physically engaging interaction offers new forms of experiential learning [8]. Research is beginning to identify the impact of different tangible designs for promoting (inter)action and movement (for example, Hornecker and Burr [6] propose a framework to analyse how movement in, and configuration of, the physical space support and affect *social* interaction). However, little work has focused on movement and action in learning contexts, and how design influences the kinds of learning opportunities engendered.

Tangible systems offer large degrees of flexibility in terms of design, requiring a detailed understanding of the impact of different designs on interaction. Of particular interest here, is the effect of different design choices on promoting action, and the subsequent implications for interaction in learning contexts. The artefact–action–representation framework [12] details the different relationships between artefacts, actions and digital representations in tangible systems, and offers a framework for research into the specific learning benefits of tangibles.

The various forms of interaction promoted by tangible systems embrace different notions of 'action'. In the studies reported in this paper, concepts of action centre around the manipulation of objects, and gross gestures / bodily movement in space with and through objects. Tangible actions are thus defined as 'non-verbal dynamics' [15] that result from 'direct engagement' [9] with tangible artefacts, e.g. object-specific manipulations such as shaking, squeezing and rotating. This notion of non-verbal dynamics is extended to include a 'whole-body interaction' view [3], such that actions include the non-verbal dynamics that happen between users and tangible artefacts, as well as whole-body interaction that happens in and around the interface. Actions can also be classified in terms of *manipulation* i.e. the physical contact (or impact) with an artefact, e.g. grasp and grip [15] and descriptions of *movement*, which refers to the characteristics of the action being performed, i.e. duration, flow, regularity, directionality [12].

To explore these notions of tangible actions, two different tangible learning systems are examined using three key design characteristics: physical space; gestural and manipulative interaction; and input/output coupling. Drawing on Price et al.'s [12] framework and building on the notion of how design affects interaction, each characteristic is considered in terms of the kinds of action that they engender, and the subsequent effect on the types of learning opportunities that these systems create.

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BACKGROUND

Interaction with tangible systems is typically based on the senses and skills from the non-digital world [14]. It encompasses the physical environment and artefacts, the digital representations, and a range of possible actions. In this section, we present some perspectives on the meaning of 'tangible interaction' that relate to our own work, and present frameworks, which contributed to our analysis.

Tangible Interaction

At one level of description, tangible interaction can be viewed as movement in physical space, which may or may not include the manipulation of objects [6]. In this description, the 'body' itself (as well as artefacts) is seen as an input device. However, an important distinction can be made between augmenting the environment with tangible artefacts to promote action and embedding a physical space with sensors to promote action. From our point of view, an environment embedded with sensors, more often called 'ubiquitous environment' [22], is not 'tangible' unless the user is physically manipulating concrete artefacts of the system. For example, a light, which turns off/on when a person waves his or her arms around is not tangible, whereas a physical switch that a person presses on and off is tangible. This distinction is an important one – tangible computing is 'impactive' [17] and dependent on a physical point of contact and as such, gestures alone are not tangible. This paper focuses on how children interact with sensors embedded in artefacts themselves rather than how they interact with sensors embedded in the physical space.

At another level of description, tangible environments can be viewed from an object-centric or subject-centric perspective [16]. From an object-centric perspective, the focus is on designing the object - on how the physical and perceptual properties of the object (such as size, weight, material) affect interaction. An object-centric view emphasizes how the design of the object itself determines the interaction style and context and has led to a plethora of tangible objects, which require 'direct manipulation' [20]. Much previous research in tangible computing has taken an object-centric approach using Gibson's theory of 'affordance' [4] as a design guideline. However, far fewer studies have approached tangible and embedded interaction from a subject-centric perspective. From a subject-centric point of view, interaction focuses on designing the action – the emphasis is on how bodily movement affects interaction. In emphasizing the subject, we turn our attention to 'direct engagement' [9], an alternative to direct manipulation, and focus on designing user experiences that exploit emotional and cognitive values. In this view, the designed actions provide the context and any objects present in interaction are there to suggest context rather than demand it. This paper examines this distinction in more detail and the impact on interaction.

Defining the Physical Space

The configuration of the physical space and of the tangible interaction facilitates, prohibits and hinders some actions, shaping behaviour and social interaction [6]. The physical space in a tangible environment is also defined by the particular objects or artefacts used, and the tasks and activities involved in the particular environment. For example, the studies reported here differ in the 'use' of physical space, due to the devices and tools that support the interaction, rather than the physical space in terms of e.g. room size or shape. The physical space in these studies, simply acts as a boundary for where the interaction with the system takes place.

Action and Representation

Tangible systems offer opportunities for meaning-making and non-verbal expression through links between action and digital representations. For example, research explores how whole-body movement and action in tangible systems can act as interaction modalities for accessing and manipulating abstract information and promote collaboration, creative expression and learning [2, 14].

This relationship between action and representation is considered key to shaping interaction. Hornecker and Burr [6] identify the relationship between material and digital representations as one of four fundamental aspects of tangible interaction (others being: the physical artefacts, the movement in space, and the configuration of physical artefacts and space). Although basing interaction on previous real world knowledge and skills should reduce the mental effort required [14], the 'perceived coupling' [6] between physical and digital representations is not always straightforward. Antle [2] suggests that design must take into account three kinds of mappings between physical and digital space: perceptual (how things appear versus how they respond); behavioral (input behaviors versus output effect); and semantic (information embedded in the physical and digital aspects of the system).

Price et al. [12] take representation as a central element in framing investigation into the effect of tangible technologies on interaction and cognition by analysing artefact – action – representation relationships. Of particular relevance to the present work is the *location* parameter of Price et al.'s [12] framework, which refers to the distance in space between physical and digital components of the system, and how this distance affects the conceptual links between them and the explicitness of the action-representation relationship. With discrete locations, input and output are separate (i.e. an object triggers a distinct digital representation); in co-located systems the digital representation is adjacent to the object; in embedded systems input and output occur both within the object. Price et al.'s [12] definition of location is adopted in this work.

Location has an impact on the kind of actions that can take place: actions are usually constrained to a surface in co-located systems, while broader kinds of movements are possible within discrete and embedded setups. Price et al. [12] analyse action in terms of manipulation (grasping, gripping and gesture manipulation) and movement (referring to the characteristics of actions such as duration, flow, regularity and directionality).

DESIGN OF THE TANGIBLE SYSTEMS

Two tangible systems were developed to investigate the impact of tangibility on interaction and science learning: an interactive tabletop and accompanying physical objects to support exploration of the concepts of the physics of light; and a system using Nintendo Wii remotes linked to visual effects to support exploration of the concepts of motion and acceleration. Studies with 43 students (21 female and 22 male) aged 11-15 years were undertaken. Participants worked in groups of three with each system for approximately 30 minutes. The aim was to observe the students as they engaged in collective and exploratory interaction rather than explicitly teach them the concepts. All sessions were video recorded. Qualitative analysis of the video data indicated a number of relationships between design and the interaction and learning opportunities discussed in this paper. This section outlines the design of and interaction with each system.

Interactive Tabletop

The tabletop system is described in technical detail in [19], but a brief outline is provided here. The system consists of a table with a frosted glass surface, which is illuminated by infrared LEDs. A variety of hand crafted and off-the-shelf plastic objects are used as input devices (Figure 1).

Figure 1. The tabletop and the input devices.

Each object is tagged with a paper marker called a 'fiducial'. When the tagged object is placed on the table surface, it is tracked by an infrared camera, through the method and software described in [7]. When distinct objects are recognized by the system, different digital effects are then projected on the surface. Digital effects appear around the corresponding object as 'co-located input and output' as described in [12].

During the studies, objects were placed to one side of the surface on an area that was not interactive. Children could choose an object at any time to use on the interactive surface. During interaction, objects were sometimes returned to the table edge and other times left on the interactive surface even if not in use. Since the objects are only tracked when they are placed on the interactive surface with the fiducials facing down, the actions children displayed during interaction were fairly simple: placing, dragging, rotating and removing objects from the surface.

The designed effects in this application are based on the physics of light. Thus, the torch acts as a light source (causing a digital white light beam to be displayed when placed on the surface), and objects reflect, refract and / or absorb the digital light beams, according to their physical properties (shape, material and colour) (Figure 2).

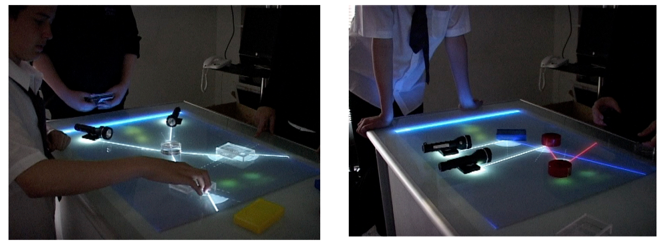

Figure 2. Children place different kinds of objects on the interactive surface to produce different effects.

The torch, when placed on the surface, is 'always on', while the other objects only produce digital effects if they are hit by the digital light beam. In other words, if an object (other than a torch) is placed on the surface and is not hit by a digital light beam, no effect will be seen on the surface.

To see the digital effects, children made arrangements on the surface using the different objects and torches. The digital effects changed when someone directly manipulated the objects - either by taking them off the table or altering their position on the table - which caused the light beam to be interrupted or redirected. Children were invited to explore the system and find out about how light behaves under different conditions. The large number of objects and the exploratory nature of the study meant that children were not restricted to turn taking and could interact whenever they wished.

Wiimotes

Nintendo Wii remotes ('Wiimotes') were used as input devices to explore the use of tangible 'exertion interfaces' [10] to understand concepts of motion and acceleration through body-based interaction. Previous work suggests that children's everyday familiarity with Wiimotes constrains the kinds of actions used [18]. Thus, the Wiimotes were placed inside cylindrical containers (as in Figure 3) to enhance their symbolic nature.

The Wiimotes were connected via Bluetooth to a MacBook Pro running Darwiin Remote (http://sourceforge.net). Acceleration data was wirelessly streamed from the Wiimotes and represented visually on a 17" computer screen, using an application written in Processing [17]. As children moved the Wiimotes around their bodies or in 3D space, their actions generated corresponding visual effects on the computer screen in real time. Although the technical implementation of the system did not force the children to point the remotes to the computer, the visual feedback provided meant that they still needed to be facing the computer screen. Unlike the interactive tabletop, the location of representation is discrete rather than co-located [12], i.e. input and output occur in different locations, creating a more significant distance between the users, objects and digital effects.

Figure 3. Children moving the cylinders with the Wiimotes up and down.

Activities

Children engaged in two activities, which explored how different kinds of interaction affect the learners' perception of concepts of motion. The first activity focused on bodily interaction. Each child held a cylinder in his or her hand and moved in any manner and wherever they wished (see Figure 3). One volunteer began using one cylinder, while the other two children observed how they used it and the digital effects generated. After about 10 minutes, all three children were given a cylinder each, so that they could interact with the system simultaneously. Common non-verbal dynamics included turning, rotating and spinning the cylinders, as well as moving them up and down, back to front and side to side.

The second activity focused on the motion using artefacts. Children could attach the cylinders to a swing and skateboards, and use flat pieces of wood as ramps (Figure 4), which provided ways of producing different kinds of movements from when they were holding the cylinders. This allowed children an alternative way of analysing the visual effects displayed on the computer screen.

Figure 4. Children use skateboard and swing with Wiimotes attached.

Visualisations

Building on previous work, suggesting the need to develop visualisations that map directly to movement in 3D space, two visualisations were used independently: a literal 3D visualisation based on the 3 axes of acceleration, and an abstract 2D visualisation (Figure 5). Each coloured line or dot corresponded to one axis of acceleration: X (green), Y (red) and Z (blue). Moving the cylinder in one axis caused the corresponding line or dot to grow larger.

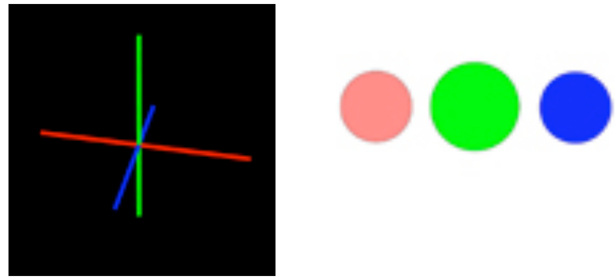

Figure 5. Literal 3D representation (left) and abstract 2D representation (right).

All children were exposed to both kinds of visualisations. When only one child was interacting, one corresponding representation was shown on the screen. When all three were interacting, three representations were shown on a single screen next to each other. In both the 3D and 2D visualisations, the graphical images never overlapped.

IMPLICATIONS FOR INTERACTION

The design of the systems create different relationships between participant and space, and object and representation, which affects the kinds of body actions and movements engendered, participation and learning activities promoted. This section outlines the effect of design on action (and interaction), in terms of space, manipulative / gestural interaction and input / output coupling.

Space (Distance and Position)

During the tabletop studies, children stood around the table, each child generally keeping to the same position throughout the session. Actions were mainly bound to the surface, and restricted to 2D space, as objects needed to be on the surface to trigger digital effects. All actions and consequent digital effects were visible to the whole group. The size of the interactive surface area of the table and the restriction of physical / digital coupling to a 2D surface meant that participants were in close proximity to each other during the session, and typically had their attention focused on the same and shared area.

In the Wiimotes studies, actions in any direction and orientation in 3D space affected the digital representation. Children were free to move as they wished, as long as they held the Wiimotes in their hands or attached them to other objects. However, the size of the screen and visuals affected how children positioned themselves in the physical space (for example, in terms of how close they needed to be to the computer screen to see the digital effects of their actions). Although this study focused on visual representations, other factors, such as type of representation [12] or screen size would affect distance sensitivity.

In the activity where children held the cylinders in their hands, they generally moved their bodies but often kept to a relatively fixed position in space, facing the screen. When one child was interacting, the observers could easily see both the child moving with the cylinder and the resulting visual effects on the screen.

In the second activity, the focus changed from using the body to move the cylinders, to moving other objects onto which the cylinders were attached. As they were manipulating objects on the floor, table (skateboards), or towards the back of the room (swing), children became less bound to the screen. However, to see the digital effects, children had to keep track of what they were doing with the objects as well as focus their attention on and position themselves around the computer screen.

Gestural versus Manipulative Interaction

In every system, size, shape and location of artefacts promote some activities and constrain others, influencing actions and providing implicit clues [6]. With the tabletop, children directly manipulated objects on the surface by placing, removing, dragging and rotating objects. The number of objects meant that children could act simultaneously and children collaboratively arranged objects on the surface, although only a subset of the objects was shared at any one time. Sometimes, one person would ask a peer to do something in particular, or to pass them a specific object so that they could use it themselves. In this case, objects were present-at-hand [5]. We can say then that the (object-centric) design in our case focused on how children would *manipulate the objects*, and reflect *about them* and what was happening *to them*.

In the Wiimotes study, the distinction between interacting through gestures or manipulation was less obvious. When the activity was designed to focus on bodily interaction, there was a mixture of manipulative and gestural interaction, and interaction fluctuated between being object-centred and subject-centred. Children were generating the effects through their bodies' movement, and acting *with the Wiimotes*. In some cases, the Wiimotes became ready-to-hand [5], like when children danced (including dance movements specifically with their arms) holding the devices. The focus here was on the action and the body, therefore interaction was subject rather than object-focused. At other times, actions were clearly determined by the affordances of the devices (like using them as swords or fishing rods), while others did not have a metaphorical meaning but had a clear goal of directly investigating changes in the visuals by moving the devices up and down, side to side, and back to front. Thus, although the Wiimotes system was designed for whole-body interaction, analysis showed interaction was a mixture of object focus and subject focus.

In the second activity, where other objects were involved, the interaction became more object-focused as children were acting *on the objects* and analysing the consequences of the objects' movement. The physical properties of the objects were relevant to the context, as they produced different kinds of movement (rolling, swinging).

Input / Output Coupling

The location of the representations (co-located or discrete [12]) influenced children's ability to interact effectively with the system and with each other, mainly with regard to the locus of attention and awareness of others' actions (eg., keeping track of the system's feedback on a separate screen in the Wiimotes activities decreased awareness of others' actions, while the shared tabletop facilitated group work).

The link between action and effect is also less clear when the location design is discrete, especially when users are interacting simultaneously (i.e. not knowing what a user's action is producing on the screen 'over there'). This corresponds to the 'isomorph effects' discussed by Hornecker and Burr [6], i.e. how easy it is to understand the relation between action and effect, considering the representations adopted in the system and how they transform the problem.

IMPLICATIONS FOR LEARNING OPPORTUNITIES

The previous section outlined how the different designs influenced the kinds of actions and interaction that took place. Analysis shows that these in turn influence the kinds of learning opportunities and activities that are made available. In particular they were noted to affect opportunities for reflection, kinds of interactions between learners, and focus of attention.

Reflection and Action

The visual effects in the tabletop system, coupled with both discrete and continuous actions (like placing and removing objects from the surface (discrete) or dragging and rotating the objects (continuous)), remained the same until a user acted on an object. This enabled acting, and opportunities to reflect on the consequences of that action, which are considered important in learning contexts [1]. With this type of system, reflecting and acting can be simultaneous or intertwined with one another.

In contrast, with the Wiimotes users moved the interaction devices to generate data, but when they stopped moving, the visuals also ceased moving. Although the study was designed to promote children's conceptual inferences of motion through their direct experience of interacting with the system through their own body movement (subject-centred interaction), this meant that children could not stop what they were doing and still see a visual representation of their actions. In this case, there was less opportunity for them to reflect on their own actions. This shows that a focus on the subject and their movement in interaction has direct implications on reflection, as the body itself acts as an input device. This suggests the need to carefully consider design to allow opportunities for reflection when system's feedback primarily depends on action. A hybrid design in which the focus can move between objects to subjects, may allow for reflective opportunities where learners can both act and observe.

However, as the observers could watch someone else moving, other forms of reflection and inference were apparent, through learner-to-learner interaction. When one child was interacting with the Wiimotes system, the other children observed the action and resulting representation, and talked (reflected) about how the visual effects linked to different actions. In these instances, the observers engaged in more discussion about the relationship between action and representation than the child moving the Wiimote.

When all of the children interacted simultaneously, they often began by moving the device very rapidly, but then slowed their movements down to look more closely at how the orientation of the device affected the visualisation. Likewise, children often slowed their movements down (or stopped completely) when they were explaining what was happening or trying to understand other children's explanations of action and effect. The direct mapping between speed of movement and visual effect was important in enabling children's interpretation of the action-effect coupling. We describe this 'fine-tuning' of movement with the Wiimotes as 'granularity' [18]. In relation to this, Hornecker and Burr [6] discuss the importance of 'lightweight interaction', meaning that, among other things, a system must allow users to take small steps and test their ideas with constant feedback. Likewise, Sheridan's Wittingness framework [16] describes that in order to fully interpret, interact and perform with a tangible system, participants must undergo a stage of 'trial and error' where they are engaged in simple and repeatable actions. With the Wiimotes constant and repetitive slowing down and speeding up acted as a small step towards understanding the action-effect relationship. Overall, this suggests that systems should adapt and respond to variations in speed, frequency and granularity of input actions to allow learners to better reflect upon the effects of their action according to their own rhythm and preference.

Facilitated Interactions

The actions in the two systems facilitated different forms of group work and different interactions between learners, particularly in terms of interference, 'puppeteering' or directing, and observing or participating relationships.

Interference

With the tabletop system, everyone's input fed into the same, common digital environment. In other words, the pupils shared a set of objects on a surface and built a collective digital representation. This allowed dispute of objects and high levels of interference with one another's arrangements and actions, leading to interesting pedagogical implications, such as co-construction of ideas through resolving emerging conflicts [13, 21]. Despite potentially disturbing individual reflection, interference in the tabletop environment is shown to promote collaboration and collective reflection (see [11] for a detailed analysis).

In contrast, when each child had their own device and distinct digital representations with the Wiimotes, no dispute or interference could happen in the virtual world. Actions were more individually-focused as each child concentrated on the representation linked to their own device, which did not overlap with the others'. If on the one hand, this guaranteed an individual action-effect link for each participant, on the other hand, it led to a more individual interaction with less attention to others' actions.

However, with the Wiimotes, interference could still happen in the physical world. Analysis showed that interacting with the skateboards and ramps (thus sharing a set of physical objects) encouraged children to work as a group. When investigating the relationship between the different ways the objects moved and the corresponding representations, children suggested a number of small 'experiments', executed them collaboratively, and discussed the effects of their decisions.

For group interaction, the possibility of constructing representations together seems to be an important factor towards collective knowledge building. In both systems, children used the objects available collectively rather than taking possession of specific ones. With the Wiimotes system, having to deal with the objects in the discrete representation design enforced collective activities in which children took on different roles to achieve a common goal. Availability of objects therefore seemed to generally invite for collaboration.

Observing, Participating and Directing

Different levels of participation were identified in the studies. To physically participate with either system, children manipulated the objects. They also verbally participated by giving opinions, answering questions and directing or observing actions. In some cases, children preferred to observe others interacting with the system.

When only one child was in control of a Wiimote device, the others would observe and suggest movements to perform. This can be seen as a form of directing, or 'puppeteering', i.e. observers took the role of guide to control their peers' movement. This directing also occurred in the tabletop study, when children explicitly asked their peers' to collaborate when trying to construct something (e.g., asking a peer to place a specific object at a specific location, in order to achieve their own goal). Each group usually had a leader, who gave instructions about using the objects.

A very similar situation occurred with the Wiimotes system, where children directed each other, when working with the skateboards and swing, and given the freedom to move around the room to interact with the system. Giving the children more objects with which to interact with the system seemed to lead to more collective activity then when they had individual devices, but interacted shoulder to shoulder in front of the computer screen. Like with the table, having a small set of objects promoted the sharing of objects between users, rather than having each participant take possession of a specific device.

Children were also found to participate in different ways, e.g. one child would manipulate an object while another looked at the screen. However, for the child who was looking at the screen to draw any conclusions from the visuals, he or she also needed to know what was happening to the object itself. A number of common strategies used to overcome this issue emerged from the analysis:

- Directing from the screen: the child watching the screen would direct another child with the object to report on his or her own actions or on how the object was moving (e.g. "roll it and tell me when it changes direction");
- Directing with the object: the child with the object would ask the child watching the screen what was happening on the screen in relation to their movements (e.g. "is mine moving?" - "a bit");
- Self-directing: a child would direct their own actions and watch the resulting output on their screen (e.g. pushing a skateboard with his or her foot while watching the visuals change on the screen)

Our analysis indicates that these different levels of participating promoted collaboration and reflection. Observing only or directing peers instead of doing things themselves could allow children more opportunity for reflection (especially considering the rapid dynamics of the systems), even when the opportunity of actually experimenting with objects themselves was always an option (which relates to the 'experiential learning cycle' [8]). Observing and participating seems therefore to complement each other during interaction.

Focus of Attention and Awareness

With the tabletop, the children's loci of attention were focused on the same and shared area during interaction. Everyone's actions, and their consequent digital effects, were visible to the whole group.

While with the tabletop participants were around the table, looking at the shared surface, with the Wiimotes children were moving independently, acting in and around the room and each other, and trying to see the screen 'over there'. With the latter, even when they were interacting simultaneously and physically co-located (standing shoulder-to-shoulder) in front of the screen, awareness of others' actions was poor, as they had to concentrate on their own activities *and* the screen. Although the children could peripherally tell what each other was doing (and sometimes imitated each other), his or her attention was focused on his or her own movement and the consequent effects. Children found it difficult to interact *and* look at the screen *and* at their peers' movements all at the same time, whereas with the table they could see everyone's hands moving *and* the effects *and* the objects.

Having other objects to manipulate in combination with the Wiimotes introduced yet further conflicts regarding the loci of attention. Actions with these other objects (skateboards, swing, ramps) were constrained by the fact that children had to keep watching the screen to see the resultant digital effects. Our analysis clearly shows that children quickly turned from the screen to the object to try to make a conceptual link between visuals and movement. This relates to what Hornecker and Burr [6] call 'non-fragmented visibility', and is demonstrated in [17] as an important aspect of spatial interaction in tangible systems: difficulty in establishing the link between input actions and system's output causes a fragmented vision of the system, which in our studies hindered learning (as input and output seen in isolation do not convey the intended conceptual understanding).

In both case studies presented here, learning concepts were conveyed through links between the digital and the physical. This means that the perceived coupling between input and output is critical in tangible learning systems, and the choice between clear and ambiguous couplings should be pedagogically grounded. Co-located designs seem to lead to a more straightforward interaction, allowing learners to keep their attention simultaneously focused on what they are doing and what the system is showing in response. Additionally, such non-fragmented visibility facilitates collaboration and increases awareness of others' actions. However, co-located designs may not always be feasible, or suitable for the kinds of concepts to be conveyed. Alternative designs, which could improve awareness and deal with loci of attention in discrete systems, should be sought.

CONCLUSION

Tangible systems offer large degrees of freedom and flexibility in terms of design. Understanding the effects of particular design choices for learning environments is an important concern. Based on two different kinds of tangible learning environments, this paper explored the effect of design choices on physical engagement, action and interaction, and the implications for learning opportunities.

Analysis showed how specific aspects of the interaction with each system (namely, spatial organisation, manipulative or gestural interaction, and input/ output coupling), influenced the kinds of learning opportunities promoted. Findings indicate that when a number of physical actions are involved in the interaction with a system, and particularly when the system's feedback primarily depends on action, the action-representation links must be carefully designed to allow and promote conceptual reflection. In particular, the location of the representations (i.e. co-located, discrete) was found to have a direct impact on children's foci of attention and awareness of others' actions. This is particularly relevant, as studies have shown that not only acting, but also observing and directing peers are important activities for learning.

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