Computer-Supported Collaborative Learning
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Interfering and resolving: How tabletop interaction facilitates co-construction of argumentative knowledge

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Abstract Tangible technologies and shared interfaces create new paradigms for mediating collaboration through dynamic, synchronous environments, where action is as important as speech for participating and contributing to the activity. However, interaction with shared interfaces has been shown to be inherently susceptible to peer interference, potentially hindering productive forms of collaborative learning. Making learners effectively engage in processes of argumentative co-construction of knowledge is challenging in such exploratory learning environments. This paper adapts the social modes dimension of Weinberger and Fischer's (Computers and Education 46(1):71–95, 2006) analytical framework (for argumentative co-construction of knowledge) to analyse episodes of interference, in the context of a shared tabletop interface, to better understand its effect on collaborative knowledge construction. Studies involved 43 students, aged 11–14 years, interacting in groups of three, with a tangible tabletop application to learn basic concepts of the behaviour of light. Contrary to the dominant perspective, our analysis suggests that interference in shared interfaces can be productive for learning, serving as a trigger for promoting argumentation and collective knowledge construction. Interference episodes led to both productive and counter-productive learning opportunities. They were resolved through quick consensus building, when students abandoned their own activity and accepted changes made by others; integration-oriented consensus building, where students reflected on and integrated what happened in the investigation; or conflict-oriented consensus building where students tried to undo others' actions and rebuild previous configurations. Overall, interference resolved through integration-oriented consensus building was found to lead to productive learning interactions, while counter-productive situations were mostly characterised by interference resolved through conflict-oriented consensus building.

Keywords Co-construction of knowledge · Interference · Physical interaction · Shared interfaces · Tangible interfaces

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Introduction

In many cases, computer-supported collaborative learning (CSCL) involves text-based communication over a network, through which learners are expected to engage in some argumentative discourse to co-construct knowledge (Weinberger and Fischer 2006). However, innovative technologies are creating new possibilities for mediating collaboration, and broadening the scope of CSCL environments that go beyond written networked communication. This paper presents an analysis of collaborative knowledge construction in the context of a shared tabletop interface, designed to support students learning scientific phenomena.

Shared interfaces are considered useful tools for mediating and supporting collaboration. They are designed for co-located users to simultaneously interact with digital information (Sharp et al. 2007), and can be implemented, for example, through multi-touch tables and tangible systems. Their physical affordances, as opposed to traditional desktop computers, result in different social affordances that have an impact on the dynamics of group work (Rogers et al. 2008; Morris et al. 2006). Previous research exploring a variety of uses of tabletops has created a general assumption that such technologies promote more enjoyable, natural and effective collaboration, particularly by enhancing awareness of others' actions and promoting more equal participation (Hornecker et al. 2008; Rogers et al. 2008).

However, the relationship between such greater engagement in collaborative activities with tabletops, and effective collaborative learning is not clear (Do-Lenh et al. 2009). Fleck et al. (2009) suggest that analysing the combination of verbal discussion and physical action is fundamental for understanding collaborative learning around tabletop computers. With tangible input devices, as opposed to multi-touch surfaces, physical interaction plays an even more important role, as users have the possibility of performing different actions with a variety of objects that must be shared and controlled collaboratively. Such simultaneous interaction through multiple input devices can easily cause episodes of 'interference', such as conflicts and clashes, that can be triggers of productive learning situations (Fleck et al. 2009; Pontual Falcão and Price 2009), but have also been considered disruptive and counter-productive (Hornecker et al. 2008). In addition, being an alternative environment for exploratory learning, tabletops have inherited critiques such as ineffectiveness in learners' argumentation and poor acquisition of knowledge, caused by lack of explicit guidance (Kollar et al. 2005). On the other hand, unlike non-augmented exploratory learning environments, tabletops provide a kind of computer scaffolding, an increasingly popular way of guiding students through collaboration and argumentation (de Jong and van Joolingen 1998; Kollar et al. 2005), as computers become more integrated in educational settings.

Overall, previous research indicates a potential of interference in shared interfaces as a trigger for promoting argumentation and co-construction of knowledge in inquiry learning. However, a detailed analysis of the nature of these learning instances and collaborative processes provoked by episodes of interference in such contexts is currently lacking. This paper seeks to address this by undertaking an in depth analysis of 'interference' data from our tangible table-top studies, drawing on Weinberger and Fischer's (2006) framework, to analyse the processes of argumentative co-construction of knowledge in this collaborative environment. Interference can be viewed as a form of peer contribution that materialises as some form of disruption to activity. Such interference can be intentional or unintentional, verbal or physical, but nevertheless generates the need for consensus building. The 'social modes' dimension of this framework, in particular, offers a structure for analysing the way learners manage contributions from their peers, and use them to build a consensus to be able to work collaboratively. We therefore apply the three categories of consensus building (quick, integration-oriented, and conflict-oriented) (Weinberger and Fischer 2006) to episodes

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of interference, during students' engagement in exploratory learning with an interactive tabletop application about the physics of light. The aim is to investigate to what extent peer interference in exploratory tabletop interaction can promote productive argumentation and co-construction of knowledge. We adapt Weinberger and Fischer's ideas, intended for analysis of text-based interaction, to a dynamic, synchronous environment where action is as important as speech for participating and contributing to the activity.

After exploring the role of technology for scaffolding inquiry learning, and how instances of interference and conflict can play an important part in the learning process, we outline the framework on which our analysis is based. A description of the studies and the tabletop interface then precedes our analysis (with detailed examples) of student interaction with the tabletop, in terms of argumentative co-construction of knowledge related to episodes of interference. Finally, we discuss the implications of the different ways of resolving interference for learning, and the role of the tabletop interface within the process of knowledge co-construction.

Background

Collaborative learning is increasingly being brought into practice in educational settings, as research has demonstrated that, on average, group work leads to better learning outcomes than individual work (Cohen 1994; Webb and Paliscar 1996). However, there is a need to move beyond measurements of individual learning outcomes from collaborative settings, to better analyse how the processes involved in such contexts contribute to building knowledge (Barron 2000).

Discovery or inquiry-based modes of learning are frequently undertaken collaboratively. Here, learners are expected to explore a model or simulation to infer underlying rules, properties and processes, and build their own conclusions. However, productively engaging in such learning processes is not straightforward for learners, who often have difficulty engaging in fruitful, substantive argumentation in their working groups. The ability to engage in constructive dialogue is fundamental for making sense of a problem together (Barron 2000). Learners must establish common frames of reference, resolve discrepancies in understanding, negotiate individual and collective action, and come to joint understanding (Rochelle 1992). However, in many cases arguments raised by one student remain unaddressed by peers, and disagreements left unresolved. Low-level argumentation might be reflected in poor elaboration of learning contents and result in a limited acquisition of domain-specific knowledge (Kollar et al. 2005).

For these reasons, several authors claim the need for providing scaffolding for inquiry learning (de Jong and van Joolingen 1998; Kollar et al. 2005), helping learners to overcome their deficiencies and, in particular, to engage in productive argumentation. As computers become more aligned to learning processes, they also turn into instrumental tools for giving this kind of support. Several approaches have been suggested to structure collaborative argumentation within inquiry activities (Bell 1997), collaboration scripts (explicit procedures for collaborative learning tasks) being one of the most popular. According to Kollar et al. (2005), many computer-supported approaches for inquiry learning are too open, where learners do not have enough explicit, instructional guidance on collaboration and argumentation, being free to choose the activities they will perform, and the way to execute them. As they often work as groups (even if not co-located), the lack of explicit collaborative procedures may lead to unequal participation and ineffective argumentation (Kollar et al. 2005).

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Much of this work, however, is situated within traditional settings of computer-assisted learning such as collaborative online environments. The advent of new technologies is creating new possibilities for implementing collaborative learning settings, especially for co-located, simultaneous interaction. One of the most prominent examples is the shared interface system for co-present collaboration, designed for multiple users to simultaneously interact with digital information (Sharp et al. 2007). Overall, they can consist of single display groupware (Stewart et al. 1999), tabletops, and tangible interfaces. Generally speaking, co-located users interact with a system via multiple input devices getting feedback from a single output display (screen, wall, or the tangible objects themselves).

One of the advantages of shared interfaces for collaboration is the potential of multiple input devices. However, this also increases conflicts and interference through incompatible actions and behaviours. Conflicts were noted during parallel work when users tried to perform incompatible actions (Stewart et al. 1999) and with document sharing (Morris et al. 2006), suggesting the need for coordination policies, to increase group awareness and encourage a sense of involvement. Hornecker et al. (2008) suggest that multi-touch interaction generates more clashes than mouse based interaction, but at the same time leads to greater awareness of others actions, and more fluid interaction. Fleck et al. (2009) found that 'intrusions' in tabletop interaction, commonly seen as harmful in collaborative settings, can promote productive elaborations and justifications. In learning contexts, forms of conflict, such as cognitive conflict (Piaget 1967), are considered important as catalysts for conceptual change. Collaborative learning contexts 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 following misunderstandings indicate highly productive collaborative interaction (Stanton and Neale 2003). However, little is known about ways in which clashes in shared interfaces are managed by learners. In particular, the effect of action-derived interference, and how this might inhibit or support co-construction of knowledge.

The development of methodological tools for analysing scientific argumentation, and extensive research into the argumentation process itself, has arisen through evidence that engaging in processes of argumentation is beneficial for students learning science, specifically their development of scientific knowledge (Schwarz et al. 2003; von Aufschneider et al. 2008). In the context of tangible interfaces, however, any formal basis for analysing such interactions and their effects is lacking. Although Hornecker and Buur (2006) outline interactive features of tangible environments to provide an analytical approach to interaction, this does not take a learning perspective. We know little about how such environments, through a combination of action and verbal dialogue, might stimulate argumentative co-construction of knowledge. Analytical research to date has focused primarily on communication in the form of verbal interaction (e.g. Weinberger and Fischer's framework (2006)). A clearer understanding of how exploratory tangible learning environments such as interactive tabletops may support productive collaborative inquiry is essential.

Studies

Participants

The studies involved 21 students from Year 7 classes, aged 11–12 years (11 female and 10 male), and 22 students from Year 9 classes (10 female and 12 male) aged 13–14 years, from two schools in the UK. Students worked with a tangible environment in groups of three, consisting of a mixture of girls and boys. The teacher selected the groups on the basis of being able to work well together. Year 7 students were aware of basic concepts about light behaviour, such as light travelling in straight lines, shadows, and opaque and transparent objects. Year 9 students had already learned about light in school, but pre-test results showed they had not yet mastered the concepts that the interface was designed to convey.

The tangible tabletop environment

A purpose built tangible environment was developed to support young students learning about the behaviour of light, and in particular, basic concepts of reflection, transmission, absorption and refraction of light, and derived concepts of colour. Although the general interaction with the system bears some similarities with *Illuminating Light* (Underkoffler and Ishii 1998), the technology employed, the application domain, and the targeted users are distinct. Our tangible tabletop system draws on the technical design of the reacTable (Jorda 2003), and used reacTIVision software for object recognition (Kaltenbrunner and Bencina 2007). The system consisted of a table with a frosted glass surface, which was illuminated by infrared light emitting diodes (LEDs). This illumination enabled an infrared camera, positioned underneath the table, to track the objects placed on the table surface. A variety of hand crafted and off-the-shelf plastic objects were used, which worked as input devices (Fig. 1, left).

Each object was tagged with a paper marker called a 'fiducial' (Fig. 1, right). Each fiducial is distinctly different and, when placed on the table surface, can be tracked by the infrared camera. The fiducials allow each particular object to be identified, together with its location and orientation. When distinct objects were recognized by the system, the reactivision software was programmed to project digital images onto the tabletop surface, via a data projector placed underneath the table, using back projection techniques to display feedback illustrating light behaviour. The digital images, or feedback, were designed to reflect light behaviour with multiple objects of different colour, texture and shape. Several objects could be recognized simultaneously enabling several participants to interact with the tabletop together (more technical detail in Sheridan et al. 2009).

Visual effects were triggered when users placed and manipulated the torch and the blocks on the surface. The torch acted as a light source (causing a digital white light beam to be displayed when placed on the surface), and objects reflected, refracted or absorbed the digital light beams, according to their physical properties (shape, material and colour). For instance, as a block looks green because it reflects green light, in this application pointing

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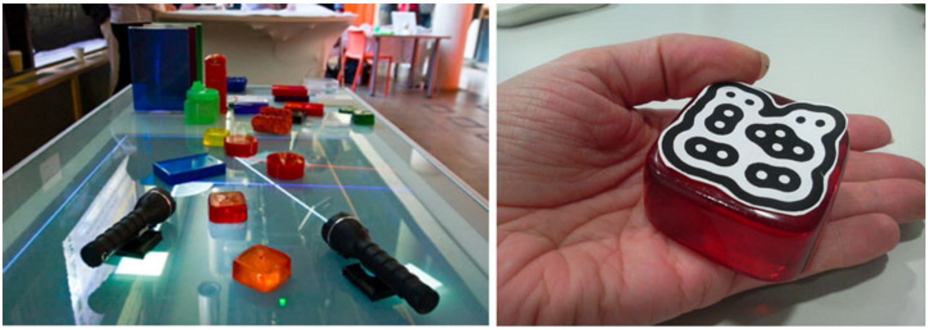

Fig. 1 **a** & **b**: the objects used as input devices (*left*) and an example of the paper markers (*right*)

the torch at a green block caused a green beam to be reflected off the block (Fig. 2, left); while pointing the torch at a transparent object caused the white light to continue from the other side of the object, refracted according to the angle that the beam came into contact with the object (Fig. 2, right).

The torch, when placed on the surface, was 'always on', while the other objects only produced digital effects when they came in contact with the digital light beam. In other words, if an object (other than a torch) was placed on the surface and was not in the path of the digital light beam, then no digital visual effect was elicited. To see the digital effects, students had to make arrangements on the surface using the torches and different objects. 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. All physical objects functioned therefore as interaction devices, and were used collectively by the students. There was no limit to the number of objects that could be used simultaneously on the surface. Despite such large availability of interaction devices, in certain situations students were interested in the same object and physically 'disputed' it, i.e. two or three students had their hands on the same object, trying to manipulate and control it on the surface. Such episodes were spontaneously resolved between the students themselves.

Procedure

The tangible tabletop was situated in a semi-darkened room in a lab-based context. Each group of students was invited to interact with the tangible interface to collectively explore and understand how light behaves, with various different kinds of materials, as described above. They worked with the system for about 35–45 min and were encouraged to develop their own explanations and understanding of the behaviour of light. When needed, the facilitator offered the students guidance with question prompts, such as, "what do you think is happening here?" and "why do you think this is happening?" All sessions were video-recorded.

Analytical approach to interference and co-construction of knowledge

Theories of situated learning take settings where learning occurs as the unit of analysis rather than the individual (Vygotsky 1978; Lave 1988). Context is seen as a co-construction of participants in a social situation, on a moment-by-moment basis (Clark 1996), where

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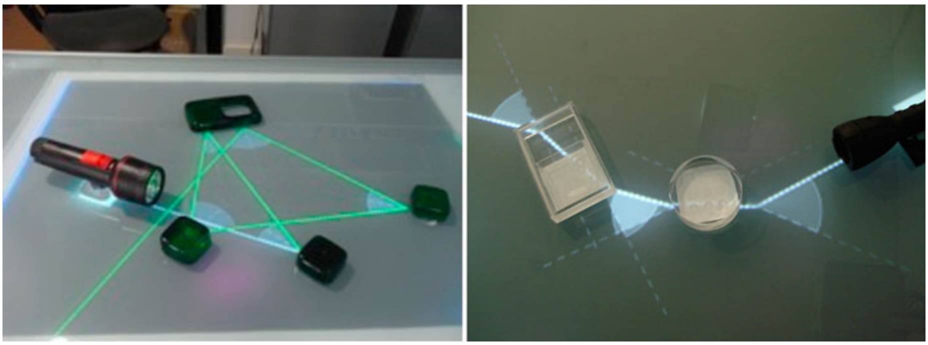

Fig. 2 **a & b**: reflection off green objects (*left*), and refraction through transparent objects (*right*)

participants mutually create possibilities and constraints for one another as they interact. Such approaches, with which the present work is aligned, focus on the group and the interactions between learners, as they manage the challenging task of working together (Barron 2000).

Previous analysis of small group interaction with a tabletop and multiple input devices highlighted the potentially important role that peer interference played for group work and collaborative interaction (Pontual Falcão and Price 2009). Despite the lack of structure, the interference-prone environment promoted curiosity, exploration and argumentation. These findings indicated the need to analyse in more detail how learners manage the disruption caused by interference from others, and what impact this had on the nature of their learning activities. In this section, we define 'interference' and explain how this concept fits into the framework chosen for analysis. Then we present our analysis of the relationships between episodes of interference and productive argumentation and co-construction of knowledge, in the context of small group interaction with an exploratory tabletop environment.

Interference

Interference often has negative connotations in the literature on tabletop interaction, associated with clashes, obstructions and breakdowns (Ha et al. 2006; Nacenta et al. 2007), indicating problems in interaction such as lack of awareness. Hornecker et al. (2008, p.3) define interference as "unintended negative influence on another user's actions", covering "all instances where coordination fails, requiring participants to interrupt their activity and to re-negotiate who does what and when".

Based on previous analysis of students interacting with a tabletop in a context of exploratory learning, we define interference as a disruption, interruption, change in the flow, or conflict, provoked by the learners during collaborative interaction in the environment. It can be accidental, when students do not predict the effect of their actions, or intentional, when students purposely change arrangements, to give demonstrations or help each other out by giving instructions (both physically and verbally), or to explore something themselves, separately from other participants. Although subtle, this is distinct from situations of collective exploration where students manipulate a number of objects simultaneously, and do not necessarily cause relevant interruptions or disruptions. For example, taking a block out of the hands of a peer does not necessarily constitute a situation of interference, as the student might not be using the block to do something that could be interrupted. Situations where students are all looking at the same configuration, and where they 'dispute' the control of the torch, or all put blocks on the beam together, are also characterised as a collective interaction rather than seeing each move of the torch or each placement of a block by a different student as an episode of interference. After all, we are looking at group interaction and not individual, where small disputes occur frequently, and it is not the intention of this paper to do a fine-grained analysis of all such instances. Instead, the focus is on understanding disruptions that lead to an important change in the flow of interaction, and the subsequent influence on the learning process. Although some forms of interference can be seen as conflicting actions or clashes, our analysis suggests that they do not necessarily have negative connotations, but give rise to collaborative activities potentially beneficial for learning (Pontual Falcão and Price 2009). Early findings indicated that the interference-prone tabletop was particularly instrumental in provoking curiosity, drawing attention to relevant instances of the phenomena, and engendering exploratory activity. At other times this led to the need for verbal negotiation and synchronisation of actions, to enable collective building of arrangements or to allow enough time for students to reflect on the underlying concepts. Overall, verbal and physical

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negotiation and attention to others' actions and speech emerged from interference, leading the group through a productive process of collective exploration (Pontual Falcão and Price 2009). However, this work primarily looked at 'interactional interference', describing situations where, when using the tabletop, students disrupted their peers' activities or thread of mind, and analysing how this affected the flow of the interaction. In the present analysis, we take a closer look at how interference influences co-construction of knowledge, rather than analysing its impact at the level of interaction.

The social modes dimension of the argumentative knowledge framework

Theoretical approaches to collaborative learning focus on different dimensions as indicators of knowledge building. Weinberger and Fischer's (2006) framework developed to analyse argumentative co-construction of knowledge in CSCL environments, works across four different dimensions:

- Participation dimension: if and how much learners participate;
- Epistemic dimension: on-task versus off-task discourse, and the adequacy of specific epistemic activities to solve a task;
- Argument dimension: construction and balance of sequences of arguments and counterarguments towards a joint solution;
- Dimension of social modes of co-construction: to what extent learners refer to and deal with contributions of their peers.

In particular, we look at the categories of the social modes dimension that refer to consensus building, as we assume that even when productive, interference creates some kind of conflict to be resolved:

- Quick consensus building: learners accept contributions of their peers to move on with the task, but are not necessarily convinced by such contributions (Clark and Brennan 1991). It is more of a coordinating discourse move than a change of perspective (Fischer et al. 2002), and can be detrimental to knowledge acquisition.
- Integration-oriented consensus building: learners integrate and apply the contributions of their peers, possibly modifying their own initial beliefs. According to Weinberger and Fischer (2006), integration-oriented consensus building takes place rarely in comparison to other social modes of co-construction, as learners seem to hardly change their perspectives in discourse.
- Conflict-oriented consensus building: learners disagree, modify or replace the contributions of their peers, being forced to think about different perspectives or to find stronger arguments for their opinions (Chan et al. 1997).

The social modes dimension has two other categories: externalisation (where learners articulate thoughts to the group, without reference to contributions from others); and elicitation (where learners use their peers as resources by asking questions, aiming at receiving information). As they do not relate directly to conflicts or consensus building, they were not considered relevant to our analysis.

Weinberger and Fischer (2006) have applied the framework to complex problems within education and educational psychology in CSCL environments, but recognise the need to validate it with respect to the analysis of knowledge construction processes in other content areas of CSCL, and for analysing argumentative knowledge construction in inquiry learning (as in (Kollar and Fischer 2004)). Here we adapt the framework, intended for analysis of text-based interaction, to a dynamic, synchronous environment where action is as important

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as speech for participating and contributing to the activity. We apply the three categories of consensus building to episodes of interference, during students' engagement in exploratory learning with an interactive tabletop application about the physics of light. The main aim of our analysis is to systematically investigate to what extent peer interference in exploratory tabletop interaction can promote productive argumentation and co-construction of knowledge.

Findings: Interfering and resolving

Interference was found to be a frequent phenomenon that influenced collaboration and knowledge construction as students interacted with the tabletop. However, it played distinct roles for different groups of students, with a different distribution of interference episodes across groups. Interestingly, interference was much more powerful when physically created (i.e. through the use of the tangible artefacts) than verbally. In other words, interfering by modifying arrangements on the tabletop had a greater impact than just saying something to peers. Such physical actions on the interface, at times were made with the intention of interfering, and at others took place unintentionally and unexpectedly. Analysis applying the social modes dimension (Weinberger and Fischer 2006) showed that interference triggered different kinds of responses within the groups, indicating that episodes of interference led to a mixture of integration-orientated consensus building, conflict-oriented consensus building and quick consensus building. Altogether, from the 11 groups analysed, episodes of interference were identified in 7 of the groups, generating a total number of 59 occurrences of interference. Below, we describe the different ways that interference events were managed by students in terms of consensus building, and illustrate these with examples. All names have been changed to preserve anonymity.

Integration-oriented consensus building

A total number of 18 episodes of interference that led to integration-orientated consensus building were found across the 7 groups. In these instances, students responded to interference episodes by attending to the configuration changes, conflicting or unexpected events, and working with those changes to think about or reason about their meaning in relation to the conceptual goal. In other words, they used the interference event as a new source of relevant information that guided their activity and/or thinking. Thus, the interference episode served as a mediating tool for reflection. The different triggers of interference led to different ways of managing this new information, as illustrated below.

Attention to peer's contribution and production of joint explanation

In instances where a student intentionally interfered with configurations on the tabletop with a related conceptual goal in mind, the interface was used as a tool for testing, explaining and demonstrating to peers (through action, with accompanying verbal explanation). One student would interfere in their peers' activity or explanation to give their own opinions about the concept being discussed. This kind of contribution created a conflict, which was resolved through integration-oriented consensus building: i.e. the peer's perspectives were integrated into the theory being built by the first student, making it more complete. Such integration could be verbally externalised (as in the example below), or shown physically (when a student reproduced a peer's action to test out the proposed idea

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for themselves). The final outcome of such episodes of interference was a collectively built contribution of conceptual knowledge.

Illustrative example Emily and Arthur investigate together the behaviour of a transparent object interacting with the light beam. The light beam travels through a transparent block and then reflects off a yellow block. Arthur is stating the hypothesis that light goes through transparent objects and can reflect off other objects afterwards (Fig. 3):

Emily deliberately interrupts him and changes the position of the objects on the table (physical and verbal intentional interference). She places the yellow object in between the torch and the transparent block (which she calls 'white'), and states her own hypothesis, that light will not go through an opaque object (Fig. 4):

Emily wants to demonstrate a different situation, apparently with the goal of falsifying Arthur's hypothesis. She creates a conflict, but she does not finish her own hypothesis, so Arthur takes over again, integrating Emily's perspective, which does not, however, falsify this own theory. Emily accepts it, and complements it.

> [Arthur] "It won't be able [to go through]…"
> [Emily] "… but it still reflects from there [the yellow block]."

Here the intentional actions that interfere with another student's hypothesis serve to create another configuration, or scenario, that can then be used by all of the students in the group to think more broadly about the circumstances under which light is, or is not, transmitted.

Collective investigation of unexpected effects produced

This situation took place as students were manipulating the objects and unexpected effects were produced due to someone's physical interference. Such interference could be intentional, but resulting in unexpected digital effects that were not related to the learner's intentions, or unintentional, where students did not realise that their actions would affect the rest of the arrangements. Although the 'contribution' was deliberately made through student physical action, it was the production of unexpected digital effects, which caused the conflict. The digital effects were therefore a surprise for the whole group, causing conflict to their expectations. In cases of collective investigation, the interference made the whole group to stop what they were doing, to try to understand what had happened. Thus, the effects of the interface triggered reasoning and knowledge construction, and a process of integration-oriented consensus building took place. For example, peers collectively investigated the effects produced to discover new facts or came up with conceptual conclusions, then moved on, following a different flow as a result of what they had just discovered. The digital augmentation of the interface in this case played an important role in triggering reflection.

Fig. 3 [Arthur]"When it's like this, it's transparent, so it can go through and it can reflect on another light through it…"

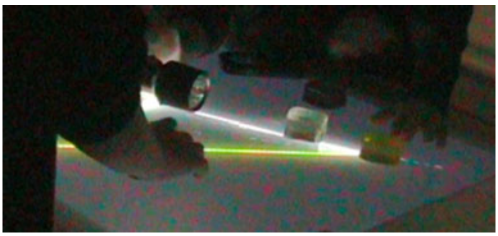

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Fig. 4 [Emily] "Yeah, but if you put the yellow there, and then the white there…"

Illustrative example With Betty's help, Diana is trying to understand what effects she is producing with the torch she is manipulating. The underlying concept involved here is the reflection of light off opaque objects, shown by reflected beams in different colours, according to the colour of the object (Fig. 5).

[Betty] "Yeah, that's your one."
[Diana] "Right, so if I…"
[Betty] "This one is mine."

Meanwhile, Terry places a purple object on the surface and the light from the torch reaches the block, producing a purple beam (physical interference) and creating a conflict (Fig. 6).

Terry was quiet and not participating in his peers' activity, but silently decided to try something out, and ended up unintentionally interfering with his peers' activity. Terry did not seem to be aware that by placing the block on the surface he would cause changes that would attract the girls' attention. Betty notices the purple beam before she realises Terry had placed a purple object on the surface, which makes her confused, as she does not understand how the purple beam was produced. Then she looks at Terry, who now is placing the same purple object elsewhere, and realises what had happened before:

[Betty] "Oh, that's because you put that down…"

As Betty 'solves' the conflict, the group integrates the explanation and uses it to feed into the next decisions. They investigate what happens to objects of other colours, after noticing the purple beam, which resulted from Terry's interference.

[Betty] "What about the orange? Try the orange and the yellow."

This example illustrates how the interface can extend students' exploration with the system, by broadening their experience of the relationships between the light beam and different objects, and consequently the learning concept.

Overall, these instances of interference and subsequent collaborative interaction, suggest that the capacity of the interface to give dynamic feedback together with multiple physical input devices provides a space that facilitates interaction mediated by action and discussion that can support effective integrated oriented consensus building.

Fig. 5 [Diana] "Wait, is that my light?"

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Fig. 6 [Betty] "That was a purple colour, though…"

Conflict-oriented consensus building

Conflict-oriented consensus building was found to take place in instances of interference, which were characterised by refusals to accept a peer's (interference) actions. Across the 7 groups 23 instances of conflict-oriented consensus building were found. Two types of reaction were identified: undoing and rebuilding (where efforts were made to go back to the configuration prior to interference); and localised dispute (where students physically disputed the same object in order to pursue their individual goals). Below we show illustrative episodes of how these different kinds of contributions were managed by the students.

Undoing and rebuilding

This category represents situations where an arrangement was changed due to someone's interference, but where the other students were unable to work with the changes. Instead they struggled to come back to the previous configuration that they had been working with. The interference did not bring the benefits of 'new' information (as above), but caused students to spend time and energy trying to reorganise the tools to proceed with their initial investigation. In some cases this meant that they lost track of what they were doing or looking for.

Illustrative example The group is trying to build an arrangement with green blocks, to investigate a point raised by the facilitator. Arthur tries to take leadership, but the girls, also interested in participating, interfere with what he is doing. Arthur chooses to take an authoritarian attitude instead of involving the girls, so he keeps trying to pursue his own goal and prevent the girls from interfering. As the girls do not concede, there is a general lack of coordination, and interference becomes counter-productive. In this episode, Arthur is arranging green blocks on the surface when Claire moves the torch, and the whole arrangement fades, causing a conflict. Arthur requests that the torch is put back into position (Fig. 7):

However, Arthur is unable to rebuild the previous arrangement, and keeps trying while the girls interfere by moving the torch and the green blocks. Again, Claire interferes by taking a green block away, and changing the arrangement. Emily and Arthur struggle to rebuild the configuration they wanted to investigate (conflict-oriented consensus-building).

[Emily, to Claire] "it was reflecting, put it there!"
[Arthur] "that goes off there, you put this one there… it's reflecting off of there"
[Emily] "it's going on to that white light. Put it back on to the white light."

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Fig. 7 [Arthur] "no, no, wait, leave it where it was"

Again the torch is moved making the whole arrangement fade, causing surprise and disappointment.

> [Arthur] "oh what!"
> [Claire] "what happened?"
> [Arthur] "you moved the torch!"

Although episodes like this illustrate situations of conflict-oriented consensus building, where learners disagreed, modified or replaced the contributions of their peers, students did not come up with stronger arguments or different perspectives for their initial opinions. Instead, a rather authoritarian way of resolving the conflict took place, where students requested actions to be undone and arrangements to be put back to their previous configuration, thus limiting the potential for developing conceptual knowledge on the basis of valuable 'new' information.

Localised dispute

In situations in this category, students disputed one or more objects to perform an action with them or to place them in a specific position. They consequently interfered with one another's arrangements as they tried to pursue their individual goals instead of coordinating, as well as rejecting others' contributions.

Illustrative example The facilitator asks a question about green objects and Oscar tries to experiment with a green block, but Samuel rotates the block. The boys do not know the answer to the facilitator's question, and both try to get hold of the same green block to find out the answer using the system. Oscar takes control of the object, but Samuel immediately moves it again (interference).

> [Oscar]: "move it that way…"

Samuel starts giving an explanation to the facilitator based on the arrangement built (conflict-oriented consensus building), but Oscar moves the other block involved in the arrangement, making one of the reflected rays fade.

> [Samuel]: "every time that you shine it on something it will reflect, look… you're moving it!"

Here students were disputing the same objects as they tried to answer the facilitator's question. However, they did not coordinate their actions and as a result were unable to give explanations or demonstrations with the system due to this peer interference. Again, students modified the contributions of their peers, but not through conceptual

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arguments; instead they did it physically (by taking control of objects) or by complaining and requesting that things to be done their way. This outcome of interference episodes did not provoke productive collaborative interaction (as in cases of integration oriented consensus building), and did not fulfil the potential to extend or broaden the learning activities.

Quick consensus building

Quick consensus building occurred when students accepted their peers' contribution without discussion or reaction. This may be from lack of interest, or a tendency to yield to someone else's decisions. Across the 7 groups, 18 instances of quick consensus building were found. Two categories of response were identified: indifference to interruption (when the current activity was interrupted and subsequently abandoned); and acceptance of peer leadership (when students readily accepted and followed the decisions of a leader). Below we show illustrative episodes of how these different kinds of contributions were managed by the students.

Indifference to interruption

Situations occurred where a student interfered by moving an object, which interrupted the current activity. However, in these cases, no efforts were made to rebuild the configuration, and students willingly abandoned their previous activity.

Illustrative example One student is investigating an arrangement, when another removes one of the objects causing the arrangement to fade (interference). The first student complains ("what are you doing!") but leaves what he was doing and the group as a whole moves on to other activities (quick-consensus-building).

Here students just accepted the interference and moved on, choosing not to engage with the interference product, but rather to proceed to something else without much thought about what had just happened. This procedure was somewhat counter-productive as it interrupted another students' activity without any beneficial outcome through building on it.

Acceptance of peer leadership

Peer leadership took place in two distinct ways: authoritarian and democratic. In authoritarian cases a leader in the group took the dominant role, leaving little opportunity for interference to occur through other's actions. Peers appeared content to follow orders and interact according to the leader's suggestions. The leader tended to be the one to interfere by changing arrangements built by peers, but such interference was accepted by the others (quick consensus building), and did not subsequently impact on the interaction. In cases with a democratic leader, the leader again took control of the interaction, but always asked for others' opinions and made sure that there was agreement about what actions to take. This led to coordinated group work, with very little interference and easy consensus.

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Similar to conflict oriented consensus building, quick consensus building did not promote productive collaborative interaction, nor further the learning experiences in ways that integrated oriented consensus building was shown to do.

Discussion

Applying the social modes dimension analysis has provided more detailed understanding of the relationship between tangible tabletop environments and collaboration in learning contexts. In particular, it exposes the important role that interference can play in mediating collaboration, together with key design features that trigger interference episodes. In addition, our analysis indicates ways in which Weinberger and Fischer's (2006) analytical framework can be extended beyond text-based environments to include action-based co-construction of knowledge.

The importance of interference

Findings from our analysis suggest that interference can lead to both productive and counter-productive learning situations, or can have a neutral effect on interaction. Episodes of interference consisted of instances where a disruption or interruption to the flow of interaction was identified. From the 7 groups where interference was identified, there was a balance of productive (18 episodes across groups), counter-productive outcomes (19 episodes across groups), and neutral outcomes (22 episodes). For the other 4 groups, interference was virtually non-existent (as with situations of peer leadership described above), or had a neutral effect on the flow of interaction (i.e. no instances of productive or counter-productive interference were identified). It is important to note that boundaries between situations that lead to neutral, counter-productive and productive interference were subtle. This is particularly the case since such situations originated from similar contexts, i.e. mostly moving devices and changing physical arrangements on the tabletop surface. This highlights the need to identify critical elements that engender productive interference (be it through integration-oriented or conflict-oriented consensus building), to inform the design of learning interfaces and modes of teacher facilitation.

'Productive' interference refers to situations that trigger curiosity, exploration, and conceptual reflection. This happened when students were open to contributions of others rather than focused solely on pursuing their own interests. They analysed the contribution, integrating it into their own thread of thought, or reacted by counter-arguing. Importantly, this 'reaction' was different from simply asking for original arrangements to be rebuilt, as in such cases no reasoning was undertaken about the digital effects produced. In the sessions analysed here, all 18 instances of interference that led to productive outcomes were instances that were resolved through integration-oriented consensus building (and vice-versa), where students integrated their peers' explanations and demonstrations, or investigated unexpected effects. As outcomes, the students were able to build knowledge together, and in some cases this prompted them to take different paths of relevant actions, broadening their investigation.

The term 'counter-productive' is used here to refer to the interruption of activities, that did not engender productive follow up (such as discussing the effects produced, or attending to previously unnoticed facts or concepts), and caused some disruption to the flow of reasoning and exploration. This occurred mostly when one student moved one of

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the physical devices, causing the arrangements to fade or change, and where the reaction of peers consisted of asking for objects to be put back or taken away, or making the rearrangements themselves. In counter-productive situations, students were not open to contributions from peers or keen to move the focus of their interest away from their own ideas, and insisted on trying to individually pursue their own hypothesis instead of exploring together, despite being bound to the same working space (the tabletop surface). In our analysis, the 19 episodes of interference that were counter-productive were episodes managed by the students mostly through conflict-oriented consensus building (14 episodes), although some situations resolved through quick consensus building (5 episodes) were also found to be counter-productive, for example, interruptions that were readily accepted by the student (meaning he or she gave up the current investigation). In cases of conflict-oriented consensus building, conflict consisted of students disagreeing and modifying their peers' contributions, but not coming up with counter-arguments as justifications. As the interference was rejected instead of integrated, it did not bring the potential benefits to the interaction, and sometimes made the students lose track of what they were trying to investigate. Such findings are coherent with previous research on collaborative problem solving (Barron 2003), where group's performance was found to depend mostly on how learners responded to peers' proposals. Barron (2003) found that more successful groups responded by accepting or discussing the proposals, and less successful groups commonly rejected or ignored peers' proposals.

A third type of situation occurred where changes were very easily 'undone', or simply ignored. Such episodes are considered 'neutral', as they did not engender productive learning situations, but were also not relevant enough to be counter-productive. From the 22 neutral episodes, 9 were resolved through conflict-oriented consensus building, and 13 through quick consensus building. For example, when one student placed a block on the beam, and another student immediately removed it to proceed with the previous configuration, the episode had no great consequence for the interaction. The student's interference did not result in a different configuration, nor did it prevent another activity from being pursued.

Groups that exhibited a predominance of quick consensus building usually showed little initiative and interest. This led to rather poor collaborative interaction, with little exploration and discovery. Less occurrence of interference went hand in hand with lower levels of action with the interface, with usually only one or two objects in use at any one time. As a result, the interaction was very organised, coordinated and planned. Although this may sound 'ideal' in terms of collaboration, in practice students were more restrained, undertaking minimal risks and experimentation, thus reducing their level of exploration and inquiry. In the studies discussed here, absence of interference was associated with less exploration, resulting in reduced discovery and less rich interaction, engendering a need for the facilitator to constantly stimulate students.

Overall, our analysis showed that when students resolved interference through integration-oriented consensus building, they created productive outcomes, whereas the forms of conflict-oriented consensus building identified here led mostly to counter-productive situations, with some also leading to neutral episodes. This is not to say that conflict-oriented consensus building is inherently negative, but it indicates that, in the context of the tabletop tangible interaction, more intervention and facilitation is necessary to encourage students to argue for their opinions instead of physically undoing their peers' actions, which can be an easy option with the tabletop. In other words, the tabletop was an interference-prone environment, which enabled a number of situations to emerge, but the learning progression from such situations depended on students' attitudes and strategies for

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managing ‘conflict’ or ‘interference’ more than on the affordances of the interface. A more detailed discussion of the affordances of the tabletop and its role for argumentative knowledge construction is presented in the following sections.

The role of the tabletop interface for collaborative exploratory learning

Overall, episodes of interference were initiated by a student moving objects on the interactive surface. However, such actions were differentiated by the context, the student’s intention, and the peers’ reaction. Collectively, and shaped by the affordances of the tabletop interface, these factors led to productive, counter-productive or neutral interaction. The tangible tabletop environment inherently promoted *high levels of physical interaction* due to the nature of the input devices being physical objects, and any system effects being directly related to action with those objects. This in itself might not offer opportunities for interference, but the design features of tangible environments in general as well as specific design features of this particular environment serve to influence the opportunities and types of interference that may take place. Design factors that influence interference:

- ○ ***Multiple resources***: having multiple resources enables all participants to be using or holding physical objects, and thus having the potential to actively contribute to and engage in the activity, as opposed to say just observing and talking about what they see. *This establishes the potential for interference, as each participant has a variety of tools to work with at any one time.*
- ○ ***Simultaneous multiple inputs**:* Multiple resources alone are not sufficient for interference to occur. The capacity of the environment to support *multiple inputs simultaneously* means that each participant can *physically engage* in the activity at the same time, removing the need for sequential collaborative activity. Concepts of turn-taking are not embedded in this kind of design, which gives rise to *opportunities for interference*, which in turn lead to different kinds of collaborative contributions, both physically and verbally.
- ○ ***Dependency on one physical-digital resource:*** In this particular environment all digital effects depended on *one* physical resource (the torch) being placed on the surface, which resulted in one key *digital resource (the digital beam).* This digital resource was the central focus for *controlling* the different effects with the use of physical objects. This served to enforce collaboration, to promote all children to be actively included in the one activity, and to engender interference.
- ○ ***Dynamic digital feedback*:** has a particular impact with respect to interference. It shows immediate cause and effect through action, which renders ‘surprise’ or unexpected events to be visually explicit. It also enables the students to test out their ideas, to see conflicting ideas taking place, and supports the *undoing and redoing of actions* due to the programmed nature of the environment.
- ○ ***Shared visual field***: means that students can readily see each other’s actions, which in itself contributes to interference in ones own thinking/ or actions.

In particular, as all participants were engaged with the same interface, where physical devices were linked to interrelated digital effects, attempts to work individually eventually resulted in episodes of interference. Such episodes forced students to take peers’ contributions into account, whether integrating or rejecting them, verbally and/ or physically negotiating a consensus. The tabletop is therefore an open learning environment with no built-in strategies of coordination or scripts of collaboration, but whose interaction

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design implicitly encourages students to engage in argumentation and collaboration, while investigating the rules of the model represented by the system.

The implicit enforcement of collaboration through shared interaction devices and connected digital effects, as opposed to explicit techniques of turn taking and delimitations of private working space and individual tools, provided constant stimuli for joint work. Although the learning situations resultant from peer interference greatly depended on the students' own reactions, the design features described above proved very efficient in creating opportunities for spontaneous and productive collaborative situations, suggesting that in contexts of exploratory learning, peer interference is to be encouraged, rather than constrained, by design.

Considerations on Weinberger and Fischer's framework

Analysis showed that the episodes of interference that led to productive outcomes during tabletop interaction were episodes resolved through integration-oriented consensus building. This meant that students' contributions were integrated and applied to the current investigation and theories. Contrary to Weinberger and Fischer's (2006) findings, situations of integration-oriented consensus building were not found to occur rarely in comparison to other forms of consensus building, and students were open to changes in their perspectives when faced with evidence from their peers' actions with the tabletop. This may be an indication that the interface can act as a powerful mediator in tangible-based exploratory learning contexts, in contrast to, for example, text-based collaborative learning settings. The possibility of acting (physically constructing), together with the explicit visual signs of the interface related to 'real' physical objects, created a learning environment which generated new information offering students opportunities to work with newly discovered facts even when such facts contradicted their previous ideas. The multi-modal context of such environments may be instrumental in strengthening evidence needed to foster conceptual change.

Furthermore, our analysis indicated that situations related to conflict-oriented consensus building identified in the tabletop interaction proved to be poorer in terms of productive learning interaction than those described by Weinberger and Fischer (2006). Although learners rejected, modified or replaced their peers' contributions, they did not engage in mutual modification of their ideas. This may be because students could disagree by simply removing objects or changing arrangements, without being obliged to give a convincing verbal justification. Furthermore, the younger age group (in contrast to those examined by Weinberger and Fischer) may be content to disagree with others without the need to jointly resolve the conflict. The mode of interaction (through action) and the design of the interface permitted a form of conflict-oriented consensus building where students were not forced to explicitly justify their actions through conceptual explanation. Conflict was limited to disputes over the control of the arrangements of the blocks, and consensus was usually 'won' by the student with the strongest personality. This generally led to counter-productive outcomes from the episodes of interference, particularly in terms of argumentation and knowledge construction.

Quick consensus building functioned in a very similar way to the original framework's description. However, in our analysis it was coded differently. The signs of acceptance of peers' contributions were demonstrated through physical action rather than verbal expression. In such situations, students did not react to their peers' interference, but instead let them proceed with their actions. Quick consensus building was, thus, more related to a lack of action or reaction. Students seemed to accept their

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peers' interference as a form of enabling interaction flow, rather than because they necessarily agreed with it. With the tabletop, this again related to individual differences, such as personalities and interest in the activity. However, contrary to Weinberger and Fischer's view that such attitudes are detrimental to knowledge acquisition, our analysis showed that quick consensus building was primarily related to situations where interference was neutral, and did not have a subsequent impact on the overall interaction. In other words, students had plenty of opportunities for knowledge acquisition that were not undermined by situations of quick consensus building. In fact, given the dynamics of the tabletop interaction, quick consensus building was sometimes necessary to allow exploratory learning to progress. Too high a level of action and interference would hinder the interaction flow.

Conclusion

Within the context of CSCL, shared interfaces create new possibilities for mediating collaboration, and new forms of computer-supported scaffolding. However, new technologies also bring about different interactions that shape learning processes. One of the key issues emergent from shared interfaces is the occurrence of clashes between users, which are often perceived as counter-productive disruption. A second challenge relates to the lack of explicit guidance for argumentation and collaboration, particularly in inquiry learning, as shared interfaces tend to be designed as open environments with a loose structure.

This article presented an analysis of student interaction with a tabletop environment for inquiry learning, simulating a simplified model of light behaviour. In particular, the analysis investigated the occurrence of episodes of peer interference and their consequences for argumentative co-construction of knowledge. Within the tabletop environment, interference occurred primarily through action, but had important consequences for argumentation, collaboration and knowledge construction. Contrary to the predominantly negative connotations found in the literature, three types of interference were identified in our analysis: productive, counter-productive, and neutral, with subtle boundaries among them. A same context could give rise to productive and counter-productive interference, as they were mostly triggered by the effects produced by the interface and how they were interpreted and used by students in their inquiry learning processes. Episodes of interference could be resolved through quick consensus building, when students simply abandon what they were doing and accept the change made by others; integration-oriented consensus building, where students reflect and discuss what happened; or conflict-oriented consensus building where students try to undo others' actions and rebuild previous configurations. In our analysis, interference resolved through integration-oriented consensus building was found to lead to productive learning interaction, while counter-productive situations were mostly characterised by interference resolved through conflict-oriented consensus building.

Analysis showed that the tabletop environment functioned as a tool for students to experiment, explain, and demonstrate to peers, but also played a very important role in triggering reflection through unexpected digital effects produced by the manipulation of objects on the surface. Despite the lack of explicit guidance, such effects, in many cases resulting from peer interference, functioned as a stimulus for exploration and argumentation. Although this analysis is an important step in understanding how interference can promote collaborative knowledge construction, the greatest challenge

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lies in designing interfaces and ways of facilitation to support and induce more instances of productive interference that engender productive collaborative knowledge building that benefits learning, while implicitly discouraging counter-productive interference.

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