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Multi-touch tables and the relationship with collaborative classroom pedagogies: A synthetic review

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Abstract This article reviews the research and evidence about multi-touch tables to provide an analysis of their key design features and capabilities and how these might relate to their use in educational settings to support collaborative learning. A typology of design features is proposed as a synthesis of the hardware and physical characteristics of the tables so that the longevity of these factors and the associated analysis can be better preserved, particularly in relation to the range of ways in which they may be used collaboratively in classrooms. The variability of features relating to software is also analysed and key pedagogic issues identified. The aim that underpins this review is to relate the design of the technical features of the technology with key pedagogic issues concerning the use of digital technologies in classrooms, so as to provide a more robust basis for their integration in classrooms in terms of their potential to support or to improve learning.

Keywords Cooperative/collaborative learning · Human-computer interaction · Interactive learning environments · Multi-touch tables · Classroom pedagogy

Introduction

The introduction of new technologies into educational settings has rarely lived up to its promise in terms of benefits for learning (e.g., Cuban 2001; Higgins 2010). Dillenbourg and Evans (2011) describe two problems: Overgeneralization and over-expectation within the CSCL research. The field is thus characterised by initial enthusiasm for novel technologies, often augmented through productive use by early adopters. However, then, when more widespread adoption occurs, there is little conclusive evidence of impact on measured learning outcomes. In the light of this, and aware of the equivocal overall association between digital technologies and learning (Weaver 2000; Fuchs and Woessmann 2004), this synthetic review aims to identify more precisely design relationships between the

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technological characteristics of large multi-touch surfaces (such as those in Fig. 1) and their pedagogical possibilities, so as to increase the likelihood of improving learning, and collaborative learning in particular, as they are adopted in classroom settings.

The authors are involved in an interdisciplinary project to develop the use of multi-touch table surfaces to support collaborative interaction and learning in school and university classrooms. As part of this goal, we have undertaken a review of the preliminary evidence from education and computer-science literature to identify the issues in the field, so as to create a productive space for discussion within and beyond our research team (Star 1996). The aim of this paper, therefore, is to review the emerging literature on multi-touch surfaces for collaborative interaction and their use in educational settings, to propose a typology of features of this technology based on this review, and to offer an analysis of the pedagogic potential of these features. The principal goal of this review is to make the design choices for developing multi-touch technologies for collaborative learning in educational settings more explicit, and more directly based on the emerging evidence in the field. The review aims to build on and extend the analysis offered by Scott and colleagues (2003a; b) in terms of their system guidelines for the design of co-located, collaborative work on a tabletop display and by Shen and colleagues (2009) in terms of usability challenges. As an extension of the 33 issues related to the design of multi-touch tables for learning described by Dillenbourg and Evans (2011), we focus on the specific implications from existing evidence about this technology in terms of collaborative interaction in classroom settings. Building on the four circles of interaction described by Dillenbourg and Evans (user-system interactions, social interactions, classroom orchestration, and institutional context) we identify the design decisions possible with current hardware, and the implications these decisions may have on the use of this technology in classrooms. We believe the evidence that we summarise and categorise in the classification presented below for our own project may be of wider use to others working in this area.

Most of the existing evidence available is based in the human-computer interaction field, providing insights into the way that users interact with the technology and with each other when doing so (see Benko et al. 2009, for an analysis of the research field). A few studies have investigated their educational use specifically with young children (e.g. Mansor et al. 2008; Rick and Rogers 2008), however, there is little information about the way that these interactions might affect learning in more explicit educational settings, so possible implications for pedagogy are outlined in this review from the broader field of research. This is particularly important in relation to the wide range of ways in which they could be used in classroom settings, with different ages of learners, across different subjects and with

Fig. 1 Multi touch surfaces in a classroom

a variety of educational outcomes. This paper is written at a time when multi-touch surfaces are becoming more commonplace in a range of devices such as phones, tablets and computer displays, in the hope that any insights generated will be of use in this broader field.

Scope

The focus for this review is on interactive surfaces that can be accessed from two or more sides, and used by more than one person at a time. There were three main strategies employed in determining the scope of this review: initially, searches were conducted on education and computer science databases (e.g. ERIC, IEEE Xplore) using terms such as tabletop, interactive surfaces and multi-touch. Due to the relatively recent and cross-disciplinary nature of this field, the database search was supplemented by reviewing all publications in the proceedings from the IEEE Tabletops Conference (2006 to 2010) and through web-based searches of all authors publishing in those proceedings, and all relevant papers were included at this stage. From these large lists, abstracts were reviewed to eliminate publications that referred to wall-mounted interactive surfaces or single-user studies. Finally, references from the first two sets of publications were screened to identify any additional relevant publications ("pearl-growing": Schlosser et al. 2006). The criteria for inclusion intentionally limits discussion to horizontal or tilted surfaces that are more naturally described as tables, rather than vertical, wall-mounted surfaces. This distinction is important, as large and significant differences in collaborative interactions between vertical and horizontal displays have been reported by Rogers and Lindley (2004). In the horizontal table condition, group members switched more between roles, explored more ideas and had a greater awareness of what each other was doing. In the vertical condition groups found it more difficult to collaborate around the display. Further, Inkpen et al. (2005) determined that users engaged in more pointing, made more preparatory statements and made more on-task comments when the display was horizontal than when it was vertical. Given these differences, the goal to design tables for classroom use and the nature of the research from which this paper is drawn, this discussion is limited to non-vertical displays. The focus is therefore on the evidence concerning the design of the size, shape and tilt of the surface, drawing on research that explores aspects of ergonomic and technical restrictions and any collaborative affordances of different surface designs.

Our research focuses on the use of multi-touch technology in formal learning situations, specifically in schools and university settings. Thus, while we are aware that research is being conducted using multi-touch technology in informal education settings, and draw on these findings to inform our research, in this review, we focus on the implications for classrooms. We approach this project with a view that the use of authentic and collaborative activities are important pedagogic strategies and that finding ways in which new technology can be leveraged to support effective collaborative learning in the classroom is beneficial (e.g. Barron and Darling-Hammond 2008; Boaler 1999; Cohen 1994). Additionally, we draw on prior CSCL research (e.g. Stahl et al. 2006) although note, as do Dillenbourg and Evans (2011), that multi-touch surfaces come at a time when there is an increasing move towards examining face-to-face CSCL rather than online CSCL, and an increasing emphasis on the physicality as well as the cognitive aspects of collaborative learning. While traditional classrooms promote teacher-led discussion, with information flow existing predominantly between teachers and individual pupils, collaborative learning activities allow for knowledge development between pupils (Blatchford et al. 2006a; b). The Q2 challenge for teachers, however, is how to orchestrate within and between group communication, in such a way that all members of the class become contributors to their peers' knowledge development and their learning. In our work, we explore how the design of activities and pedagogies can support whole-class engagement in learning, through the use of multi-touch technologies.

Derivation of factors for classification

Software is infinitely malleable (Brooks 1987). This is an obvious opportunity in the design and development of interactive tabletops, but it also poses a challenge when attempting to enumerate or categorise design factors of tabletops themselves, as it is software that drives the high degree of variability of features, capability and, by implication, affordances. A more robust method for determining these factors is in examining tabletop hardware and physical characteristics first and foremost, and only then discussing the impact of these characteristics on the software. By choosing a minimal set of physical characteristics, we suggest that the longevity of the identified factors and associated analysis can be preserved. Variability in software can then be discussed against each factor and implications for pedagogy discussed. We believe that this is an important approach that will enable the guidelines suggested by Scott et al. (2003, p 159) to be evaluated relative to the underpinning physical characteristics of the technology. This, in turn, is a necessary step to achieve one of their key directions for future research in terms of evaluating the impact of existing system configurations on collaboration.

We propose a working definition for an interactive tabletop as: "a computer system that allows direct physical interaction with its non-vertical display surface". From this definition, the key elements are display surface, direct interaction and computer system. These elements form the top-level classification of the factors (Fig. 2). Note that the proposed top-level classification names are adjusted from the definition above for brevity and as a result of lower-level analysis, discussed later.

For each of these top-level categories, the hardware and physical characteristics are identified and grouped in such a way that allows for current and future variability to be classified easily. The process for the sub-division of each top-level category is described along with a review of the literature appropriate to each classification. The coverage of the literature indicates the impact of the hardware and physical characteristics on software and on pedagogy. Key aspects of each of these features influence the pedagogic interaction of learners using the technology. So, for example, the design of the table surface affects the physical positioning of learners around the table surface and the ease with which they can reach for content, the type of touch interaction influences the way that learners can take ownership of resources on the table and the connectivity determines the kinds of resources displayed and the control by the teacher or learners of this content. There is evidence about

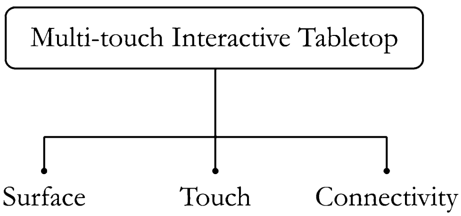


Fig. 2 Top level classification of the typology

these aspects of design in the existing literature that we have analysed in relation to this classification.

Analysing the evidence for the typology

Each of the three top-level classifications of surface, touch and connectivity are explored below, and additional detail and sub-categories will be defined, emerging from the analysis of the literature. As we explore each of these classifications, we also consider how they can influence or be adopted within classroom learning environments, and the implications of design choices on classroom pedagogy and learning.

Surface

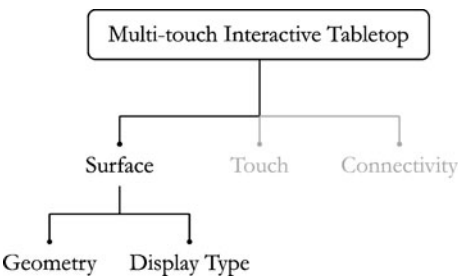
In considering the physical characteristics of the surface itself, two further sub-categories are evident. The first of these is the Geometry of the table, which describes properties that relate to its physical construction. Included in this are the table's size, shape and angle of inclination. The second sub-category is Display Type. There are many different technologies used for establishing the display on the surface, from top-down projection systems to integrated liquid crystal displays (LCDs). These sub-categories are illustrated in Fig. 3.

As the literature shows, variance in each of these categories has significant implications in the suitability of tabletops for particular learning activities and the interaction of learners.

Geometry

A major issue that arises when considering non-vertical displays is the choice to use horizontal or tilted surfaces. While initially some interactive surfaces were tilted to account for technological constraints, particularly projection, advances in technology now allow for completely horizontal surfaces, making the tilt of a table a design choice rather than a necessity. Muller-Tomfelde et al. (2008) summarize prior research on the tilt of tables, concluding that understanding the effects of table-tilt on task completion is still an open question. In their modelling task, they found that a majority of participants indicated that they thought they would prefer a tilted surface when working on a collaborative task. Participants cited ease of reach and view of the surface as reasons, but further user studies are needed to confirm this preference in actual interaction settings, and across task types in terms of actual impact on task interaction and outcomes.

Fig. 3 Surface sub-categories



The choice to use horizontal or tilted surfaces can affect whether orientation becomes an issue that needs to be addressed by the design of the table or of the task. Horizontal tables are particularly suited for visual activities such as maps and plans (Furuichi et al. 2005). Tilted surfaces tend to have clear signalling of top and bottom, which helps indicate directionality, and appropriate orientation of content. They can also create a dominant position for interacting with the table (at the centre of the bottom of the table). This influences how interaction occurs around the surface (around three sides or four), which is also influenced by the reach of users and the orientation of text and images. This therefore suggests that tilted surfaces are more likely to be suitable for very small groups of learners (particularly pairs) who can naturally collaborate standing at the lowest edge of the surface. Similarly, activities where clear orientation is beneficial, such as those involving text, for example, may be easier, due to the signalling of top and bottom by the geometry or surface design of the tabletop.

Wigdor and Balakrishnan (2005) explored the effect of orientation on readability, noting that although people prefer a 'normal' orientation for reading text, orientation can play an important feature in collaborative interactions (signifying ownership, attention, and attempts to recruit attention). So designing interactive surfaces with auto-rotate features for text (Shen et al. 2004) is not necessarily the correct solution to the orientation issue. Additionally, they found that reading text at different orientations on an interactive table was less taxing, and occurred more quickly, than previous studies of text orientation had reported. They argue that this is due to the fact that participants were allowed to move when reading at the table, suggesting they were compensating for the orientation, and that their task was more ecologically valid, relying on reading contextually accurate sentences rather than identifying non-words as is more common in this type of study. They suggest from their study, that while they found a delay in reading when text is not normally orientated, the decision to re-orientate all text towards the reader has implications for collaborative interactions and so might not be the best solution.

Kruger et al. (2004) conducted an observational study to explore what role orientation of content played in tabletop collaboration. They determined that orientation plays three roles—comprehension, coordination and communication. They found that, as expected, people rotate text or images to help with comprehension, making text easier to read, making the task easier or to have an alternate perspective on the content. However they also found that rotation and orientation were used as a way to coordinate the task, managing the individual and joint space on the table by orienting content either towards themselves, or toward group members, and to indicate ownership of content (see also Morris et al. 2004). Additionally, orientation was used to facilitate intentional communication. Orienting an object towards oneself was seen as a signal of personal work with the object, while orienting the object towards another person, was seen as a bid to communicate over the object, as was orienting an object towards the whole group. Again, the findings of this study indicate the importance of the ability of participants to alter the orientation of objects, as a way of supporting collaboration, rather than auto-orienting the content. The effects of orientation on readers with different levels of experience and skill, however, has not yet been explored, and should be considered when designing for classroom use. In our preliminary work (Higgins et al. 2011) we designed text objects that could be shared, rotated and reoriented deliberately when required by children involved in collaborative problem-solving tasks, rather than using auto-rotation. Automatic reorientation is more suitable for sequential ownership of objects (passing information from one learner to another) rather than genuine joint attention to support co-construction of meaning.

The size and shape of interactive surfaces can also be varied, possibly influencing the way in which people interact with each other and a task. The issue of physical reach is an essential aspect to consider when the size of a table is being decided, as this can influence how users interact with the surface. A number of designs have been explored in the literature, including circular and rotary designs (Koike et al. 2007). Toney and Thomas (2006) define three areas of a surface, as determined by reach—the personal space, storage space, and the rest of the table. This indicates that the area closest to the user is where most ‘work’ gets done, while users move items back and forth between their personal space and the storage space, dictating the limits of the user-interface, regardless of the size of the table. Of course, this becomes more complicated when surfaces are used by more than one person, with the addition of personal spaces where overlaps in such spaces become part of the territoriality of interactive surfaces (Liu et al. 2008). In such circumstances, co-ordination of activity becomes important and the design features of the environment a crucial factor in the success of collaborative interaction (Smeaton et al. 2006).

This idea of territoriality, as described by Scott and colleagues (e.g. Scott 2004; Scott and Carpendale 2006; Scott et al. 2003a; b), refers to the use of personal space, storage and group space on a shared table. They describe the unspoken use of personal space in an experimental group task, with minimal use of a participant’s personal space by other collaborators, indicating a social norm whereby the space immediately in front of a person is reserved only for that person. They also note the use of flexible storage space, for objects that were not in use, and that these storage spaces had an impermanence not seen in the personal space. Group space was used for the main task activities, and for giving help or for shared activity. They note the importance of considering the size of a table, to allow for the interaction of these different spaces, when designing interactive surfaces. In designing for the classroom a number of further constraints are evident in that most learning spaces in schools involved quite large groups of learners (30 or so) meaning that a classroom would need to accommodate sufficient interactive tabletops for the class, implying seven or eight tables for groups of four or five learners.

Table size and group size were explored by Ryall et al. (2004) in a study of groups of two, three or four adult participants re-creating a poem that they had on paper, from individual words presented on one of two multi-touch tables (80 cm or 107 cm diagonally). They found that large groups recreated the poems significantly faster than small groups, and that table size had no effect on speed of recreation, and that there was no interaction between group and table size. They also found that participants were reluctant to grab a word that was very close to a collaborator, indicating a reluctance to enter the personal space as defined by Scott and colleagues (Scott 2004; Scott et al. 2003a; b). They conclude that, for this particular task, table size does not seem to influence task completion, and that group size needs to be considered relative to the task that is being attempted by the group, a finding that resonates with the cooperative and collaborative learning literature that tasks must be suitable for the number of students in a group (e.g. Barron and Darling-Hammond 2008; Johnson and Johnson 1999).

In terms of the opportunities for classroom learning one of the key issues that emerges from this analysis is that of the relationship between the table design and the way that this is likely to influence its use in classroom settings. Physical positioning in a group and a classroom influences interaction (Marx et al. 1999; Morrison 2010). Collaborative group work has been notoriously difficult to embed in classroom pedagogy (e.g. Mercier et al. 2009), and issues such as dominance within groups, status issues and unequal participation are frequently identified as factors associated with this challenge (e.g. Cohen 1994; Blatchford et al. 2003a; b; Yuill et al. 2009). One attractive aspect of interactive surfaces for educational settings is that they can be used simultaneously by a group (Morris et al. 2006) without a single person able to take control (as happens with a mouse or single-touch surface). Features that therefore encourage a hierarchy according to position and which allow dominance over information according to where users sit or stand are therefore undesirable, if the aim is to enable more even or equitable participation across groups. Other features in this area of our taxonomy which relate to pedagogical dimensions are the facility for individual (private) and shared (public) workspace as this may mitigate some the challenges of individual and group assessment (Boud et al. 1999) enabling both to be addressed at the same time. This approach might enable the individual work that a student undertook on a task, say in designing a classroom layout (such as reported in Harris et al. 2009), as well as their personal contribution to the group outcome by recording or taking snapshots at different stages of the design process.

Display type

Currently, two technology types are predominantly used for screen display in multi-touch tables: video projector or display screens. For this classification, these are characterised as indirect or direct display types. Video projectors throw focused light onto a projection surface. As the projection surface is disjoint from the light source, it can be termed 'indirect'. Video projectors function in one of two ways. One approach is to project onto the display surface by positioning the projector at 'the front', that is, where the projector is located on the same side of the projection surface as the viewer. The alternative indirect approach is to project onto the display surface from behind, known as rear-projection. In contrast with thin-film transistor (TFT) or liquid crystal display (LCD) based systems, projectors are typically capable of lower resolutions. UWXGA (Ultra-Widescreen eXtended Graphics Array, 1920×1080) resolution is commonly found for TFT/LCD whereas XGA (eXtended Graphics Array, 1024×768) or WXGA (Widescreen eXtended Graphics Array, 1280×720) are typical for projectors. Studies have long suggested that screen quality is an important factor in legibility (Dillon et al. 1988) and that resolution and luminance (Lin and Huang 2006) are both important, determining the size of text which can be read easily (Tao et al. 2006).

Front-projection systems are reported to have issues with occlusion (e.g. Forlines et al. 2006a; b), in comparison with rear-projection systems. This occurs when a user moves their hands or body over the display surface, causing a shadow to fall on the surface, rather than the intended image. As Forlines et al. (2006a; b) report, this has particular problems for accurate manipulation in direct touch interfaces (though this may also be an issue also related to the collaborative nature of the task (see Everitt et al. 2005 for example).

Further complexity is evident in the literature on interactive surfaces where the display surface can be varied according to a user's position. For example Matsuda et al. (2006) investigated a table display where a person seated on each side of a square table had a different view of the table content and Kakehi and Naemura (2008) demonstrated view-dependent display. Additionally Chan et al. (2008) proposed virtual privacy where the viewing position allowed for some public and some private content.

Pedagogically what is important here is the quality of the shared display for learners in terms of screen resolution for legibility or for recognition of information and learners' perceptions of this (Bernard et al. 2002). In particular, the legibility of text is an important feature for classrooms where the predominant mode of communication is still through text, albeit in a range of forms. The facility to combine media on a tabletop display also offers significant potential for integrating a wider range of representations into classroom learning, particularly in terms of dynamic (Ainsworth and Van Labeke 2004) or multiple representations (Ainsworth 1999) and facilitating movement between public and private (Vahey et al. 2007) or between individual, group and class level discussion and interaction (Zurita and Nussbaum, 2007).

The facility for public and private viewing angles also has opportunities for competitive rather than collaborative group work or where learners are expected to work as individuals (such as in assessment or testing), rather than the gaming environments so far explored in the literature. Occlusion or blocking line of sight of the display is most likely to affect individuals when they are working in parallel on proximal areas of the surface, rather than when there is joint attention on the same part of the table surface. This suggests that collaborative activities can best be supported on tabletops, rather than learners working in parallel or on separate tasks.

Touch

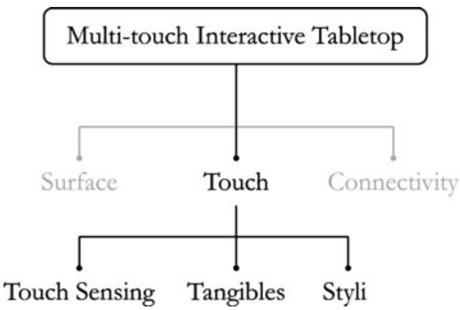
As the classification system used in this article is based essentially on physical and hardware provision for the reasons given above, discussion on interaction is able to leave aside software-based interaction techniques. Instead, the touch category focuses purely on the affordances of the sensing technology used to provide a multi-touch capable surface. Again, this is advantageous as there is considerable work on pointing, selecting, gestures, and novel interaction techniques that are all based purely on interpretation of touch-data in software (Tse et al. 2008; Forlines et al. 2006a; b; Hancock et al. 2006).

The top-level category touch can therefore be divided into several areas that describe the physical means by which a person can directly interact with a multi-touch surface (Fig. 4). This necessarily requires a discussion of the sensing technology that enables a surface to detect contact points.

Research on multi-touch technology has not sought to classify the technology itself, largely due to variability in the intended number of contact points, users, purposes and sensing technology. For this reason, a continuum of these features of multi-touch is proposed (Table 1) in which the dimensions of complexity are the number of users and potential contact points aligned with the characteristics of the technology regarding its connectivity and sensing capabilities.

This continuum of multi-touch types and purposes illustrates the range of sensing technologies and typical numbers of contact points to support multiple users undertaking a range of tasks and activities. This has an impact on the choice of technology for use in learning environments. The influence of different input devices and approaches to control the design of technologies for learning can be seen through a brief overview of the recent

Fig. 4 Touch sub-categories



t1.1 **Table 1** Multi-touch continuum

		Multiplicity	Contacts	Purpose	Characteristics	Typical Sensing Technology
t1.2						
t1.3	Type 0	Single user	≲5	Input device	Device such as a trackpad or mouse.	Resistive, Capacitive, Vision
t1.4	Type 1	Single user	≲10	Personal computing device	Handheld, laptop, tablet, desktop, iPad	Capacitive
t1.5	Type 2	Multi-user	≲10	Installation (Museum, Gallery, etc.)	Stand-alone, single purpose surface, either single or multi-user.	Vision System
t1.6	Type 3	Multi-user	>10	Generic	Multi-application, multi-purpose, multi-user.	Vision System
t1.7	Type 4	Multi-user, multi-surface	>10 per surface	Generic, Networked	Multi-application, multi-purpose, multi-user, multi-surface, distributed.	Vision System

developments in technology enhanced learning, and the CSCL literature which exemplify the different dimensions and types in our hierarchy (Table 1).

Type 0 devices are typically those where the single or multi-touch capabilities do not offer direct interaction with the content, such as through a game controller, trackpad or tablet, where more complex gestures than a mouse click enable more precise or more complex control. They are primarily input devices with limitations noted in terms of the indirectness of interaction and fatigue from more demanding gestures (Yee 2009).

Type 1 devices, such as handhelds (e.g. PDAs, tablets and iPads) typically allow individual users to interact with and control digital content but are primarily designed for personal use (Druin 2009). Many of the early learning tools echo the two strands seen in most of the design of technology for learning science, either providing opportunities for practice (Kulik and Kulik 1991), or providing new experiences, something that could only be experienced or learned through the use of technology (e.g. Papert 1980). Beyond the personal computer, individual use of technology has expanded through the use of these smaller Type 1 devices, where laptops, tablets and handheld devices have been used to create new opportunities for students to work alone on a particular task (e.g. Kraemer et al. 2009; Grimes and Warschauer 2008), or to work in cooperative groups sharing or gathering unique information to create a common solution, or to compete to reach a solution the fastest (Roschelle and Pea 2002).

Adaptations to devices that fall into the first two categories can provide opportunities for shared access to the technology. These include the addition of more than one input device, and activities that require more than one user to confirm a decision before moving forward. Examples of such tools include the use of two mice with a personal computer or Type 1 device, where collaboration is encouraged through the system (Yuill et al. 2009), or the use of multiple-mice, where a large display must be controlled through more than one device, creating a form of interaction between the large display and numerous participants (e.g. Moraveji et al. 2009). While these adaptations go some way to support collaborative interactions during learning, they do so at a possible cost of over-scripting the interactions, limiting the potential of more naturally occurring forms of collaboration.

The use of Type 2 devices are seen typically in public spaces (e.g. Peltonen et al. 2008) or museum settings (e.g. Hornecker 2008) where several people can interact with the installation or exhibit, but where the tabletop or multi-touch display has a single purpose.

Our work focuses on Type 3 and 4 devices, where the number of users and applications is more open, supporting more flexible and intuitive forms of collaboration. In particular this review focuses on the implications that can be drawn from current work on Type 3 devices to support the design of learning environments for the multiple networked, Type 4 devices that we are developing.

The principal advantage of direct-touch interfaces is that they are more natural (Shneiderman 1982; Ryall et al. 2006). For two-handed or bi-manual interaction, direct-touch is, as intuition would suggest, a much more effective mode of interaction than using two mice (Forlines et al. 2007). Direct touch interfaces are not without their problems, however. Fingers give a touch point with an associated area, rather than a single point on the surface (Esenther and Ryall 2006a; Shen et al. 2009) and control when enlarging objects in overlapping spaces can be a problem (Forlines and Shen 2005). This means that errors in the accuracy of selection can be considerably higher in direct-touch interfaces than traditional mouse input (Forlines et al. 2007; Voida et al. 2009). This suggests that these kind of multi-touch surfaces will support collaboration, but not where a high degree of precision is required in the tasks or activities.

For larger surfaces, reaching and stretching or other body movement may be required for a person to touch some parts of the surface. This can cause occlusion problems in collaborative activities, but this move-to-point problem can also result in fatigue. In mouse interfaces, pointing occurs in a relative manner: small movements in the mouse can yield large movements on-screen, whereas in direct-touch interaction, this pointing is absolute. Some effort has been invested in supporting both relative and absolute pointing in direct-touch interfaces, and making the transition between the two, as seamless as possible (Forlines et al. 2006a; b). The support of relative pointing does reduce the problems associated with move-to-point, but does so at the cost of 'naturalness'. Hornecker and colleagues' (2008) analysis suggests that users are more aware of each other's movements in a multi-touch environment, and that as a consequence one person's interactions are more likely to interfere with someone else's. However they also note that these interactions tend to be more fluid and any interference is soon resolved. This again indicates that multi-touch is a productive environment for collaboration.

Many researchers have evaluated pen or stylus interaction techniques for multi-touch surfaces (e.g. Block et al. 2008; Hinrichs et al. 2007; Mohamed et al. 2006; Qin et al. 2010). Pens are more suitable for use in handwriting-based systems over the use of fingers because of the problems regarding accuracy of finger-based direct touch (Forlines et al. 2006a; b). Less obvious benefits have also been observed. Ha and colleagues' (2006) study of input devices on collaboration found that people used more communicative gestures and were more aware of the actions of others when using styli when compared to mouse input. However, natural (direct) touch yielded improved awareness of the actions of others during collaborative tasks. Exploration of combined touch and pen (Brandl et al. 2008) suggest that some features are more effectively controlled manually and others that require more precise touch by a stylus or pen (see also Fiebrink et al. (2009), for an exploration of dynamically re-mappable physical controllers as an alternative means of developing precision).

While some sensing technologies are able to identify those who touch the surface, such as Mitsubishi's DiamondTouch (Dietz and Leigh 2001) interfaces, others are not. Vision system based multi-touch systems, for example, are rarely able to discern which finger belongs to a particular person. Pens can also provide a means of identifying users (Bi et al. 2006). Both of these approaches can lead to capabilities such as assigning privileges to certain people or to identify particular contributions that individual users have made to tasks. This potentially has advantages for recognition of different contributions to tasks and more individual assessment (see below for a more extended discussion of this issue).

One capability that vision systems can support is with the sensing of tangibles, identifiable objects that can be placed on the surface and used as interaction devices or imbued with specific properties. Tangible interaction includes a wide range of systems and interfaces which involve “embodied interaction, tangible manipulation and physical representation (of data), embeddedness in real space and digitally augmenting physical spaces” (Hornecker and Buur 2006) While these have been developed for a number of collaborative learning activities (e.g. Maher and Kim 2006; Rogers et al. 2006; Falcão and Price 2009): The potential of tangibles relates more directly to horizontal surfaces more broadly, rather than multi-touch in particular, which therefore exceeds the scope of this review.

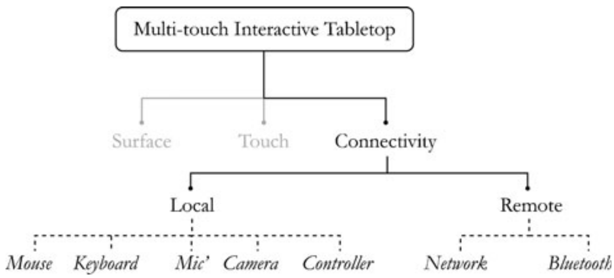
The implications in terms of teaching and learning are particularly related to ownership of information and recognition of different learners’ contributions to a task. Gesture recognition for holding and releasing objects (Ringel et al. 2004) can support temporary private ownership. Sensing technologies, such as through capacitance or with a particular pen, which can recognise a user, offer some advantages where ascription of individual contribution is important. However this individual identification may also militate against effective collaboration where group success is more valued than each person’s role in that success (Johnson et al. 1993). This is one of the identified challenges in the perceived value of effective collaborative work in classrooms in terms of individual assessment (Blatchford et al. 2003a; b).

Connectivity

For this classification, connectivity (Fig. 5) describes the range of input and output capabilities that a tabletop can support, from directly connected local devices such as mice, keyboards, microphones and cameras, to indirectly connected devices that are reachable over a remote network or wireless link, such as other computers, surfaces, laptops or other mobile computing. Examples of the vast range of local and remote devices are illustrated italicised in Fig. 5, however this level of detail is not discussed as part of the typology in this article due to limitations of space. The key issue, discussed below, is the potential role of multi-touch tabletops in a teaching and learning situation, where they can be integrated into a wider digital environment.

Interactive tabletops have been used as pivotal components of technology rich environments that are designed to support collaborative activities, and this trend is

Fig. 5 Connectivity sub-categories



continuing (Shen 2006; Wigdor et al. 2006). Multi-user, multi-touch tabletops are typically used as a shareable interface within an environment of peripheral technologies requiring management of multiple input devices (Hutterer et al. 2006) where ‘scrap displays’ (Shen et al. 2003) or the ‘spilling’ of information between devices is possible (Olsen et al. 2007). These additional systems are often deployed to address some of the limitations of interactive tabletops.

MultiSpace (Everitt et al. 2006) facilitates collaboration in a multi-device, table-centric environment that combines devices such as interactive tabletops, wall-displays and laptops. In this environment, eDocuments can be moved between the devices through portal-based transfer where graphical representations of gateways are displayed around the edges of displays. When content is moved to these portals, the content is then transferred to the device the portal represents. The researchers observed that participants tended to use the wall display first as this had a single orientation, and is relatively large compared with the tabletop. However, Everitt and colleagues (2006) assert that the research clearly demonstrates the importance of tabletops in this kind of environment. Participants also demonstrated the ability to move fluidly between table-based interaction and wall-and-table interaction. By providing different technologies with different capabilities, participants were able to choose the most amenable technology for a particular task. This, perhaps, has implications for the use of laptops or wireless keyboards for text input in such an environment. With respect to collaboration, the researchers also observed that participants tended to provide support to people who were using shared technologies such as wall or table, but tended not to help those with laptops or tablets.

Some of the technologies and capabilities that have been added to an interactive tabletop are obvious; adding additional displays improves the available display space for an activity (Jiang et al. 2008) as can the addition of portable workspaces (“TableTrays”) on the work surface (Pinelle et al. 2008). Some strategies are less obvious. Rogers et al. (2006) for example, attempt to circumvent the limitations of the size of a tabletop by including physical items through RFID technology. By having electronically identifiable physical resources, pertinent to the task, people are able to move items from the physical space into the digital space. Principally, this meant that people were able to take advantage of a much larger space in which information was placed: that of the physical space. They observed that people in the physical plus digital condition explored the problem space from more perspectives than in the purely digital condition.

In a similar way to single-touch devices, multi-touch devices are also being evaluated in the context of remote collaboration. Esenther and Ryall (2006b) remotely connected a single user with a desktop and phone together with a co-located group using a tabletop. In this evaluation, three modes of interaction were supported. In the simplest case, participants were able to take control over a shared mouse through a simple first-come-first-served basis. The second mode of collaboration provides the ability to annotate an image, such as an image of the computer’s desktop. In the third mode, the software supported multiple pointers, where participants were able to position a remote pointer over some content in order to highlight points of interest or discussion. What is highlighted in this study is that traditional window-based interfaces are not sufficient in providing support for distributed collaboration with interactive tabletops and that new approaches to user interface are needed (see also Chatty et al. 2007).

Through remote desktop software, interactive tabletops can provide gateways through to regular computers. Tse et al. (2007) demonstrate this approach in their multi-modal split view tabletop where Virtual Network Computing (VNC) software is used to allow collaborators to view remote desktops. One input mode used in this study is speech. Each

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participant was equipped with a microphone and was able to issue commands to the system such as navigating backward and forward through a browsing history, or instructing the system to open a keyboard. The complexity of the management of multi-modal input (gesture, pen and speech) suggests that this is an area that requires substantial further development (Tse et al. 2008).

The connectivity of a tabletop is important pedagogically in three key ways. This is in terms of the capacity and range of information (Kennewell 2001) which can easily be incorporated either for learners to be directed to or for them to introduce themselves. Production of written text emerges as a particular issue; both in terms of orientation, readability and input with a range of possibilities explored such as pens, handwriting recognition, voice input, keyboards, and other devices. Second, the opportunity for the teacher to interact with a group remotely (to send content or to get feedback) is a key feature of classrooms and so is desirable for classroom use. Finally the facility to share information or content between multi-touch surfaces is also relevant to a classroom situation where it may be desirable for groups to interact with each other collaboratively or competitively (Blumenfeld et al. 1996; Blatchford et al. 2003a; b). Learners could add to or extend work in mathematics or in writing started by another group or provide feedback on each other's progress. In one task we are developing, learners complete as many calculations as they can to equal a given total, then these are moved on to another table for the next group to add to and extend, thus modelling a wider range of possibilities than one group might generate. Teachers could also swap content between groups during a task so that they each have to understand other groups' ways of working as well as their solutions.

Using multi-touch tables to support collaborative learning

While the majority of this review has focused of the importance of understanding the affordances of multi-touch tables, and the interaction between the technical affordances and pedagogical design, some recent work has explored the use of multi-touch tables in collaborative learning situations. In this section, we review this literature, noting the early stage that most of this work is at, and that there is a continued focus on reporting development of tools, rather than learning outcomes, of in-vivo studies. The research to date can be divided into five main categories, with some research focusing on understanding differences between multi-touch tables and other types of technology, a number of studies that explore the use of multi-touch tables for story-telling activities, some studies that explore software developed for multi-touch tables that aim to support collaboration, and research that focuses on the use of multi-touch technology to support social interaction between people with autism spectrum disorders. Additionally, we note that there are numerous ideas in this area that are still in the early stages of development, which cannot be yet used to support claims of the value of this technology to support learning, but recognize the potential for the development of collaborative learning activities on multi-touch tables being explored throughout the world.

Relatively little research contrasts collaborative learning activities using multi-touch tables and other types of technology, however, what work exists indicates that multi-touch tables influence the way groups interact, with potential for influencing learning outcomes. In a study that contrasted groups of school children completing the same design task on either a single-touch or multi-touch table, Harris et al. (2009) found that there was more task-focused talk in the multi-touch condition, and more talk about turn-taking in the single-touch condition. Similarly, in a study comparing groups working on a history mystery task in multi-touch or paper-based conditions, Higgins et al. (2011) found that groups in the multi-touch condition developed a joint understanding of the problem more quickly and engaged in more interactive discourse (elaboration and negotiation) than groups in the paper-based condition. Piper and Hollan (2009) report on a comparison between students using a multi-touch table to study for an exam, and students using paper. They found that students in the multi-touch condition were more likely to attempt problems before looking at the answer key, and more likely to repeat tasks than students in the paper condition, suggesting that including a table top application in study sessions may be useful.

Multi-touch tables have been used to support the development of story telling skills, including the TellTable (Helmes et al. 2009) and ToonTastic (Russell 2010). These tools provide a structure within which children can work individually or in groups to develop and animate stories, sharing them with peers or adults. Studies of the use of these story-telling tools indicate that children drew inspiration from other stories, creating stories that draw on the ideas that their peers are in the process of developing. This exchange of ideas suggests a form of cooperative story telling, which is supported by engaging in collaborative or parallel story creation.

A third category of multi-touch table software that has been developed for collaborative learning are tables that are designed explicitly to support collaboration by monitoring and providing feedback during the collaborative process. One such example is the Reflect table (Bachour et al. 2009), which displays colour-coded circles to indicate how much each member of a group is speaking or how much a particular topic is discussed (as identified by a member of the research team, listening from another room). This tool, which is based upon the premise that equitable participation is important (Cohen 1994) aims to increase participation by increasing awareness of this feature of collaboration. Results indicate that awareness of participation increases with the use of the Reflect table, generally leading to a decrease in participation from over-participators, rather than an increase in participation from under-participators. This type of tool suggests the possibility for reflective tools to support the collaborative learning process, however, it also indicates the need to be aware of how this influences engagement, possibly increasing awareness of the types of status differences that Cohen (1994) considered foundational to inequities in participation, and the need for appropriate interventions to further support engagement.

An extension of the category of software to support collaboration is software specifically designed to support interaction between people with autism spectrum disorders. These include games designed to encourage correct turn-taking behaviour (e.g. Piper et al. 2006), games that require cooperative actions (e.g. Battocchi et al. 2009) and a story-telling tool, StoryTable, which promotes social communication (e.g. Gal et al. 2009). Both of the games (Piper et al. 2006; Battocchi et al. 2009) have been tested with children with autism spectrum disorders, and show increased cooperative and interaction behaviours while using the tools. Additionally, studies conducted with StoryTable (Gal et al. 2009) indicate that children with high-functioning autism show evidence of increased initiation of positive social interaction after using the StoryTable. This indicates the potential of tools created for multi-touch tables to teach social skills that can be transferred to new situations, helping to remedy one of the core deficits identified in autism spectrum disorders.

A final category, as noted above, includes early prototypes or proposals for using multi-touch tables to support collaborative learning. This includes work such as the SimMed project (Kaschny et al. 2010), which is beginning to develop a patient simulation for medical students, PhysicsBox (Langner et al. 2010), a prototype of three physics games, work by Conradi and colleagues (2010) to design activities to support the learning on physical computing on interactive surfaces and work by Butler and colleagues (2010) to develop activities that support the development of phonemic awareness. While each of these indicate the potential of multi-touch to support learning, the early stage of development of this work means that there are not yet findings of their impact on learning outcomes or interaction.

As a whole, however, the completed studies indicate that multi-touch tables can change the way collaborative learning groups interact with each other and the content of learning activities. While none of these studies use multiple tables in a classroom setting, they all suggest the importance of designing the multi-touch table activities and supporting activities, in such a way as to maximize the types of interactions that support learning.

Summary and conclusions

This typology (Fig. 6) is offered as a means of distinguishing between the capabilities of the range of multi-touch tables which are emerging and provides an analysis based on the features of these systems so as to identify distinguishing characteristics and significant features which may related to their pedagogic capability.

Features related to the surface and its design broadly set the parameters for physical collaboration around the surface. However, the detail of the way that individuals interact with the technology also influences the way that they interact with each other. Further, the way that content is accessed and shared on one table and between tables influences the educational opportunities in a multi-touch classroom. The analysis above is provided so that further discussions of the educational capabilities of the technology are related to the appropriate similarities between different systems. We have used the analysis to compare our own research with other related research in this field. In our project, SynergyNet (Higgins et al. 2009), four rectangular, horizontal rear-projection tables are networked in a classroom with an angled teacher table that can control the other tables individually or collectively (Fig. 7). The pupils' tables can send and receive content to and from each other as well as the teacher's table in a fully networked environment.

The finger-touch control allows small groups of learners to work together at each table with up to 30 simultaneous touches reliably recognised. This contrasts with other research projects, such as Multi-Space (Everitt et al. 2006) for example, where a single, front-projected table, capable of recognising inputs from a small group of users, was linked to an interactive wall display and handheld PDAs. In SynergyNet, the focus is on group collaboration (intra-group) and interaction between groups (inter-group), orchestrated by the teacher. In Multi-Space, the focus was on data-rich collaboration within the group (intra-group). The analysis of the literature indicates that horizontal multi-touch table

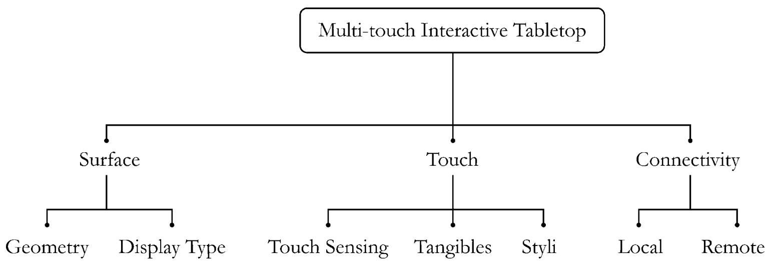

Fig. 6 The complete typology

Fig. 7 The SynergyNet Project classroom

surfaces seem to offer significant benefits for collaborative interaction with digital content both within and between groups (intra-group and inter-group collaboration) but variation in the technologies used may make it difficult to generalise across the types of technologies used and the range of potential educational tasks for which they could be used. However it is also evident from this review that task design and task variability are critical features in the use of multi-touch. Some common limitations also emerge, particularly in terms of text entry (Hirche et al. 2008), for example, which may restrict their educational potential in terms of the requirement of most current school classrooms where learners spend a considerable amount of time in individual production of texts (Galton et al. 1999).

The key pedagogic features identified in this analysis with specific implications for collaborative interaction are the way that the features of the tables relate to individual and group control. This starts to set the parameters for group interaction and collaboration. The central feature for exploration in educational settings is the way that on a multi-touch surface control of digital content can be equally distributed across the group. However, there may, be disadvantages of this feature that also need to be considered. Most of the existing work on collaboration in classrooms uses the mouse, a single point of control, as a feature that requires explicit agreement and articulation (such as through 'talk-rules': Wegerif et al. 1999); multi-touch surfaces may therefore reduce the need to articulate thinking and reasoning to the group where physical demonstration may be sufficient (Marshall et al. 2008). Examining the quality of talk and interaction will therefore be an important dimension of their impact on collaborative activity to investigate the impact of multiple points of control on coordinated group interaction. Another issue for exploration is the role of the teacher in interacting with the group. Kennewell (2001) emphasises the importance of teacher 'orchestration' of learning and the importance of varying the conditions of support to ensure learning.

The use of new technology in classrooms comes at a cost; a financial cost for the hardware but also a cost of technical and pedagogic support. At this stage, the tables are not sufficiently stable for constant classroom use, and teachers are not yet familiar with the orchestration demands that such technology brings. Also, as noted by Dillenbourg and Evans (2011), unless there is sufficient reason to use this technology across the curriculum, they will become another form of hardware, placed in labs and used sporadically. One of the opportunities for CSCL researchers, at this stage in the development of this technology, is the chance to examine their use in education settings before they become affordable and stable, and get incorporated into current practices. Ideally, research at this stage will allow us to provide insight into how this technology can be used to change collaborative learning practices in the classroom. As such the central question for future exploration and evaluation of multi-touch tables in educational settings is therefore to find out under what circumstances and with what technological configuration the advantages for more equally distributed control over direct touch interaction with digital content can be educationally beneficial. The implicit and explicit design decisions about technological and pedagogical choices suggests that it is all too easy for the technological and pedagogical choices to be misaligned, resulting in the development of technology that does little to alter classroom learning.

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