What have you done! The role of 'interference' in tangible environments for supporting collaborative learning

Taciana Pontual Falcão, Sara Price
London Knowledge Lab, 23-29 Emerald Street WC1N 3QS, London, UK
Email: t.pontual@ioe.ac.uk, s.price@ioe.ac.uk

Abstract: This paper presents a study that investigated collaborative activity in a tangible tabletop environment to support learning about the physics of light. In co-located groups of three, children performed exploratory activities, using tangible artefacts, to find out about light. Analysis suggests that the environment can support various collaborative activities, but of central interest, demonstrated the role of peer interference in learning activities. Verbal negotiation and synchronization of actions emerged as conflict-resolution strategies and an implicit agreement by the children for sharing the physical and virtual resources of the system was noticed. The physicality and 'present at hand' nature of the input devices contributed to balanced levels of participation, particularly through action. Overall, the interference-prone tabletop environment contributed to creating a highly collaborative environment in which individual exploration was discouraged, leading the group through a productive process of collective exploration and knowledge construction.

Introduction

Tangible and tabletop interfaces offer new opportunities for collaboration in digitally augmented spaces, particularly due to the facility for multiple simultaneous input, and the sharing of physical resources. The value of tangible and tabletop environments has been demonstrated in terms of engagement and enjoyment (Xie and Antle, 2007), intuitive interaction and appeal for collaboration (Morris et al., 2006; Piper et al., 2006). However, much research to date on shared interfaces has focused on CSCW (Computer Supported Co-operative Work). Shared interfaces for co-located collaborative learning pose different challenges, and little research has yet investigated how collaborative interactions around tangible tabletop environments might support learning.

Shared interfaces are considered appealing for collaboration and learning for a number of reasons. Shared interfaces can support co-located interaction for multiple users to simultaneously interact with digital information (Sharp et al., 2007), and are shown to provide more equal access and participation (Rogers et al., 2008). Tangible-based interfaces also provide tools for mediating new kinds of external representations, potentially supporting new forms of collaborative interaction and learning. Interaction centres around physical action and manipulation of multiple objects offering opportunities to build on everyday interaction and experience with the world, and opportunities for expression and communication through action. This sits in contrast to mouse-based interaction where mappings between action on object or virtual representation are indirect. Furthermore the use of physical artefacts can provide a more fluid way of sharing control, and encourage participation of reticent users (Rogers et al., 2008).

Tangible technologies, in the form of physical artefacts coupled with digital information, allow access to more or different information than is normally available in the immediate physical environment. The close mapping of physical properties of objects to the learning domain, and direct mapping of manipulation and action to digital output can illustrate domain concepts more explicitly. However, such environments are also inherently dynamic, comprising multiple representations and transient information, and where both physical and digital representations can change in form, space or time. This results in an environment with multiple representations and transient information (e.g. Stenning, 1998; Price, 2002; Ainsworth, et al., 2002), and the effect on reasoning and collaborative interaction for learning needs further investigation.

As part of an ongoing research programme, this paper presents a study that explored collaborative activity in a purpose built tangible tabletop environment to support co-located learning about the physics of light. This investigates how shared interfaces affect the way that collaborative activity is structured, and examines the kinds of collaborative interactions that are productive for learning, and in particular, the role of parallel actions with physical interaction devices in mediating collaborative activity and communication that supports learning. Analysis indicated the role of interference through action in structuring and mediating collaborative interaction and communication, both verbal and physical. The findings are discussed in relation to levels of participation, interference from action in a rapidly changing dynamic environment, and its effect on curiosity, exploratory and inquiry activity, negotiation and synchronization of actions, sharing and control of resources and the subsequent implications for collaborative learning.

Related work

Shared interfaces for co-present collaboration, are designed for multiple users to simultaneously interact with digital information (Sharp et al., 2007), aiming to provide more equal access and participation, with a more fluid way of sharing control (Rogers et al., 2008). Shared interfaces can be implemented through Single Display Groupware (SDG) (Stewart et al., 1999), tabletops, and tangible interfaces. In SDG environments, co-located users interact with a system via multiple input devices getting feedback from a single output display (usually screen or wall). Tabletops can be viewed as face-to-face SDG's as opposed to the shoulder-to-shoulder interaction promoted by vertical displays (Piper et al., 2006). Much research on tabletops focuses on multi-touch interfaces (e.g. SenseTable (Patten et al., 2001), SmartSkin (Rekimoto, 2002) and DiamondTouch (Deitz and Leigh, 2001)) as opposed to interaction through physical devices (Reactable (Jordà, 2003)). Recently, however, the implementation of tangible interfaces through tabletop surfaces has become more common. The kind of interaction they provide comes closer to traditional tabletop activities and allows alternating between individual and collaborative use (Scott & Carpendale, 2006). This paper explores co-located collaboration in a learning context using a tabletop display surface with tangible input devices.

One of the advantages of shared interfaces for collaboration is the potential of multiple input devices. One strand of related work has explored the use of multiple mice with traditional computer interfaces. Studies with children indicate higher levels of activity (Inkpen et al., 1999); less time off task (Inkpen et al., 1999; Stanton et al., 2002a); less monopolization of the task (Stewart, 1999) greater equity of activity (Stanton et al., 2002a); higher levels of motivation (Stanton et al., 2002a); and more effectiveness of task completion (through parallel or co-operative work) (Stanton et al., 2002a). However, shared control was also shown to result in less collaboration due to parallel working without having to share the input device (Stewart et al., 1999); and less verbal reciprocity (Stanton et al., 2002a) with little elaboration of ideas as children were primarily engaged in their own actions (Stanton & Neale, 2003). Enabling more equal access to the physical input devices by decreasing the competition for access (Stewart et al., 1999) does not directly imply an increase in collaboration.

Another strand of work focuses on physical artefacts (multiple input devices) as resources to support collaboration and shared understanding (e.g. Stanton et al, 2002b; Rogers et al., 2008)). With *Kidpad* (Stanton et al., 2002b) the visibility of actions characteristic of tangible environments were found to make users aware of the collective action during synchronous interaction, though asynchronous interaction was reported to allow reflection and reaction time. The action with inputs was identified as important in aiding collaborative behaviour. For instance, children often collaborated through action without verbal communication and observed others' actions interrupting or reacting accordingly (Stanton et al., 2002b). Furthermore, children would assume tutoring roles to help each other out (Stanton et al., 2002b). Rogers et al.'s (2008) analysis of participation and collaboration using a laptop, a multi-touch tabletop and a tabletop with physical artefacts as input devices, showed that the physical objects enabled groups to systematically consider and discuss different possibilities. Also, participants who spoke the least demonstrated high levels of physical activity, suggesting that physical devices allow reticent users to contribute to the activity in non-verbal ways. External representations and artefacts are also thought to play a key role in shaping thinking (e.g. Wertsch, 1998; Scaife & Rogers, 1996) through their ability to both constrain and enable thinking and acting. Crook (1995) claims the value of referential anchors in the form of external representations in supporting construction of shared understanding. This paper explores the use of multiple physical artefacts as input devices and external representations in supporting and structuring collaborative activity.

The potential for increased conflicts and interference in shareable interfaces through incompatible actions and behaviours has also been highlighted (Stewart et al., 1999; Morris et al., 2006; Hornecker et al., 2008). Comparing different input devices on shared interfaces, Hornecker et al. (2008) suggest that multi-touch (as opposed to mouse based) interaction generates more "clashes", but leads to greater awareness of others actions, and more fluid interaction. Furthermore, conflicts may emerge from parallel work when users try to perform incompatible actions (Stewart et al., 1999). Morris et al. (2006) report conflict behaviours in document sharing, and suggest the need for coordination policies, to increase group awareness and encourage a sense of involvement. In learning contexts forms of conflict have been identified as being important catalysts for conceptual change, for example, through forms of cognitive conflict (Piaget, 1967) or perturbation (Laurillard, 1997). Collaborative learning contexts in general extend opportunities for such conflicts to arise through peer-peer discussion and negotiation or adult-child and even computer-child interaction. The resolution of conflicts and co-construction of ideas and repairs following misunderstandings indicate highly productive collaborative interaction (Roschelle & Teasley, 1995; Stanton & Neale, 2003). However, little is known about the occurrence and effect of action clashes in shared interfaces for learning, particularly within an environment designed to support exploratory discovery learning, and whether they inhibit or support co-construction of knowledge. This paper discusses the effect of 'interference' on various aspects of collaborative interaction and learning.

The benefits of collaboration, from a learning perspective, depend on the styles of the collaborative behaviour (Stanton & Neale, 2003), and the nature of the activity and learning domain (Stewart et al., 1999; Stanton & Neale, 2003). Wegerif & Scrimshaw (1997) address the "educationally important talk"; Littleton (1999) suggests the computer not only supports collaboration, but transforms the way in which collaborative activity is structured. Within creative, problem-solving, or exploratory environments, collaboration may support co-constructing a story or resolving differences of opinions, where sharing ideas and perspectives is more important than efficiently producing a final answer. This paper involves an exploratory learning environment where the process of knowledge building is central rather than production of a particular answer.

A large body of the research focuses on how computers and technologies can support collaborative learning through communication, primarily through verbal interaction and social negotiation. A key aspect of this involves challenging others about their views, as well as reaching an understanding of their world through collective agreement (Piaget, 1967; Vygotsky, 1978). Furthermore, externalisation through verbal expression in the form of self-explanation, is shown to make explicit to oneself and (in the context of collaborative activity) to others, any discrepancies in understanding, providing opportunities to revise thinking and understanding (Chi, 1997). A part of such verbal interaction creates "conflicts" which are shown to enable higher performance than if working alone (Crook, 1998). However, cognitive or social conflict alone is not necessarily predictive of conceptual development, Scardamalia & Bereiter (1993) emphasising the importance of the explanation accompanying the conflict as a mediating factor in knowledge building. Primarily communication has taken the form of verbal interaction, expression, and argumentation, with less understanding of the role of action in the collaborative dialogue. This paper discusses the how communication may be supported in collaborative environments through action, and in combination with verbal interaction.

The tabletop environment

An interactive tangible tabletop environment was built based on reacTIVision technology (Kaltenbrunner & Bencina, 2007). The software application developed (in Processing language) to run with the table aims to support students learning about the behaviour of light, exploring concepts of colour and light reflection, transmission and absorption. In the context of this application, interaction with the system is enabled exclusively through a set of concrete objects: several different coloured plastic blocks and a torch tagged with fiducial icons (Figure 1). The objects are only recognized when fiducials are facing down (in contact with the table surface), enabling the camera placed underneath the table to see them and identify each particular object and its location.

Figure 1. Objects tagged with fiducials (left) and their position on the table (right).

Multiple objects can be simultaneously recognized, enabling several users to interact at the same time. Visual effects projected on the tabletop show light reflection (Figure 1, right), absorption, transmission and refraction, triggered by the interaction amongst the torch and the blocks on the table surface. As the torch is the only source of light in the application, all effects are dependent on its presence on the table. Placing the torch on the surface immediately produces a white light beam, and all other effects result from the interaction of this beam with the concrete blocks. Similarly, removing the torch from the surface causes all effects to disappear.

Different objects (Figure 1, left) were designed to illustrate each phenomenon: square coloured blocks reflected light; rectangular coloured blocks with holes (as a way of 'seeing inside' the object) illustrated reflection and absorption; and transparent blocks showed transmission and refraction. "Digital light" travels in the environment respecting laws of reflection and refraction, thus even subtle rotations of an object changes the angle (and direction) of the reflected beam and affects the whole arrangement on the table.

Studies

A study was undertaken to evaluate the tangible environment in terms of engagement, collaboration, and the effect of locations and metaphorical mappings (Price, 2008). In this paper, we focus on the findings relating to collaboration.

The study involved 21 children aged 11-12 years (11 female and 10 male), from Year 7 classes of two schools in the outskirts of London (UK). Children worked with the tangible system in groups of three, consisting of a mixture of girls and boys, making 7 groups of children. Each session lasted 35-45 minutes. Some children were aware of basic 'light' concepts such as light traveling in straight lines, shadows, and opaque and transparent objects. They were told that they were not being assessed or evaluated and there were no right or wrong answers, but they were expected to use the system to find out more about the behaviour of light and express their opinions and ideas. The system was therefore designed to support exploratory interaction to support knowledge construction of the domain, rather than to complete a fixed task with a final answer.

Children were initially given five minutes of free play to familiarize themselves with the system. Few instructions were needed, as the environment was very intuitive and pupils were able to interact easily. The facilitator prompted the group only where necessary with general questions such as *"what's happening here?"* and *"why do you think this is happening?"*, to guide students through the exploration of the concepts towards making inferences and drawing conclusions. Eventually, the facilitator called children's attention to particular objects or phenomenon, or to ask children how they could find specific information or produce a particular effect. At the end of the sessions, post activities consisted of using transparent objects that behaved as coloured ones. The aim of the activity was to verify whether children had grasped basic concepts regarding the relationship between colour and the physics of light behaviour (i.e. a green object reflects green light from the white beam).

All sessions were video-recorded. After engaging with the tangible system children were informally interviewed in their groups to obtain information on their understanding of key concepts of behaviour of light, feedback on the usability of the system as a whole, and their general experience.

Key findings

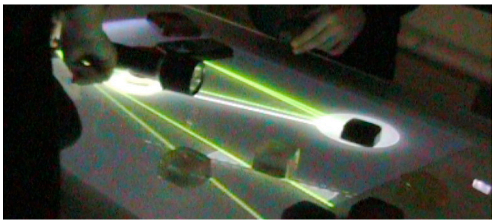
Findings based on collective qualitative analysis of observation, video data and interview data, focused on collaborative interaction in the tangible environment. All of the children expressed their enjoyment from interacting with the environment, and indicated that it would help them remember what they had been doing "*because it was fun"*. All the children found interaction with the objects and table unproblematic. Evidence from their interaction, and their explanations with demonstration to their teachers following the activity suggest that children were grasping the concepts being explored. The findings presented here centre around the role of combined artefacts, action and representation in supporting collaborative activity, both physical and verbal.

The Role of Interference

When using the tabletop environment, children interacted both physically (taking complementary or opposing actions) and verbally (contributing to one another's ideas or giving orders), and both in terms of how the environment works and in terms of the concepts of light. By building on each other's ideas and actions, they could reach a collective understanding. The facility of tangible environments to support action on external representations, means that interaction is centred around moving and manipulating objects, and action becomes the central mediating factor in the collaborative interaction. Thus, the design features of the environment supported a high level of physical interaction. Shared interfaces also support multiple users to simultaneously physically engage in the environment. This means that sequential collaborative activity is not necessary, and concepts of turn-taking are not embedded in the functioning of the system. The analysis showed that such design features promoted episodes of interference, both physical and verbal. Although this sometimes caused interruption in activity, e.g. where children were prevented from building an arrangement to explore a concept, our analysis revealed the positive role of interference in providing opportunities to challenge children's thinking and understanding about the concept and promoting reflection through unexpected events. Despite having to deal with rapid and uncontrolled changes, one may benefit more from having other people's interference (bringing more challenge and variety of situations) than from performing actions on one's own, or through a rigid sequential turn-taking process. In this section, different forms of interference and the contexts in which they were observed are described and discussed, considering their role in a collaborative learning process.

Effects of Local Actions x Global Interference

The fact that the environment presented in this paper accurately modeled the theoretical phenomena we were exploring meant that it was extremely dynamic: moving any object involved in a particular arrangement affected all digital effects displayed. Very small (and even unnoticed and unintentional) changes may "destroy" the current configuration. For example, a blue object placed on a red beam will "stop" the beam, whereas a red one will reflect the light, therefore changing the direction of the beam. Thus, when one child decided to try something out while another child was working on the current arrangement, or using it for explanations, this interfered with another's activity. For example, while one child was trying to find out what happened with white light on a transparent object and then onto a further object, another child placed a red object between the torch and the transparent object, thus blocking the pathway of the light beam to the transparent object. On other occasions, while one child was responding to facilitator and using the table to verify answers, the others used the blocks to do something different, interrupting the attempt to focus on one particular idea. Although the children may think they are only dealing with that particular object or area of the surface, and may not notice their own interference in another's actions, the effect will be widespread if the local action involves the beam of light. While it may be difficult to control the changes when the group is dealing with many objects at the same time, our findings suggest that this "unintentional interference" promoted productive effects on the interaction and collaboration, and in particular stimulated curiosity (promoting reflection) and effective coordination of actions towards common goal and understanding. For example, when trying to understand reflection from multiple objects, one group collectively built an arrangement on the table (Figure 2, left), then suddenly the digital reflected rays vanished (Figure 2, right), causing general surprise (*"oh, what!"; "what happened?"; "you moved the torch!"*). One of the children then moved the torch, producing different effects and promoting discussion about reflection *("reflect back to the white light"; "it's not reflecting on the white light"*).



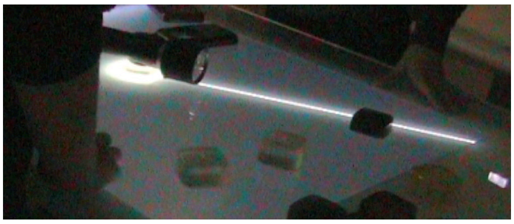


Figure 2. Unintentional interference leading to complete changes in configuration

The parallel actions, favoured by the multi-user feature of the interface and the collection of objects available, provoked rapid and continuous changes to the digital display in relation to the physical objects. Often this led children to request peers to *"stop – leave it, leave it"* or to slow down (*"wait, wait – what was that?"*) when they wanted to see what was happening. Drawing on research on animation (e.g. Price, 2002), which suggests that dynamic representations may be problematic for learning, particularly due to the speed in which things change during interaction, would suggest that there may not be enough time for reflection on each configuration. In some cases, children would take turns and act sequentially, allowing more time to think. However, with the tangible tabletop interface the immediate effect of actions performed with the input devices allowed the children to identify that others' actions had caused the changes. Evidence of their attention to each other's actions or speech were apparent in exclamations like *"what have you done!"*; *"you've moved the torch!"*, and rhetoric questions such as *"what's that?"*; *"what have you got on there?"*; *"what about this one?"*. In instances like this, when the relationship between action and effect was unclear, interference provoked curiosity, an important stimulus for conceptual development (Lehtinen et al., 1999; Price et al., 2003), and drew children's attention to the phenomena caused by others. This led to group explorations through action and verbal interaction of the particular 'light behaviour', engaging them in a knowledge production process. As an example, when asked by the facilitator what happens when objects of the same colour are used simultaneously, a group started experimenting with green blocks. At first, the girl had not realised green light would reflect from green objects, until she saw the boy producing such an arrangement (*"oh, yes, you can!"*). Trying to formulate an explanation, the boy suggested *"because it's the same colour, is it?"*, to which the girl added: *"so it makes it able to bounce off"*. The girl then decided to build on the current arrangement adding other green blocks, but the boy interrupted her plans by moving the first block she had placed. After asking him to *"put it back"* the girl tried placing another block on the green beam, but accidently captured the white beam instead, completely changing the configuration, to her own surprise (*"what did I do?"*). The boy took out the block explaining that she had put it in front of the white light. The third child in the group then moved the torch, causing instant reactions of *"no, no, leave it where it was!"; "put it back there"*. As they still struggled to rebuild an arrangement with multiple reflections, the children made comments like *"it's not reflecting";"but it was reflecting!"* Thus, combined action with the rapid dynamic changes of the environment mediated productive episodes of collaborative interaction focused around the phenomena being learned.

At other times the relationship between others' actions and the resultant digital changes were apparent to the children, and enabled them to request, for instance, a block to be taken away so that the on-going exploration of a current configuration could be continued, or some action to be repeated to be analysed (*"do that again"*). Collective activities were sometimes hard to perform: for example, when a group tried to reflect light off several green objects, with each child controlling one object, they initially kept moving them, thus changing the direction of light and making it difficult to get it to bounce off all of them. In instances like this, awareness of action promoted the development of negotiation and synchronization between the children. Overall, constant interference led to a unique focus of attention within the system, serving to draw attention to relevant instances of the phenomena, generate inquiry around those instances, and support effective collaborative activity.

Encouraged by the continuous interference inherent in the system, children instigated engagement in a collective process of knowledge production. Once they became more aware of the global effect of their actions, they understood that they needed to coordinate in order to achieve their goals. Both verbal and physical negotiation emerged during this synchronization. In groups where one child stood out as a leader, verbal orders would be common, such as *"put all the green ones"*, *"shine it there"*, *"move it round"*, *"put it back"*, *"reflect light into that"*, *"put this in front of there"*. Through those orders, the child tried to decide the flow of the activity and build arrangements as they wished, still having the participation of the rest of the group, but keeping it somehow under their control. The synchronization was also done in a more democratic way, when children invited peers to collaborate: *"can we try that one?"*, *"let's try this one"*. Children also reported their own actions, making peers aware of what was going to happen: *“I’ll turn it on”*, *“I’ll put that orange one in front of the torch”*; or would simply call attention to their actions: *“look! Look!”*. After a discussion with the facilitator about white light being made of different colours, one group decided to *“put them* [the objects] *all together, it probably makes white”*. While the others assembled the objects, one child held the torch, and then pointed it towards the blocks. In this way the environment supported constructive child-negotiated collaborative activity.

Sometimes a child would directly and intentionally interfere in their peers’ actions or arrangements, though in a constructive manner, like: giving demonstrations (for example, one girl moved a block on the table and told her friend: *“if I put this here… you lost your colour”*, rebuilding the previous configuration afterwards: *“now you’ve got your colour again”*); giving helpful instructions (e.g. showing how to make the system work: *“you have to put it down”* or when a peer was trying to achieve something *“if you put it down that way and take that out…”*); collectively exploring the system (building on each other’s actions to test their own hypotheses while thinking aloud *“what happens if…”, “what if I do this…”*). These instances of interference illustrate how the environment encouraged externalization, both through verbal explanation and through action in the form of demonstration. In one instance, a boy was making assumptions on an arrangement in which a light beam was going through a transparent block and subsequently reflected by a yellow block (Figure 3, left). A girl then interfered by changing the order of blocks and showing that the light would no longer reach the transparent block; the boy agreed, but added that they would still get reflection off the yellow block (Figure 3, right).

Figure 3 Direct interference leading to reflection on concepts

Impact of Controlling and Sharing Resources

Besides the interference caused by the global effects of users’ actions, the design features of this tabletop environment also encouraged particular kinds of group interaction through the input devices: namely, the torch; the virtual resources or digital effects; and the physical blocks. These were noted to affect equality of collaboration, control of the activity and sharing of resources.

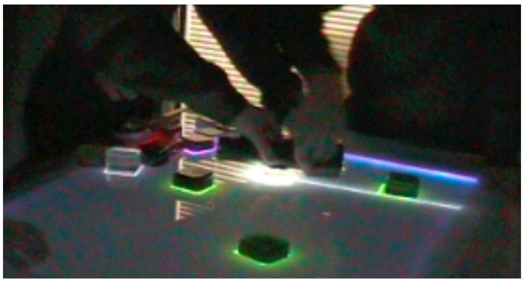


Figure 4. Three children disputing the torch

In this environment all digital effects depended on *one* physical resource (the torch) being placed on the surface (see Section The Tabletop Environment). The torch, being the source of all digital effects, was essentially a “control tool”. As such it was occasionally the centre of dispute, for example, in one instance three children physically (though gently) disputed the torch (Figure 4): they had their hands placed on the object and tried to point it to different objects. These kinds of dispute usually ended with someone naturally giving up. In some groups, one child would clearly stand out as a leader and keep the torch under his control (and on his “territory”, i.e., closer area of the table) most of the time, though in other groups interaction flowed very collaboratively, with a shared – rather than centralized – control of the torch. Although this feature had the potential to cause centralized control depending on the personal characteristics of users, it actually turned out to be a smooth way of implicitly enforcing collaboration through the interface (Piper et al., 2006). In the case of shy children, for example, despite their tendency to play in their own corner of the interface, they needed to get involved with the group activity to gain access to the light beam and therefore be able to produce some effect from the objects they were manipulating. Thus, this design was useful in promoting all children to be actively included in the collaborative activity. Furthermore, as interaction did not depend on possession of a physical object (i.e. the torch) itself, to engage in exploratory activity using the objects but the virtual light beam emitted from the torch, the potential for inclusive collaborative activity was enhanced.

Virtual resources in the environment (i.e. virtual beams of light) could be easily "captured" by children using physical blocks, which transmit, absorb or reflect the virtual beam. Interference here can be seen as a kind of 'control' action, where children were trying to exert, or maintain control of the digital effects from their actions, and in so doing caused interference for others actions. Sometimes this was intentional and sometimes not. For example, children very often: placed an object in between the torch and another object placed by their peer, therefore intentionally "stealing" the white beam; pushed objects out of the light pathway using another object; or simply rotated the torch. On the other hand, children could rotate a block without noticing they were depriving a peer of the light beam.

The concrete blocks themselves were sometimes taken from others, not because of interest in the particular object (as there were enough blocks available for everyone), but rather to control the current arrangement, which involved that block. This raises issues about feelings of possession. In the environment presented here, children did not stick to using a specific block – the arrangements were of more concern than the objects themselves. In one situation, a child took control not only of the torch, but also of objects being used by peers, to prevent them making changes. This was not about "possessing" the objects themselves, but about having the control of the patterns built on the table. However, despite this wish for control, our findings suggest that the dynamics of the environment contributed to a lack of attachment to personal creations (as all would easily fade), as well as the collective process of building them.

There were some situations where children would individually create configurations, but because of the 'interference' properties of the environment they automatically became involved in group activity. In one group, while building something, a boy "dictated" what the others should do so that *he* would reach *his* goal. He dragged all objects near him and pointed the torch to his territory. Another boy spent most of the session exploring the interface on his own, silently building his own arrangements, and would occasionally take objects from his peers' arrangements for his individual goals, purposely unaware of the group activity. However, as he did not always have the control of the torch, he was forced to pay attention and get involved in the group activity, even if with the only goal of getting hold of the torch at some point. In cases like these, children were using the interface "on their own, but together", i.e. although they were pursuing individual goals, the constant interference of the shared interface and the dependence of the one torch made the activity collective anyway. In other words, their effort to individually use a shared interface was prevented by a design feature. Children therefore switched between actual, explicit collaboration (dialogue and actions clearly synchronized towards a common goal) and some serendipitous collaboration, forced by the design of the interface. The only way for someone to work totally isolated would be taking control of all objects, which seems unlikely to happen (and never did in the studies presented here).

Most of the time, "stealing" concrete resources was done very smoothly, almost as if children were sharing them through mutual agreement, or "physically asking" to borrow them. For instance, sometimes children did not believe their eyes when someone else was testing an arrangement and had to *do* it themselves to check. In this case, the child would take the relevant object from their peer's hands and try out the same arrangement. In some way, such situations were part of an implicit protocol of handing resources over, according to which children would silently agree to share the objects. No situations occurred where children verbally asked for objects (by saying "give it to me"). This suggests that the physical presence of artefacts provided a way of mediating sharing (as well as constructing), without collaborators having to be verbally explicit. Awareness of others actions (as a physical form of communication) may not only facilitate fluid interaction (Hornecker et al., 2008), but also seamless sharing of physical objects as tools. This has implications for issues of inclusivity as well as providing the verbally shy with better opportunities for equal interaction.

Overall, sharing of resources happened spontaneously and contributed to the group activity. Commonly, a subset of the available objects was used collectively by the group, whose attention was focused on the arrangement produced. Children alternated control of the objects, interfering in the collective arrangement to test different hypotheses that were shared within the group, either visually or verbally.

Discussion

A key finding from the studies presented here was the 'interference' activity that occurred in different forms during collaborative interaction in the environment. It was accidental, when children did not predict the effect of their actions, or intentional, when children purposely changed arrangements, to give demonstrations or help each other out by giving instructions (both physically and verbally). Although some forms of interference can be seen as conflicting actions or clashes as mentioned by Hornecker et al. (2008), Morris et al., (2006) and Stewart et al. (1999), they do not have the negative connotation (found in the literature) within our environment, as they promoted specific kinds of collaboration, giving rise to collaborative activities that are beneficial for learning.

The tabletop environment invited parallel actions and the dynamics, which arose from those actions, provoked rapid changes in the configurations built on the table, together with high levels of interference. The global effect of local actions frequently interfered in the whole arrangement when dealing with any beam of light. As noted by Rogers et al. (2008), the technological setup had a great influence on the resulting interaction patterns. The interference-prone tabletop was particularly instrumental in provoking curiosity, drawing attention to relevant instances of the phenomena, and engendering exploratory and inquiry activity. At other times this led to the need for verbal negotiation and synchronization of actions, either to enable collective building of arrangements or to allow enough time for children to reflect on the underlying concepts. The latter case confirms findings from Stanton et al. (2002a), regarding the difficulty in finding time to reflect in synchronous interaction as opposed to a taking-turn environment; and Barron (2003), who highlights the need for learners to manage both their own effort to understand the problem and what others are doing, in such collaborative contexts. However, the visibility of everyone's actions within the environment (also reported by Stanton et al., 2002) made negotiation possible through explicit requests for slowing down or going back. Therefore, external coordination policies as suggested by Morris et al. (2006) to mediate the activity, were not needed. Instead, the children naturally found their way through a collective exploratory activity with resolution of conflicts that proved to be a constructive process, supporting the reported benefits of conflicts (Stanton & Neale, 2003). Conflicts due to shared control of resources occasionally caused longer task completion, confirming findings by Stewart et al. (1999), but provoked more reflection facing children with unexpected events (cf Price et al., 2003). In an exploratory environment in which task completion is not the main focus of the activity, longer exploration may actually be a benefit more than a problem.

Negotiation was also apparent in children's discourse through orders, suggestions, invitations to collaborate, comments on peers' actions and reporting on one's own action. This coordination of attention, said to be fundamental for joint engagement (Barron, 2003), enabled children to collectively build arrangements and test their hypotheses, answer facilitator's questions, or just explore the interface. The need for synchronization and agreement also supported constructive child-negotiated collaborative activity and promoted a collaborative process of exploration and knowledge production. Therefore, verbal interaction involved not only reporting actions (Stanton et al., 2002a) when multiple input devices are available, but also conceptual discussion and elaboration of ideas. Although physical action often surpassed conversation, children were not usually left without answers, indicating a high level of verbal reciprocity (as opposed to findings by Stanton et al. (2002a)).

Interference also played a role in the sharing and control of the system's virtual and physical resources. Digital effects (light beams) could be captured (intentionally or accidentally) by the concrete blocks, which were themselves also handed over or disputed throughout the interaction. However, this "dispute" occurred naturally and blocks were handed over allowing everyone to try out different objects themselves. Therefore, though monopolization of activities was still possible (Stanton & Neale., 2003), the characteristics of the environment made domination very unlikely, allowing the equity of participation mentioned in the literature (Stewart, 1999; Stanton et al., 2002a). The physicality and availability of input devices contributed to more balanced levels of participation, including more reticent children, and encouraged collective hypotheses' testing, as reported by Rogers et al. (2008).

As the objects did not embody representations of the users, but behaved as actual concrete blocks within the environment, they were shared with no feelings of identity or possession. Of more concern for the children were the particular arrangements, although the collaborative building process conveyed a sense of collective belonging rather than individual production. This collective ownership of productions favoured the co-construction of ideas as opposed to the co-operative individual activities that Stanton & Neale (2003) report. In our environment, children did not divide tasks, partly because the design of interface would not allow such procedure, nor did they collaborate less for having multiple input devices, as found by Stewart et al. (1999). Instead, resources were shared around a unique focus of attention and everyone had the right of interfering in the arrangements at any time (although some implicit agreement on taking turns, keeping the flow of actions reasonably sensible, respecting others' choices and allowing time for reflection was noticed).

Although synchronization was not always easily achieved and parallel actions sometimes provoked too rapid changes to allow reflection, overall interference (both through actions and their consequences and through sharing virtual and physical resources) contributed to creating a highly collaborative environment in which separate individual exploration was implicitly discouraged. Verbal and physical negotiation as well as attention to others' actions and speech emerged from the interference, leading the group through a productive process of collective exploration and knowledge construction.

Children were not formally tested on the concepts involved in the study, nor were they explicitly taught during the sessions, but their exploratory activities and post-interviews provide initial evidence of the conclusions they were drawing about light. Light reflection, being a reasonably familiar concept to the children (mainly through experience with mirrors in everyday life), was easily identified and discussed during interaction and reported in the post-interviews. On the other hand children described processes of absorption, transmission and refraction in their own words illustrating their understanding. For instance, the representation of absorption through the spectrum of colours inside the object led to statements like *"the rainbow was inside, but the green wasn't there because the green was already reflecting"*. Transmission was invariably explained as light "going through" *("it was transparent so it goes through"*); and refraction as "bending" (*"it just goes straight through it unless you've got an angle, then instead of going straight it goes down there"*). The concept of white light being made of different colours was also brought up during the interviews *("white light can separate into little parts, the colours"*), as well as the notion that an object reflects the colour you see *("so what happens if I put a white light against a blue object? Blue light will shine."*). Diffusion from rough surfaces was mentioned with enthusiasm as the virtual representation seemed to convey the correct concept *("an object with a rough surface, the light just reflects everywhere, but without it just reflects in one direction"*).

Conclusion

Recent developments in sensor based and touch screen technologies provide new tools for collaborative activity. Shared interfaces for collaborative learning pose specific challenges, and require design for activities that support productive learning through collaboration. Little work yet exists that examines the processes of collaborative interaction in co-located tangible shared interfaces and their implications for learning. A purpose-built interactive tangible tabletop environment running a software application was built to support children learning about the behaviour of light. This paper presented the findings from a study undertaken to investigate children's collaborative interaction and learning. A key finding from the studies was the different forms of "interference" and their effect on the collaborative activity. The interference-prone tabletop was particularly instrumental in provoking curiosity, drawing attention to relevant instances of the phenomena, and engendering exploratory and inquiry activity, as well as promoting verbal negotiation and synchronization of actions. The concrete input devices were shared through an implicit protocol of handing resources over and the collective nature of arrangements produced on the tabletop favoured the co-construction of ideas as opposed to co-operative individual activities. The physicality and availability of the input devices contributed to more balanced levels of participation. Overall, interference led to a highly collaborative environment, which supported collective exploration and knowledge production, although the dynamics of the interface sometimes caused too rapid changes and challenged synchronization of actions. Evidence of nascent understanding of the phenomena was noticed through children's dialogues and actions during interaction and in the post-interviews.

References

Ainsworth, S, Bibby, P. & Wood, D (2002). Examining the effects of different multiple representational systems in learning primary mathematics. *Journal of the Learning Sciences.* 11(1), 25-62.

Barron, B. (2003).When smart groups fail. *Journal of the Learning Sciences*, 12 (3), 307-359.

Chi, M. (1997). Why is self explaining an effective domain general learning activity. In (ed) Glaser, R. *Advances in Instructional Psychology*. Lawrence Erlbaum Associates.

Crook, C. (1995). On resourcing concern for collaboration within peer interactions. *Cognition and Instruction* 13, 541-547.

Crook, C. (1998). Children as computer users: the case of collaborative learning. *Computers and Education, 30*, 3/4, 237-247.

Dietz, P., & Leigh, D. (2001). DiamondTouch: A Multi-User Touch technology. *Proceedings of Annual ACM Symposium on User Interface Software and Technology*, Orlando, USA, pp. 219-226, ACM Press.

Hornecker, E., Marshall, P., Dalton, S., & Rogers, Y. (2008). Collaboration and Interference: Awareness with Mice or Touch Input. To appear in *Proceedings of Computer Supported Cooperative Work (CSCW'08)*, San Diego, USA. ACM Press.

Inkpen, K.M., Ho-Ching, W., Kuederle, O., Scott, S.D., & Shoemaker, G.B.D. (1999). This is fun! We're all best friends and we're all playing: Supporting children's synchronous collaboration. *Proceedings of Computer Supported Collaborative Learning (CSCL'99).*

Jorda, S. (2003). Sonigraphical Instruments: From FMOL to the reacTable. *Proceedings of the 3rd Conference on New Interfaces for Musical Expression (NIME 03),* Montreal (Canada).

Kaltenbrunner, M., & Bencina, R. (2007). reacTIVision: A Computer-Vision Framework for Table-Based Tangible Interaction. *Proceedings of the first international conference on Tangible and Embedded Interaction (TEI07).* Baton Rouge, Louisiana.

Laurillard, D. (1997). *Rethinking University Teaching: A framework for the effective use of educational technology*. London: Routledge.

Lehtinen, E., Hakkarainen, K., Lipponen, L., Rahikainen, M., & Muukkonen, H. (1999). Computer supported collaborative learning: A review of research and development. *The J.H.G.I Giesbers Reports on Education, 10*. Department of Educational Sciences University of Nijmegen.

Littleton, K. (1999). Productivity through interaction: An overview. *Learning with Computers: Analysing Productive Interaction* (eds. K. Littleton & P. Light) pp. 179–194. Routledge, London.

Morris, M. R., Cassanego, A., Paepcke, A., Winograd, T., Piper, A. M., & Huang, A. (2006). Mediating Group Dynamics through Tabletop Interface Design. *IEEE Computer Graphics and Applications*, 26 (5), pp. 65-73.

Piaget, J. (1967). *The psychology of intelligence.* London: Routledge & Kegan.
Piper, A. M., O'Brien, E., Morris, M. R., & Winograd, T. (2006). SIDES: a cooperative tabletop computer game for social skills development. *Proceedings of Computer Supported Cooperative Work (CSCW'06)*. Banff, Canada. ACM Press.
Price, S. (2002) Animated Diagrams: How effective are explicit dynamics for learners? In P. Bell, R. Stevens, & T. Satwitz (eds), *Keeping Learning Complex: The Proceedings of the Fifth International Conference of the Learning Sciences* (ICLS) 344-351. Mahwah, NJ: Erlbaum.
Price, S., Rogers, Y., Scaife, M., Stanton, D. & Neale, H. (2003) Using 'tangibles' to promote novel forms of playful learning. *Interacting with Computers,* 15/2, May 2003, pp 169-185.
Price, S. (2008). A Representation Approach to Conceptualising Tangible Learning Environments. *Proceedings of the Second International Conference on Tangible and Embedded Interaction*. Bonn, Germany.
Rekimoto, J., Ullmer, B., & Oba, H. (2001). DataTiles: a modular platform for mixed physical and graphical interactions, *Proceedings of SIGCHI Conference of Human Factors in Computing Systems (CHI'01)*, Seattle, USA, pp. 269-276, ACM Press.
Rogers, Y., Lim, Y., Hazlewood, W. R., & Marshall, P. (2008). Equal Opportunities: Do Shareable Interfaces Promote More Group Participation than Single User Displays? *Human Computer Interaction 24(2)*.
Roschelle, J., & Teasley, S.D. (1995). The construction of shared knowledge in collaborative problem solving. *Computer Supported Collaborative Learning* (ed. C. O'Malley) pp. 67–97. Springer Verlag.
Scaife, M., & Rogers, Y. (1996). External Cognition: how do graphical representations work? *International Journal of Human-Computer Studies* 45, 185-213.
Scardamalia, M., & Bereiter, C. (1993). Technologies for knowledge-building discourse. *Communications of the ACM*, 36, 37-41.
Scarlatos, L.L., Dushkina, Y., Landy, S. (1999). TICLE: A Tangible Interface For Collaborative Learning Environments. *Extended Abstracts of SIGCHI Conference of Human Factors in Computing Systems (CHI 99)*, 260-261, Pittsburgh, USA. ACM Press.
Sharp, H., Rogers, Y., & Preece, J. (2007). *Interaction Design: Beyond Human-Computer Interaction*. 2nd Edition, Wiley.
Scott, S. D., & Carpendale, S. (2006). Guest Editors Introduction: Interacting with Digital Tabletops. *IEEE Computer Graphics and Applications*, 26 (5). IEEE Computer Society.
Stanton, D., & Neale, H. R. (2003). The effects of multiple mice on children's talk and interaction. *Journal of Computer Assisted Learning* 19, 229-238, Blackwell Publishing.
Stanton, D., Neale, H. R., & Bayon, V. (2002a). Interfaces to support children's co-present collaboration: Multiple mice and tangible technologies. *Proceedings of Computer Supported Collaborative Learning (CSCL'02)* pp. 342-351, Boulder, USA. ACM Press.
Stanton, D., Bayon, V., Abnett, C., Cobb, S., & O'Malley, C. (2002b). The effect of tangible interfaces on children's collaborative behaviour. Short Talk: Supporting Collaboration through HCI. *SIGCHI Conference of Human Factors in Computing Systems (CHI 02)*, Minneapolis, USA. ACM Press.
Stenning, K. (1998) Distinguishing Semantic from Processing Explanations of Usability of Representations: Applying Expressiveness Analysis to Animation. In (eds.) J. Lee, *Intelligence and Multimodality in Multimedia Interfaces: Research and Applications*, AAAI Press.
Stewart, J., Bederson, B. B., & Druin, A. (1999). Single Display Groupware: A Model for Co-present Collaboration. *Proceedings of SIGCHI Conference of Human Factors in Computing Systems (CHI 99)*, 286 – 293, Pittsburgh, USA. ACM Press
Vygotsky, L. (1978). *Mind in society.* London: Harvard Press.
Wegerif, R., & Scrimshaw, P. (1997). Computers and Talk in the Primary Classroom. *Multilingual Matters*, Clevedon.
Wertsch, J. (1998). Mind as Action. Oxford: Oxford University Press.
Xie, L., Antle, A., & Motamedi, N. (2008). Are tangibles more fun? comparing children's enjoyment and engagement using physical, graphical and tangible user interfaces. *Proceedings of the 2nd International Conference on Tangible and Embedded Interaction*, Bonn, Germany. ACM Press.

Acknowledgments

This research is supported by the EPSRC: grant number EP/F018436. We would like to acknowledge Jennifer Sheridan and George Roussos for their instrumental collaboration in the research. We would also like to thank students and teachers from Woodlands and Sweyne Park schools for their participation in the research studies.