A Conceptual Framework for Mixed Reality Environments:
Designing Novel Learning Activities for Young Children

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Abstract
How do we conceptualise and design mixed reality environments (MREs)? Here we describe a first pass at a conceptual framework and use it to inform the design of different kinds of activities for children to experiment with. Our aim was to investigate how different MRE set-ups affected children's exploratory behaviour and their understanding of them. The familiar activity of colour mixing was used; different set-ups were provided, where paint or light colours could be mixed, by using either physical tools, digital tools or a combination of these. The findings of our study showed that novel mixes of physical and digital 'transforms' engendered much exploration and reflection.

1. Introduction

Recent advances in the design of interactive technologies have allowed the possibility of designing 'mixed reality environments' (MREs). Drascic and Milgram (1996) describe them as: "between the extremes of real life and Virtual Reality lies the spectrum of *Mixed Reality*, in which views of the real world are combined in some proportion with views of a virtual environment" (p. 123). A number of claims have been made about the benefits of different kinds of mixed realities (also sometimes called augmented reality), including enriching the user experience (Camarata et al., 2002; Schnadelbach et al., 2002), enhancing learning (Underkoffler and Ishii, 1998) and improving collaborative working and planning (Fjeld et al., 2002). However, little is known as to why and how augmenting real life with digital representations produce such effects One main thesis that has been proposed is that manipulating familiar physical artefacts (e.g. toy bricks) or acting in physical spaces, when interacting with digital information, provides greater embodiment for the user, where embodiment refers to immanent presence, compared with interacting with more abstract representations, e.g. interface metaphors that conventional computer-user interactions provide (Dourish, 2001). In other words, the kinds of interactions experienced in mixed reality environments fit more naturally with the way we act and interact with the everyday world. They do so by capitalizing on our familiarity with the everyday physical world, especially our innate and well-learned repertoire of physical actions (e.g. grasping, pushing, lifting).

Such claims about the value of physical embodiment in computer-mediated interactions are usually supported by recourse to philosophical and phenomenological writings, typically Heidegger, Merleau-Ponty and Gibson. To begin to understand how different kinds of *mixed realities* might produce different user experiences that differ from other kinds of computer-mediated interactions, requires us also to begin systematically examining them from a theoretical and empirical perspective. From a theoretical point of view we can consider a potential distinction as being that between: (i) the 'real' world where spaces and artefacts are acted on by conventional physical actions and where the user's understanding is, therefore, in terms of general causal models of the world and (ii) the 'virtual' where a different, and as yet little-understood, set of causal models operate and action is arbitrarily coupled to the properties of the perceived world. However, we now also have the possibility of extending the ontological profusion of worlds and objects to include environments with pervasive computing properties, building artefacts that have embedded digital intelligence. To some extent such objects have properties of both the former two. This raises the question of how people will deal, not only with the virtual spaces that Drascic and Milgram describe, but with *mixed reality environments* that combine real, virtual and ubiquitous forms.

Minimally, we need a terminology/taxonomy that allows us to describe acting in and on these forms and we offer a beginning set below. But we also need to link this to appropriate empirical work, to see how far these concepts have utility and whether they can be useful for future design of MREs.

The area we have chosen to empirically investigate our conceptualisation of mixed reality environments is play and learning. Our focus is on examining how new forms of physical/digital embodiment might encourage children to explore more and reflect on what they are doing. Promotion of reflection in children is a general learning goal, as it is well known to stimulate awareness and enhance learning (e.g. Piaget and Inhelder, 1967). A number of researchers have started to experiment with manipulative materials and physical artefacts to provide novel playing and learning activities, with this goal in mind (e.g. Colella et al., 1998; Druin and Perlin, 1994; Resnick et al., 1998; Stanton et al., 2001). Most well known, is the work of the MIT lab, where a main emphasis has been on creating a variety of physical toys and learning tools, embedded with computational and communication capabilities, aimed at enhancing interactivity and to engage children in new ways of thinking (e.g. Cassell and Ryokai, 2001; Kolomyjec et al.,1997).
Specific projects that have developed physical and virtual spaces to support children's creativity, include StoryMat (Ryokai and Cassell, 1999), Video Sandbox (Gislen and Harvard, 2000) and KidStory (Alborzi et al., 2000). These have all centred on the familiar activity of storytelling, but mediated and enacted out through quite different means compared with traditional aural and verbal methods. Children are encouraged to construct and manipulate aspects of the physical environment to create and listen to theirs and other's stories. This includes getting children to record and replay stories through moving toy animals around a mat, creating stories in conjunction with using video projections and manipulating 3-D structures by changing their colour, texture and form, respectively. KidsRoom (Bobick et al., 1999) was also designed as an interactive narrative *playspace*, using images, music, narration, light, and sound effects, where children were guided through a reactive adventure story.

The notion of *tangibles* is increasingly gaining currency as a way of describing physical artefacts embedded with computational power or closely coupled with digital responses. Within the context of learning, they are often designed to enable the occurrence of unexpected events, novel reactions, novel activities, novel combinations of activities or events, which in turn facilitate children to question them and to reflect on their experiences (e.g. Hoyles and Noss 1999; Stanton et al., 2001; Rogers et al., 2002).

Much of this line of research has so far been *ad hoc* in its design, focusing on enabling children to appropriate technologies in creative ways, rather than on understanding the nature of mixed realities *per se*. A general approach has been to provide a *bricolage* of tangibles and activity spaces. In contrast, our goal here is to begin to understand better what the effects are of particular kinds of mixed realities on children's exploratory behaviour and reflection. In particular, we are interested in how a very familiar embodied activity can be 'dressed up' in the context of different mixed realities, creating 'deviations' from what children usually expect to happen and to see how they react to them. To this end, we have developed a conceptual framework of mixed realities, which we categorize below in terms of the set of four possible combinations of the physical and the digital.

2. Conceptualising mixed reality spaces in terms of transforms

Previous research into conceptualising mixed realities has focused on moving from one physical place to another virtual one and vice versa via *boundaries*, that transparently connect separate, non-overlayed physical and virtual spaces. For example, Koleva et al. (2000, 2001) describe the properties of a 'traversable' interface, as something which "gives the illusion of joining physical and virtual worlds together and that users can physically cross from one to the other" (p.233). A number of properties have been suggested that can affect the success of these kinds of traversal illusions, namely permeability (how information passes through a boundary), situation (the boundary's spatial properties) and dynamics (its temporal properties). In addition to the idea of crossing boundaries, we propose the basic construct of *transforms* as a way of conceptualising a mixed reality space. By this we mean changes in the state of the world. In everyday life, people routinely encounter and represent, transforms between states of the world, for example in perception (e.g. seeing an object disappear and then reappear or changing one's viewpoint), in action (e.g. when the purpose of a gesture changes) and in cognition (as when we re-represent and re-interpret the state of the world). Dealing with transforms involves some implicit or explicit theory of what causes changes of perceptual/cognitive states, i.e. some sort of causal link is usually involved. Hence, transforms are a constant feature of ongoing perception and cognition. Here, we propose the additional term *transform type* to identify the different kinds of forms involved, viz the real, virtual and digitally-enhanced trio identified in our definition of mixed reality environments. For our purposes, however, we will use the term 'physical', rather than 'real', in this paper to allude to actions/activities/effects which do not involve virtual/digitally-enhanced artefacts. For the latter we shall use 'digital' as a cover-all term.

Our framework divides the conceptual space up into four kinds of transform types, coupling different combinations of actions and effects, varying along physical and digital dimensions (see Table 1).

Transform type	Level of familiarity
Physical action→ Physical effect (PPt)	Highly familiar
Physical action→ Digital effect (PDt)	Unfamiliar
Digital action→ Digital effect (DDt)	Familiar
Digital action→ Physical effect (DPt)	Highly unfamiliar

Table 1: Transform type and children's existing level of familiarity with them

These include a physical action with a physical effect (e.g. making a mark on paper with a pencil) and a physical action with a digital effect (e.g. moving a wand causing an animation to appear). The conceptual spaces are also characterized in terms of how familiar the transforms are to the children. The rationale for using familiar/unfamiliar as an organising concept here is that it should reflect experience and, consequently, as our previous research has shown, that unfamiliarity provokes reflection by the child (Rogers et al., 2002).

3. Using the conceptual framework to design an experimental setting

In order to investigate the four conceptual distinctions we designed a mixed reality environment for young children as part of the Equator project (www.equator.ac.uk). Our goal, within this research initiative, is to develop novel mixed reality spaces that enable children to experiment and play across different media and representations, while engaged in simple or more complex activities. In particular we wish to demonstrate something of the unique properties of the digital to enhance the physical by offering certain kinds of external cognitive support (Scaife and Rogers, 2001). The chief objective in the design of the present MRE was to get children to both experience and reflect upon their interactions, allowing hypotheses about their conceptualisations of these environments. At the heart of our design was the need to exemplify a variety of transforms within a specific knowledge domain, based on the combinatorial possibilities of real, virtual and ubiquitous forms.

To this end, we developed an activity space called the *Chromarium* – an environment where colour may be contained, observed and experimented on in a variety of ways. The core activity the children were required to engage in was discovering and experimenting with the mixing of colours. This is a very familiar physical activity that children normally enjoy using pots of paint, and which we wished to extend through providing novel transforms that they were unfamiliar with. To achieve this, we considered how colour mixing changes when using different media (i.e. using light) in conjunction with designing the various transforms (e.g. digital to physical). While children are very familiar with the effects of mixing coloured paints they are unfamiliar with the different effects of mixing lights (e.g. mixing all three additive primary colours using light produces white, whereas mixing equivalent primary paint colours, subtractive primaries, produces a brown-black colour).

For each kind of transform type we asked the children to guess what would happen if they mixed different colours and then subsequently got them to experiment with the different set-ups. Sample questions included:

- which secondary colours are obtained from mixing two primary ones (e.g. "what colour do you make when mixing red and yellow?")

- what happens when you mix two secondary colours together (e.g. “what colour do you make when mixing green and purple?”)
- what happens when all the primary paint colours are mixed together (e.g. “what colour do you make when mixing red, yellow and blue?”).
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In all cases the identity of the transform – namely colour mixing – remains constant (although the particular form of this obviously varies). What we have done in our design here is to alter the transform type, following our conceptual framework. Four types were set up, and labelled according to the mechanisms involved. It is important to realise that we are referring here to the *mechanism* which potentiates the transform. Thus a ‘digital action’ (like using a painting program on a display screen), inevitably involves some degree of physical action on the part of the user, but it is the (digital) mechanism that allows this, that is crucial here. The four transform types developed for the Chromarium study were:

Condition 1: Physical to physical transform (PPt: action and effect of same kind)
In this condition, we used the highly familiar activity of mixing paints as a baseline. In addition, we asked the children to mix lights using a set of torches that had different coloured filters and were shone underneath a perspex surface (Fig. 1). Mixing colours with paint involved using a paintbrush and selecting wet paints from different pots and combining them on a palette. The main constraint with this medium (that the children are highly familiar with) is that it is easy to add colours but not to remove them In contrast, this constraint does not occur when mixing lights, as it is easy to both add and remove colours by moving the torches towards and away from the surface. We were interested in whether the children discovered this in their experimenting and if they reflected upon this.

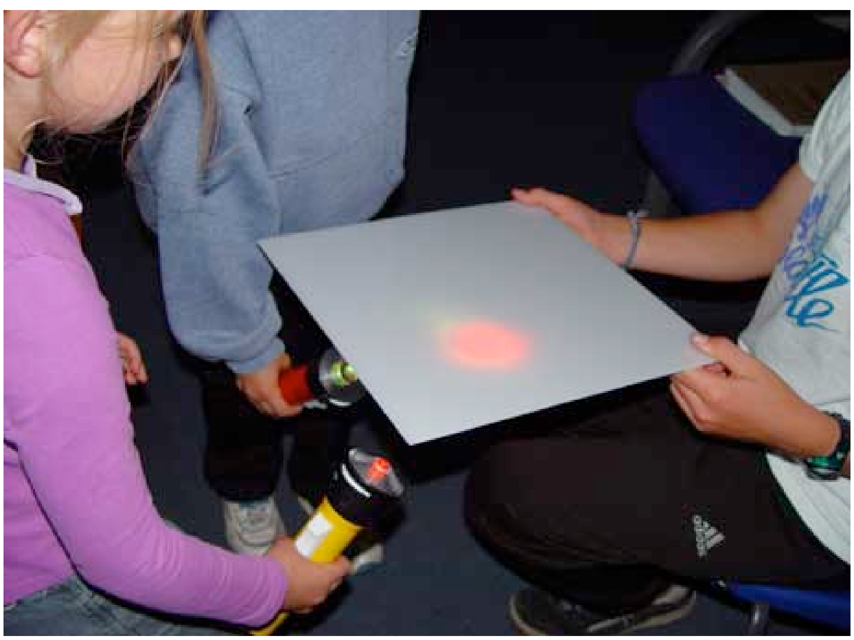

Fig. 1: Physical to physical transform (PPt): using torches to mix light colours

Condition 2: Physical to digital transform (PDt: action in physical with digitally-based effect)

In this condition, we used RFID tags to enable physical actions to trigger virtual effects. We built two coloured blocks, having a different colour displayed on each of their six faces. Each face of the block was also embedded with a hidden RF tag, so that it had a unique identifier. When a face of the block was placed on the RF tag reader, an animation mirroring the colour of the identified face was triggered and projected onto an adjacent vertical display (see fig 2). When two blocks were placed together on the tag reader, the two surfaces were read at the same time, triggering an animation of the colour that would result if the two were mixed (e.g. a red and yellow face would show an orange animation). As with condition 1, the children were asked to guess and subsequently experiment with what colours might result when combining the surfaces of the blocks together.

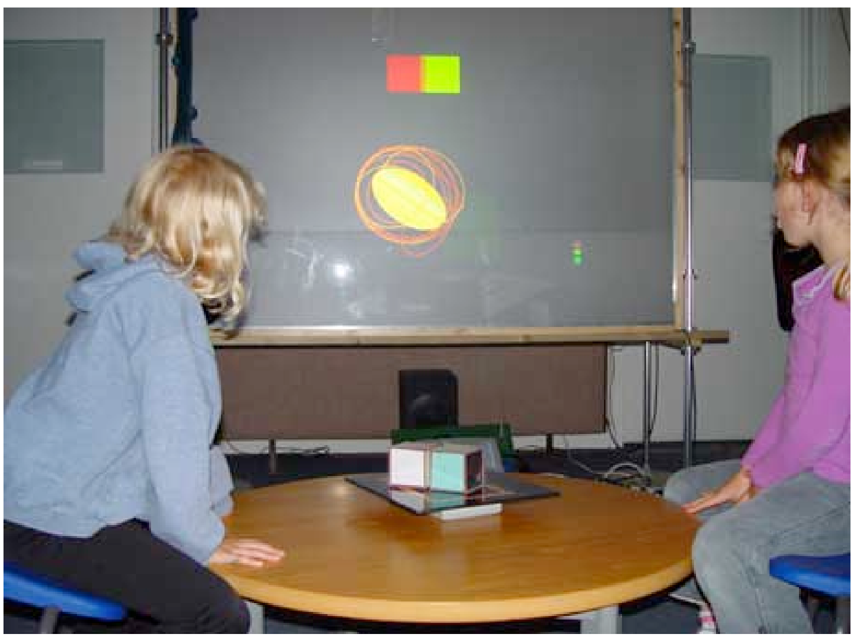

Fig. 2: Physical to digital transform (PDt): using coloured building blocks to mix digital colours

Condition 3: Digital to digital transform (DDt: action and effect of same kind)

For this condition we provided an interactive horizontal surface (mimio™) that enabled digitally-potentiated actions to trigger digital effects. Two software tools were used that supported mixing light or paint in a digital space, respectively (Mixing Colours and Computer Crayons). Both involved dragging coloured discs (representing paint or light) to overlap. Mimio input devices, disguised as either a paintbrush or a torch, were used for selecting the colours. The "paintbrush" activated the digital discs to move when the brush hairs were pressed against them (Fig. 3). The "torch" was held slightly away from the surface and a button on its side was pressed to activate it. Hence, the set-up for the DDt condition mirrored the two kinds of activities of the PPt condition. A main difference between the two conditions, however, was that colours could be both added and subtracted when mixing either digital paint or light.

Fig. 3: Digital to digital transform (DDt): using digital paint and light tools to mix digital colours

Condition 4: Digital to physical transform (DPt: digital action with physical effect)

This was the most difficult condition to provide a plausible transform. In the end, we used the Mimio set-up to enable a digitally-potentiated action to trigger a physical effect. A two-coloured (e.g. blue and white) digital windmill was displayed on the desk surface. Moving the arms of the digital windmill triggered the spinning of a physical windmill placed nearby, which had corresponding sets of coloured arms (see Fig. 4). The effect was to produce a spinning colour in the physical windmill (e.g. light blue-silver when blue and white arms were selected).

Fig. 4: Digital to physical transform (DPt): using digital colours to mix physical colours (DPt)

It should be pointed out, that the four conditions were not designed to be functionally equivalent, but as different kinds of mixed realities, with the aim of helping us to understand how different combinations of the physical and the digital affect children's behaviour. In particular, we were interested in how children understand and reflect upon novel transforms (i.e. DPt and PDt) compared with more familiar ones (i.e. DDt and PPt). Accordingly, we analysed our observations qualitatively.

4. Method

Ten pairs of children, aged between 5 and 6, were asked to take part in the Chromarium study. They were told that they would be mixing colours in fun and sometimes unusual ways. They took part in all four conditions, starting with the familiar activity of mixing physical paints. Pairs of children were asked to collaborate since this is generally considered to be a more effective way of getting children to talk openly and reflect upon their experiences. To elicit their understanding of the transforms, we prompted them to talk about their experience in the different conditions, by asking open-ended questions such as: "What do you think will happen if...?" or "How do you think this is working…?" To elicit further explanations from the children we also made use of counterfactual questions, such as asking the children to say what would happen if they tried to mix other materials (e.g. paper, fabric). The children were video recorded during the study.

5. Findings

The children's interactions and verbal reports were transcribed from the video data. These were analysed in terms of:

- what kinds of exploration took place in the different conditions
- what kinds of accounts were given by the children when talking about the underlying cause-effects of the various transforms

Children's explorations with the transforms

As we had predicted, the children experimented and reflected more with the less familiar transform types (PDt, DPt, DDt). The most experimenting was done in the PDt condition, and involved using the coloured blocks to mix colours. For example, several of the pairs of children tried to discover if the tag-reader surface was able to identify or capture other objects besides the coloured blocks. Two girls, for example, touched the tag reader area with their faces, expecting them to be scanned as digital images and projected onto the screen – just like the blocks. Their assumption was that the tag reader acted like a scanning device and could read any kind of object.

All the children tried experimenting with the various physical properties of the blocks to see what other effects they might produce. For example, several pairs of the children placed the coloured blocks in towers to see whether different colours would emerge with different combinations of coloured blocks. The way the RF tags had been engineered in the blocks meant, however, that only two surfaces could be read and mixed at any one time. One pair of children also expected digital mixing to happen when moving the blocks together, away from the table surface. Another pair tried to put the blocks against the digital image projected onto the wall to see if any effect was produced. They also tried to see if they could select a block's face by orienting it towards the area projected on the surface. Three of the pairs of children pressed the blocks down hard on the table surface, trying to amplify the mixing (e.g. making it darker).

We also found that the children experimented the most with the transforms, where the coupling between the cause and effect could be rapidly observed and reversed. This was most noticeable for the coloured blocks, where mixing new colours could be done rapidly simply by turning the blocks over. Indeed, all pairs of children placed most, if not all (with several repeats) of the possible permutations of the six different sides of the two coloured blocks on the RF tag reader. Turning the blocks over to recombine different surfaces and then watching the immediate effect as a digital representation on the screen was very satisfying and perpetuated further explorations. It also proved to be a highly collaborative activity. Typically, both children would grab a block and turn it or sometimes one would take both, while the other made suggestions as to what faces to mix.

In contrast, in the DDt condition, the children tended to explore colour mixing using the software tools by themselves and chose not to talk with each other or make suggestions as to what each should do. A consequence was that they did not explore nearly as many combinations, even though there was the same scope for experimenting with and reversing actions as in the PDt condition.

Children's accounts of the transforms

The very familiar activity of mixing colours using paints elicited unremarkable responses; the children knew beforehand the outcome of mixing two or three colours and this was confirmed by their actions. When provided with the torches they were bemused at first by the fact that the result of shining the torches together under the Perspex surface produced a different colour from mixing the same coloured paints (e.g. mixing red and green made a yellow colour as opposed to brown). When questioned about this, however, the children were unable to explain why there was a difference between mixing lights and paints, nor did they try to experiment further with other combinations that might produce different effects. Only one child was able to come up with an account, which they did by resorting to the use of analogy:

Facilitator: "Did you know you can mix colours like that with torch light?"
Child: "No, but I do know what you can do with sun and rain. I know how you make a rainbow. Sun reflects on rain".
To try to get the children to reflect and reason more about the differences when mixing colours in the different conditions, we tried a different tact, which was to ask counterfactual questions, to which the children were much more forthcoming with their answers. For example, when asked "Why is material not like paint?" all the children were able to respond with answers like "…because it's not gooey!" or "it is not runny" This implies they were aware of a key property of paint that is what enables colour to be mixed, but that other media or materials do not have and which prevents them from being mixed in the same fashion. When it came to understanding how the hard surfaces of the coloured blocks could be combined to make a new colour the children were able to make an exception to this 'rule'. The 'mixing' was done through the transform, producing a digital representation of the resultant colour. Hence, it did not conflict with the logic of their earlier reasoning, since they understood a different cause-effect model to be underlying it. In fact, the children's understanding of the causality involved in this condition were largely techno-centric. When asked to explain how the digital colour mixing worked, they said things like: "the effect is coming from the computer's screen

over there, and it arrives here by means of electricity" (6 year-old girl). Another child (a 5 year-old boy) pointing first at the table under which the tag-reader was concealed, then to the projected image, then to the computer said "…connect, connect, connect…wire…it is connected under here [*table*] and goes all the way up to there [*PC behind him*]!".

Similarly in the DPt condition, the children often resorted to techno-centric explanations of what caused their actions in the digital environment to mix colours in the physical windmill. One pair said '…this [*digital windmill*] is making that go round and round, because we are using this [*the mimio pen and the digital windmill*] …and they are connected with wires!'. They also looked under the table to discover which device was causing an effect and how the different pieces of technology were connected to each other.

The action of pushing was also considered an important part of the explanation: one pair of children explained that the physical windmill made a silver green-blue colour because they were pressing on the blue and white arms of the digital windmill. Another child said to the other, "this is making it go round and round" to which the other said "it's because we're pressing the computer". Interestingly, similar to the children's reasoning about the pushing down of the coloured blocks, one pair thought that the faster they moved the digital windmill round, the paler the colour would become in the corresponding physical windmill, as its arms would likewise move faster (this was not actually possible to do, although the perceptual effect of the physical windmill starting up and slowing down did convey this).

6. Discussion

A main objective of the work reported here was to develop a conceptualisation of mixed realities that could provide a means of systematically investigating and informing the design of novel 'user experiences' In particular, we wanted to begin understanding how people dealt with mixed realities that combine different physical and digital forms, especially those which capitalize on familiar actions. Do they treat the mixed reality experiences differently from everyday experiences and, if so, are there differences across the possible set of physical and digital combinations? To begin answering this question, we argued, needed both theoretical and empirical investigation.

Whereas others have focused on conceptualising the properties of traversals across physical and virtual spaces, and different ways of augmenting the physical, we chose to conceptualise mixed reality here in terms of how activities can be transformed through different ways of combining the digital and physical. We provided a simple classification of transform types, which enabled us to design different kinds of mixed realities, varying in their degree of novelty and type of underlying cause-effect.

The framework has since then been used by us to develop other novel learning environments for children (Price et al., *in press*). It has provided us with a structure to inform the design of different kinds of activity spaces, that combine and chain familiar actions with unfamiliar effects. In so doing, it has allowed us to be systematic in combining the digital with the physical and vice versa, based on our understanding of familiar physical-physical transforms.

The most interesting transform that was found in our empirical study of colour mixing was where the children manipulated physical artefacts (coloured blocks) to create digital

results. The combination of reversibility and immediate feedback enabled by this transform was central. In addition, the affordances of the physical blocks invited 'embodied' actions. Namely, the physical blocks were 'ready-at-hand' for manipulating and sharing: they could easily be picked up by both children simultaneously or in close succession and a range of highly visible and natural actions performed on them, like swapping, turning, combining and placing them on the surface or on top of each other.
In contrast, even though the digital-digital transform provided the same scope for reversibility and immediate feedback, it was discovered that the selection of the digital disks of colour using the mimio pen or torch did not support anything like the same kind of ready-at-handedness. Instead, the degrees of freedom of what actions could be performed on the disks was heavily constrained (only dragging allowed) and just one child could perform an action at a time, while the other remained essentially an onlooker. Moreover, to switch roles required one child to consciously and deliberately hand over the input device to the other child – a gesture that is often socially difficult for children to do, since it requires them to hand over 'control', which often can be problematic, either through the child forgetting about the other or not wanting to for various reasons (e.g. being submissive, showing failure). Studies of collaborative learning, where children have to share the same mouse when using a piece of software, point to how awkward and difficult such change-overs can be (e.g. Stanton et al, 2001).

In terms of designing novel transforms, our study has shown that the most challenging transforms to create are digital to physical ones as it was hard to provide a range of plausible effects. Nevertheless, what we did create was very intriguing to the children. We are currently exploring more diverse digital-physical combinations. A crucial feature is to ensure that there is immediate feedback, with as little delay as possible between the performance of an action and the perception of its effect (as happens with everyday physical to physical transforms). We are also looking at how to design counterintuitive and more complex types of cause-effects to see if they can facilitate more elaborate forms of exploration and reflection in mixed reality environments. Finally, one of the claims we would make about the benefits of designing novel mixed realities in the context of play and learning is that by juxtaposing the 'unexpected' with the highly familiar promotes 'richer' experiences, prolonged interest and more reflection.

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