Original article

doi: 10.1111/jcal.12052

Journal of Computer Assisted Learning

Creating joint representations of collaborative problem solving with multi-touch technology

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Abstract Multi-touch surfaces have the potential to change the nature of computer-supported collaborative learning, allowing more equitable access to shared digital content. In this paper, we explore how large multi-touch tables can be used by groups of students as an external representation of their group interaction processes. Video data from 24 groups of students working on a logic reasoning problem was examined to identify their levels of reasoning about the task, and how they used the table to support their reasoning. Results indicate that of the 13 groups who solved or nearly solved the problem, 12 used the table to represent their reasoning process, while only four groups who used the table to support their reasoning process did not solve the problem. Examples from three groups are used to explore the different ways the table was used as an external representation of the groups' processes. The findings indicate that the group problem-solving process can be enhanced with the use of multi-touch tables, although students may need support in using the technology effectively to support their collaborative reasoning.

Keywords: collaboration, CSCL, logical reasoning, multi-touch technology.

Introduction

The introduction of multi-touch technology, and the creation of devices that allow for multiple points of contact, and therefore multiple simultaneous users, presents the possibility of changing the way learners interact with each other and engage with content. This potential comes from two features of this technology: (1) a large shared display for group members to view simultaneously, rather than using individual small displays or crowding around a smaller shared display, and (2) the ability for all members of a group interact directly with the content on the tables, rather than use a single input device such as a mouse or keyboard whose control needs to be negotiated. The tables also provide a flat surface, rather than an upright screen that can block the students' faces from each other or the teacher, while not requiring individual to hold onto a device, which could potentially improve the interactions both within groups and between groups of students and the teacher. Thus, in contrast to other technologies that have been used to support collaborative learning in classrooms, such as traditional computers, tablets or handheld devices, multi-touch tables may reduce the need to monitor participation, provide a better setting for face-to-face interaction and support collaborative discussions (Dillenbourg & Evans, 2011; Higgins, Mercier, Burd, & Hatch, 2011). However, it is yet to be shown that students can effectively use this shared space to support their joint cognition, leveraging it as part of their collaboration to lead to deeper learning. In this paper, we describe a study in which 24 groups of

Accepted: 29 September 2013
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students worked on a logical reasoning problem using a multi-touch table. We then explore the ways in which they used the table to provide an external representation of their interaction processes.

Multi-touch tables and collaborative learning

While research on multi-touch surfaces and collaborative learning is in its infancy, there is some evidence that this type of technology allows different forms of interaction from single-touch surfaces or paper-based activities. In a study that contrasted groups using a single-touch table and a multi-touch table, Harris *et al*. (2009) report that there was less process-focused and more task-focused conversation in the multi-touch condition. They argue that group members could focus on the task, rather than monitoring participation when using the multi-touch table. This task would be equivalent to using a single-touch interactive whiteboard, and shows that the use of multi-touch technology can reduce the need for students to negotiate turn-taking and process issues during collaborative activities.

Research that contrasted using multi-touch and traditional personal computers (PCs), has shown that the use of multi-touch led to increased time spent in shared engagement in the task, while in the PC condition, more time was spent with one student working on the PC, while the other student sat back and watched (Basheri, Burd, & Baghaei, 2012). Again, this work indicates increased collaborative engagement using multi-touch technology, and different interaction patterns across the two types of devices.

In our earlier work, we have examined differences between students using a multi-touch table compared with working on a paper-based version of the same tasks. In both history and maths 'mystery' tasks, we found that the groups in the multi-touch condition were able to use the surface to recruit and maintain joint attention, with all group members looking at the same clues as they took turns reading them aloud, and then discussing their relevance in the multi-touch condition, while in the paper-based condition, groups distributed clues so that only the student reading the clue was able to see its content. (Higgins, Mercier, Burd, & Joyce-Gibbons, 2012; Mercier, Vourloumi, & Higgins, 2013). During the historical mystery that promoted divergent thinking, we found that groups were more likely to build on the ideas that their group members proposed in the multi-touch condition, responding more often with negotiating or elaborating comments, when compared with the same task in a paper-based condition, where the students were more likely to make independent or quasi-independent statements (Higgins *et al*., 2012). In a comparison of maths mysteries, which were designed to promote convergent thinking, including the logic task described in this paper, we found that the students responded more often to ideas proposed by other students in the multi-touch condition than in the paper condition. These responses were also more likely to be elaborations of the ideas that the other student proposed, or statements that built on the proposed ideas by combining them with other ideas (Mercier *et al*., 2013).

Taken together, these results indicate that multi-touch surfaces can support group processes and shared cognition. We hypothesize that this is done by providing a space in which the group can create a shared representation of their processes. This reduces the need for aspects of the negotiating process, and allows more concurrent engagement and activity than other researched technologies or paper-based versions of the same task. We explore this issue in the current paper.

Collaborative learning and problem solving

Research on collaborative learning has identified the importance of the development of a conceptual joint problem space in supporting a group's process in solving complex problems. Drawing on the cognitive psychology concept of a problem space (Newell & Simon, 1972), a joint problem space needs to be created by members of a collaborative group to ensure that all members of the group understand the problem that is being worked on, and how the group is going about solving the problem. The development of a joint problem space was described by Roschelle (1992) in a case study of students making sense of scientific phenomena. To successfully create a joint understanding of the concept, the members of a group need to converge on a shared meaning of the problem and the solution processes, and from there, create a joint understanding of the concept or solution. This is particularly important in mathematics tasks where modelling, representing and symbolizing are important features of mathematical communication in classrooms (Gravemeijer, Cobb, Bowers, & Whitenack, 2000).

Later studies indicate that when groups work to reason clearly about an issue, elaborate on ideas and verbalize the features that are causing difficulty, they are more likely to solve the problem or learn from the activity. Barron (2003) reports on different outcomes between groups where all participants had been selected based on their prior high levels of achievement in maths tasks. Despite the assumption that all groups should have been able to complete the task, not all groups solved the problem, or transferred the skills in individual post-tests. These differences were ascribed to differences in the manner in which the groups interacted over the problems and solution while all groups proposed the correct ideas during the task, those who solved the problems and learned from the process engaged with the ideas, asking questions and building upon their teammates' ideas, again indicating the need for a joint understanding for successful collaborative learning. Hogan, Nastasi, and Pressley (1999) found that the key features of groups who successfully reasoned about scientific principles were those who worked with incomplete ideas to develop and improve them, rather than ignoring their teammate's misconceptions. In this way, the participants who succeeded had been creating a situation in which they discussed the complexities of the problem, considering each members' understanding until the formed a shared understanding of the problem. These, and other studies, indicate the importance of identifying misconceptions or points of confusion or conflict within groups and then working to understand how all members of the group are conceptualizing a task so as to come to a common understanding of the task and solution process.

The use of external representations to support joint problem spaces

While significant attention has been paid to the verbal and interactional processes by which groups come to converge on a problem space, less attention has been paid to the use of external representations that could be used to support this process. However, the use of external representations has been found to be a useful tool for individual problem solvers (e.g., Hatano & Inagaki, 1986). Martin and Schwartz (2009) describe the development of external representations as a form of adaptive expertise, suggesting that representations are used spontaneously in situations where the task becomes too burdensome to complete without support or sometimes, in anticipation of a complex activity. In their study comparing undergraduate students who had constant or intermittent access to resources, they found that the undergraduates with intermittent access were more likely to create a representation to support their reasoning than those with constant access. While the creation of a representation was associated with a slower solution time initially, those who created the representations solved later tasks more quickly and with more accurate solutions.

In collaborative learning episodes, tasks are often designed to be either too complex for a single individual to hold in working memory, or sufficiently challenging to require multiple perspectives and joint engagement. These situations lend themselves to the development of external representations, both as a way to manage a complex task and in order to ensure a common understanding of the problem. The choice to use a representation to support the group process, however, requires the availability of tools or artefacts to create representations, the knowledge of the value of this practice and either implicit or explicit negotiation within the group about how to create the representation (Barron *et al*., 2009).

Schwartz (1995), in a study of dyads reasoning about turning cogs, found that some dyads converged on the manner in which to represent the cogs, and that those dyads were more likely to develop an abstract representation of the problem, thus coming to a solution more quickly when given a more complex problem. This leads to the claim that group performance will always fall short of individual performance if the group does not create a shared representation of the problem, indicating the importance of creating or adapting a representation to support group process.

The development of tools, particularly technology tools, to support the use of representations in groups further indicates the importance of representations for groups. Pea (1992) describes the role of technology in augmenting learning conversations in such a way that the representations created with or by the technology can foster greater understanding and more scientifically valuable conversations. Using the Dynagrams project, Pea illustrated how the use of visualizations and tools can support interaction and, coupled with the timely contributions of a teacher, can foster more complex understandings. Further work in computer-supported collaborative learning supports this view. In a re-analysis of four prior studies that examined differences between scaffolds that support the collaborative process and scaffolds that support consensus building, Gijlers, Saab, Van Joolingen, De Jong, & Van Hout-Wolters (2009), report that a concept mapping tool and respect, intelligent collaboration, deciding together and encouragement (RIDE), a series of communication rules that were taught to the participants, were most associated with consensus building interactions. While indicating the need for caution in over-interpreting their re-analysis of prior work, the authors note that having the opportunity to display the thinking of members of a group, and where it diverged, may explain why this form of support was useful to the groups.

The present study

The research on representations, both at the individual and group level, indicates that they should play a key role in the development of a joint problem space, and abstracting from details to a general understanding of the problem. Building on our prior work comparing this task in paper-based and multi-touch conditions (Mercier *et al*., 2013), in this study, we examine the use of collaborative representations in a logical reasoning task, asking whether the groups of students automatically use representation of the digital clues on the table to support their reasoning, and whether there are differences in outcomes between groups who use the table and groups who do not.

Logical reasoning and the solving of non-numerical word problems and logic puzzles are part of the mathematics curriculum in England (Department for Education and Employment (DfEE, 1999) and standards in the USA (National Council of Teachers of Mathematics, 2000). Reasoning is also an essential feature of mathematics as a subject (Steen, 1999), which underpins mathematical learning and understanding (Russell, 1999). Though the link between developing or improving reasoning performance and increasing mathematical attainment is harder to establish (Barkl, Porter, & Ginns, 2012). Initial ideas were that development or maturation was the key constraint in children's reasoning (e.g., Piaget & Inhelder, 1969). Although these ideas have now been largely rejected, other limitations have been proposed, such as the application of pragmatic schemas (Light, Blaye, Gilly, & Girotto, 1989), limited knowledge or a weak knowledge base (Brown & Campione, 1994; Metz, 1997) and teachers' difficulties in scaffolding reasoning effectively (Metz, 1997; Diezmann, Watters, & English, 2002). Other factors such as working memory and informational complexity have also been identified as difficulties in logical reasoning and problem-solving tasks for young children at school (Hoffman, McCrudden, Schraw, & Hartley, 2008).

The particular task in this study was designed to be more complex than a single student could solve alone, with one piece of information that provided background, but was not relevant to the solution, and ten pieces of information that needed to be parsed and related to real-world knowledge in order to find a solution. In this way, the task lent itself to the first of Martin and Schwartz's (2009) reasons for the use of representations, namely, that the task was too burdensome to complete without additional resources. While it was theoretically possible for the students to use their joint memory to recall their solution, it is not possible to solve the task using this strategy. Thus, the task demands an externalization of the group's thought process, in an effort to facilitate within-group collaborative learning (Leat & Nichols, 2000).

As prior research comparing multi-touch technology to other tools indicates higher levels of joint attention, more task focused talk and increased amount of interactive talk that builds on the ideas of other group members when compared with other tools, this study aimed to explore how the multi-touch table might support the collaborative interactions in a larger sample of students using multi-touch tables. With the hypothesis that the tables may help the group represent their process, as one form of supporting their collaborative interactions, the study aimed first to ask whether groups of students used the multi-touch table to represent and support their reasoning process. The second questions addressed in this study is whether the use of the table to represent the group process supported the students in reaching a solution.

Method

Participants were 96 pupils (10–11-year-olds; mean age 10.58; SD = 0.39) who attended six local primary schools in England. There were 48 male and 48 female students in the sample. Eight male and eight female students came to the lab-classroom from each school, working in groups of four in the lab-classroom. Groups from four of the schools worked in same-gender groups, while groups from two schools worked in mixed-gender groups (two male and two female students in each group), thus there were eight all-male groups, eight all-female groups and eight mixed-gender groups in the study.

All six schools were invited to participate agreed to be part of the study. All the schools are ranked as average, or just below average, on standardized tests of academic achievement in England. For each of the schools, two or three of the experimenters went to their classrooms and led the pupils through a number of introductory activities and showed a video of the multi-touch classroom. Parental consent forms were distributed, and teachers selected the students who could attend from those who returned consent forms.

The multi-touch classroom

This study took place in a multi-touch classroom, a room that had been designed to develop and test multi-touch technology for learning. As can be seen in Figure 1, the classroom consists of four sit-to-use, multi-touch tables for up to four students to use simultaneously. There is also a multi-touch teacher desk, from where the teacher can control the student tables, send or remove content from the student tables and project the content of the student tables to the multi-touch interactive whiteboard. The room is also equipped with cameras and microphones to record interaction data (see Higgins *et al*., 2011, 2012 for more details).

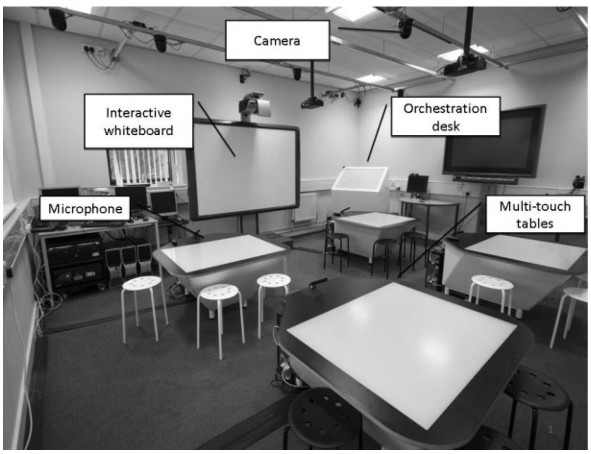

Figure 1 The Multi-touch Classroom

Experiment procedure and the task

The students spent up to 5 h in the multi-touch classroom on the day of the experiment. They completed a number of activities to become familiar with the multi-touch tables, and then a history 'mystery' activity. After a short break, the participants returned to the classroom and completed three maths tasks using the same 'mystery' format. The third of these, a logic problem, is the focus of this paper. At this stage in the day, the students were very familiar both with using the multi-touch tables, and with the structure and affordances of the task design. They were familiar with the presentaion of digital information and the way in which these 'clues' could be moved and resized.

The logic problem, like all three maths problems, was designed to have a single correct answer. Students received six clues, which they had to sort through in order to find the answer to the question 'What should Mike have for dinner?' One of the clues gave the students more context for the problem, while the content of the other five clues was necessary to solve the problem. The clues are shown in Table 1, with the correct answers. The clues were presented on the multi-touch tables in text boxes, which could be moved and resized as necessary. The most productive approach to solve the problem is to create a circular arrangement (see Figure 2).

Data

The multi-touch classroom is designed for data collection of group interaction. It allows for video recording of each group from two angles, and audio recording from a microphone placed in each table. The teacher was recorded with a radio microphone and a fishbowl camera was used to record the entire classroom. Screen capture software was used to collect video of the use of the interactive table. The audio streams from each group were transcribed alongside the video and screen capture data, using a tool developed by the project team. Transcripts were created along a timeline, producing time-stamped information for each turn

Table 1. Dinner Disaster Clues and Correct Answers

Clue	Child	Meal	Correct child
The new cook at school, Mrs Baker, has mixed up the trays with the children's school dinners on.			
Mike scooped up a spoonful of his yogurt and grumbled, 'Everybody knows I'm allergic to this stuff.'	Mike	Yogurt	Tanya
'Well yogurt is the only thing I like on the menu' replied Tanya. 'And there's no way I'm going to eat THIS!' At that, she poked her salad with a fork.	Tanya	Salad	Grace
'Hey, anybody want these chicken wings?' asked Grace. 'I don't like anything with meat in it.'	Grace	Chicken wings	Jack
'Don't look at me', moaned Jack. 'I hate any food with cheese on it.' At that, he pushed away his cheeseburger.	Jack	Cheeseburger	Ruby
'Yuck!' cried Ruby, making a face at the slice of pizza in front of her. 'I can't stand pepperoni!'	Ruby	Pizza	Mike

(see Mercier, Higgins, Burd, & Joyce-Gibbons, 2012; Mercier, Vourloumi, & Higgins, 2013 for an example of this tool).

Coding scheme

Building on prior research that views the group as the unit of analysis (Stahl, 2006), and taking a socio-cultural rather than cognitive approach to the study of collaborative learning, we focused on understanding how the group processes and the use of the technology led to the level of success achieved by each group. A coding scheme was developed to capture the levels of reasoning necessary to solve the logic problem and to capture the use of the table to support the group's problem-solving behaviour. The coding scheme was designed to be applied to 30-second segments of interaction, during periods when the groups were working on the task, and not during whole-class discussion. These codes are described in Table 2.

Figure 2 Circular Pattern to Solve the Dinner Disasters Mystery

The video of each group was broken into 30-s segments, starting from the time the teacher sent the clues to the table and unlocked it for use. If the teacher stopped the groups during the task for a whole-class discussion, this time was not included in the analysis, as the students could not move the clues when the tables were locked (this happened in three of the six class sessions). When the final segment was shorter than 30 s, it was included in the penultimate segment, so that no segment was shorter than 30 s, but up to two segments per session could be longer than 30 s (one at the end of the whole session, and one before a mid-session whole-class discussion). As four groups participated in each class, each class had the same length and number of segments, but these differed between classes.

The codes that were developed to capture the table use were recorded as either present or absent within each 30-s segment; a single incident was sufficient for

Table 2. Coding Scheme for Levels of Reasoning

Level	Description
0	No discussion of the content (e.g., students are either discussing procedural matters or engaged in off-topic conversation)
1	No links are made (reading clues, summarizing clues)
2	A link is made with one other clue
3	The relationship between three or more clues is considered.

Table 3. Coding of Table Use

Code	Description
Shrink unimportant	The students shrink the clues they deem to be unimportant (it is most useful to shrink the first clue).
Enlarge important	The students increase the size of the clues they deem to be important.
Evident use of structure	The students use a structure of some kind to help them solve the problem.
Higher levels of structure	The students use the table or space to develop a higher level of reasoning about the clues (e.g., assign clues to people and parts of the table).

the code to be marked as present (see Table 3 for a description of the coding scheme). Two members of the research team coded three of the videos to assess reliability of the codes, with 86% agreement on shrinking unimportant clues, 86% agreement on enlarging important clues and use of structure and 100% agreement on higher levels of structure. Disagreements were mostly found in sections where it was necessary to infer the meaning of the movement of a clue on the table. The segments that contained disagreements were watched and discussed until the coders agreed on the code for that segment.

The codes for reasoning were assigned to the highest level of reasoning made during the segment. Two members of the research team coded three of the videos to assess reliability of the codes for reasoning, agreeing 72% of the time (Cohen's kappa = .727; weighted Cohen's kappa = .781). Disagreement arose primarily between Level 1 and 2 during segments where the participants were discussing the way they were going to solve the problem, but not actually making connections between the clues, therefore, not actually showing the higher level of reasoning (although usually reaching it in the subsequent segments).

Results

Time on task

The length of time the task took in each of the six classes was calculated, as was the amount of time the students spent working in a group or in whole class discussion. The mean length of time for the dinner disasters activity was 7 min, 40 s (SD = 79.25 s), with a mean of 4 min, 40 s spent in groups work (SD = 72.19 s) and 3 min spent in whole class discussion (SD = 52.16 s). In three of the classes, there was one period of group time, followed by a whole-class discussion, while in the other three classes, there were two periods of group time, broken up with one period of class discussion to consider the process for solving the problem and a final discussion of the outcome.

Success

Although the task was difficult, all of the groups made an attempt to solve the problem. Not all groups were successful in finding the solution. Ten groups came to the correct answer before the teacher called the class to a whole-class discussion, although three of these had help from the teacher in finding the solution. Of the 14 groups who did not find the solution, three were close– either needing a little more time to make the final connection or making an incorrect decision so coming to the incorrect answer, but understanding the principle of the activity and successfully coming to a reasoned solution. For the purposes of the analysis below, the three groups who appeared to be on the path to finding the correct solution will be classified with the groups who did solve the task, in recognition that the process by which the group was managing the task is the key question in our analysis.

Reasoning and use of table

Each 30-s segment was coded to determine the highest level of reasoning attained according to the coding scheme. While some groups moved up through the scale, many groups jumped from Level 1 to Level 3. Additionally, each group's use of the table was coded to identify where they had used the tables to help structure their argument. A summary of these codes is shown in Table 4, and described in detail below.

Five of the 24 groups did not progress beyond Level 1–dealing with each clue in isolation, but never making links between the clues. As expected, none of these groups solved the problem. Two of these five groups only used the table to display the clues. They made no

Table 4. Number of Groups Who Solved the Task, Their Highest Level of Reasoning and How They Used the Table

Number of groups	Highest level of reasoning	Use of table to structure task	Solved (or almost solved) the problem?
5	1	No	No
2	2	No	No
4	2	Yes	No
1	3	No	Yes
12	3	Yes	Yes

attempt to alter the size of the clues to denote importance, or use the clues to help them structure their argument. Additionally, one group made an attempt to alter the size of the clues to denote importance, but did not grasp the concept of the task, and therefore discarded many of the important clues. Of the other two groups who did not reason about relationships between clues, both made some attempt to increase the size of clues that they thought were important, and to put the clues in some sort of order to help them solve the task. However, in these cases, the students did not make explicit links in their ordering, basically arranging rather than ordering the clues.

Six groups reached the second level of reasoning, drawing links between two of the clues at a time, but not considering the larger problem. Again, none of the groups who only reached Level 2 solved the problem during the time available to them. Of these six groups, one group made no use of the table to support their work, and one group made a single move to increase the size of an important clue, but otherwise did not use the table as a resource to support their reasoning. Of the remaining four, two groups did not resize to denote relative importance of clues, but all four made some attempt to arrange the clues in an order that supported their thinking. In one of these groups, the arrangement of the clues was done by one student at a different time to the Level-2 reasoning; the arranging occurred in the last two 30-s time periods, suggesting that the group may have been attempting to reconceptualize the task, but did not have time to proceed any further.

The 13 groups who reached the third level of reasoning in this task also either successfully found the answer or came close to the answer, and all but one group ordered their clues on the table to support their reasoning. The differences between these groups and the four groups who did not solve the problem but attempted to use the table to support their solution, appears to be in the higher level of reasoning that was connected to their use of the table. Thus, the groups who were making reasoned links were also ordering the items on the table in a more complex manner, to illustrate the chain of links, rather than simply denoting pairs with a connection. The one group who did not appear to use the table to support their reasoning solved the problem with the teacher's support. This suggests that the teacher may have provided the external support necessary for this group to solve the problem.

Vignettes of groups

In the section below, the interactions of three groups are described in detail, to explore different ways in which the groups used the table to support their thinking about the task. These groups were selected from the list of students who were classified as either getting the answer correct or coming close. They illustrate three different uses of the table that could support the group process and solution.

Vignette 1: Using the clues to aid memory

The first vignette is drawn from an all male group from Shadbrook primary school (all school and child names are pseudonyms). This group, Joshua, Samuel, Thomas and John, had successfully solved the previous two tasks and appeared to be keen to solve this third task, starting to read the clues as soon as they were made available by the teacher. This group reasoned about the task, using the table as an external representation of their thinking almost immediately. All of the students appeared to quickly understand the process necessary to complete the task.

In the first minute, Joshua, who has read two of the clues, draws links between them, saying 'he, he's allergic to cheeseburger, he's allergic to yogurt so, if we mix them around they won't be allergic to it, but instead', thus immediately reasoning at Level 2 as defined by the coding scheme. While he is saying this, Joshua also places his hands on the screen, making a swapping motion as if to indicate the foods were moving between the clues (see Figure 3).

While the idea of swapping food gets the group on the right track, it is not the correct way to reach a complete solution. However, Samuel immediately highlights a clue that might be better, an unstated strategy that is quickly picked up by Joshua.

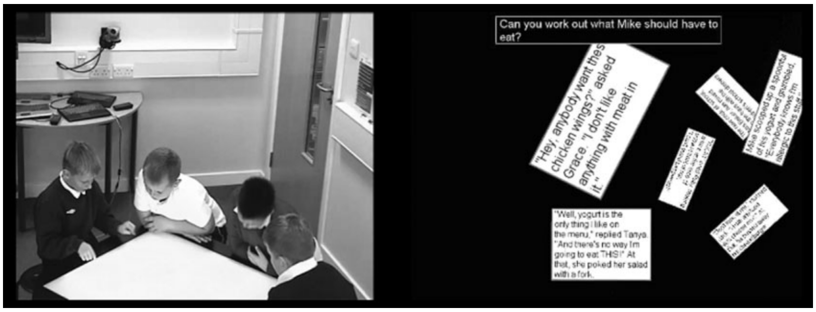

Figure 3 Shadbrook Red

> Samuel: this one likes yogurt [referring to the clue in front of him]
> Joshua: does that guy like yogurt?
> Samuel: yeah
> Joshua: then he gets Mike's [yogurt].

When the teacher brings the group back together to check that all students understand what the task entails, Thomas is the child who tells the whole class that they need to work out what everyone gets to eat, not just Mike, in order to be sure they have the correct answer. This indicates that while the strategy has not been articulated, the members of the group understand what they are trying to do. The group return to the task immediately and focus on finding the answer. At this stage, they have the clues laid out so they are all visible, making the clue about the cook smaller as they deem it unnecessary to their solution. However, they try to create links by pointing, but do not use the table to help them structure their answer. Between this, and the fact that they have not realized that Jack cannot have pizza (it has cheese on it), they come up with an incorrect solution, and are joined by the teacher who helps them work through the task to find their mistake.

Once the teacher leaves, the rest of the groups are still working on the task, this group return to the task, moving one clue in front of each child as a way of remembering how to solve the task. In this way, rather than using the clues to explicitly structure their answer, they each take ownership of a clue, and remember what the person in that clue should have to eat (taking joint responsibility for the fifth clue, which was left in the centre of the table).

Vignette 2: Issues caused by the structure used

The red group from Seacrest was a mixed-gender group, made up of two boys and two girls. In this class, the teacher introduced the session by telling the students that the school dinners had been mixed up and that every child had the wrong meal, so they had to sort it out, particularly working out what Mike should eat. This meant the students began the task with a better idea of how to deal with it than most school groups, and the knowledge that most clues would be important. The red group spent the first six 30-s segments moving between reading the clues, and making links between two clues (Levels 1 and 2), with the teacher helping them to make the first and second connections. They then move to Level 3, before just reading for one more 30-s segment, and then have four segments, which were classified as Level 3. This group managed to solve the problem just as the teacher call the class to an end, struggling to work out how to make the last connection, partly due to how they structured the clues.

As can be seen in Figure 4, the students in this group used a linear structure to help them sort out

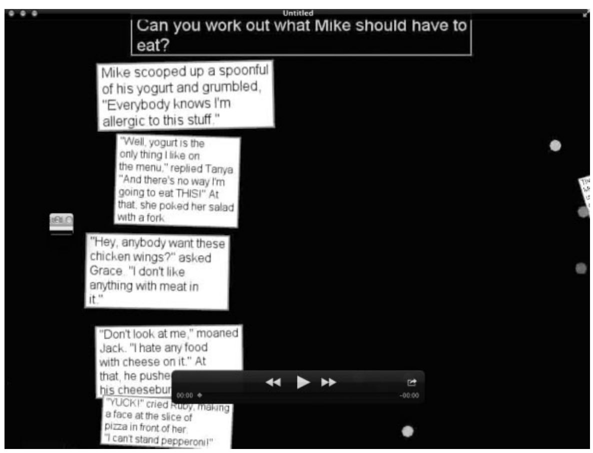

Figure 4 Seacrest Red Screen during the Last Minute of the Task

the task. They used the clues to identify the child, and placed it below the clue that had the food that that particular child should have (e.g., the clue about Tanya was placed below the clue about Mike, indicating that Tanya should get Mike's yogurt). While this pattern was useful for the students to identify the first four links in this chain correctly, they became stuck when trying to work out how to make the final link, where it is necessary to complete the loop and determine what Mike should eat. As can be seen in the extract below, which occurred just before the end of the activity, the students had worked out the first four links, but were struggling to work out what Mike should have.

Molly: Right, so Mike's got yogurt. Tanya gets the yogurt.
Ben: Oh god.
Molly: Then, she gets Tanya's salad [pointing to clue about Grace]. Who gets the chicken?
Molly: That one will get the chicken. [pointing to clue about Jack] The one who didn't like the cheeseburger and then she can get emmm..
Megan: Yeah, but what's Mike gonna get?
Molly: I dunno.
Nathan: Nothing.
Molly: Mike's got the yogurt, so she gets a yogurt, she gets a salad, she gets the chicken wings. [reviewing the clues again]
Nathan: Ben, what you doing?
Megan: Oh, Ben! He's hiding our things.
Ben: Just move it!
Nathan: Come on, get off it.
Ben: I've passed it.
Molly: So, if Tanya got the yogurt, Grace got the salad, Jack got the chicken wings, Ruby got the cheeseburger, and Mike got the pizza. [making the final link]

Vignette 3: Teacher models use of the clues to structure thinking

The yellow group from Easterbrook was a male group, who solved the problem with the help of the teacher. They started by reading the clues aloud, making some commentary on them–both in relation to the task, and their own food preferences and purchasing habits. The teacher joined them after the first minute, telling them that in order to solve what Mike should eat, they would need to work out what everyone wanted to eat, and that they should look for a clue about someone wanting to eat yogurt. The students correctly identified the clue about Tanya's preference for yogurt, and the teacher moved it below the clue about Mike, modelling the use of the clues to support their solving of the problem (see Figure 5).

The teacher prompts the discussion that follows, and again moves the third clue into place when the students agree on it. He allows them to discuss further, but corrects them when they consider whether the fact that Mike is allergic to yogurt also means he cannot have cheese. This quickly leads the students to decide that Jack must get the chicken wings, so Ruby has the cheeseburger leaving Mike with the pizza. Again, the teacher moves the clues into place, allowing them to view the pattern to their solution. The teacher moved on to other groups, and after a brief few moments of excitement about completing the task, the group began to take another look at the clues, deciding to make the clue about the cook much smaller, as it was unnecessary, and moving the clue about Mike to a more central position above the clues about Tanya and Ruby, making the circular pattern more obvious (see Figure 6).

Figure 5 Teacher Models Use of Table

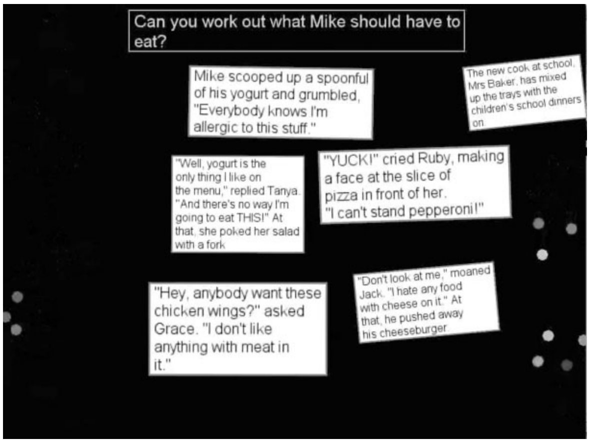

Figure 6 Final Screen for Easterbrook Yellow Uses a Circle to Document Solution

Discussion

This study set out to explore whether multi-touch tabletop computers could be used to support the use of digital resources as an external representation for groups working on a logic problem. The logic task was designed to be fairly difficult for the age group who participated in the study, and to be cognitively demanding, exceeding the working memory capacity of most individual students. Thus, the activity was designed in such a way as to require collaboration and promote the use of external representations. When examining the number of groups who solved the task, results indicated that almost half of the groups (11 of 24) did not come close to solving the task, while ten clearly came to the solution, and three other groups appeared to be close to the solution. This indicates that the task was sufficiently difficult for the groups, and sufficiently burdensome to benefit from the use of external representations (e.g., Martin & Schwartz, 2009).

When the process data was examined, the reasons why groups did not solve the task appears to be associated both with the way the groups reasoned about the task, and the way in which they used the movement of the digital clues on the table to represent their problem space and solution. As expected, the level of reasoning was directly associated with finding the solution, as the problem could not be solved without reaching the third level, and making connections between more than two of the clues. However, the use of the table was associated with this higher level of reasoning, with all but one group who reached Level 3 using the table to represent their reasoning. This finding suggests that the external representation seems likely to have supported the groups in their joint reasoning about the task, although it is also possible that reasoning at this higher level could have led groups to represent their thinking process externally on the table. This finding replicates prior research on the function of representations in groups, which suggests that the representations may help groups create a shared understanding of the task, and so engage in more complex reasoning about the activity (e.g., Schwartz, 1995; Leat & Nichols, 2000).

However, as can be seen in the second vignette, the choice of how to represent the problem in itself led to difficulties with the problem-solving process, as the linear structure that this group led them to struggle with the final link. This suggests that, not only was the reasoning process leading to the use of the tables, but also that the representations had the possibility to influence and limit the reasoning process of the group. The red group from Seacrest had to work through their representation, re-conceptualizing how it was representing their reasoning, as they grasped the logic of the problem they were trying to solve. As described by Suthers and Hundhausen (2003), the tools that are available to groups can influence how the groups engage in a task. This can either support their problem-solving activities, or lead them to attend to unimportant features. In this study, we saw how the decision to use a linear display caused difficulty for the students in the final step of the task. Future work should examine whether providing a structure to support the creation of a representation avoids these issues, without removing the need for groups to negotiate the development and meaning of joint representations.

Martin and Schwartz (2009) described reasons why individuals might choose to create representations in a problem-solving situation. They found that undergraduates who knew their access to supportive resources would be limited, and graduate students who had experience complex representations, both spontaneously created representations to support their thinking process. In our study, the 10-year-old participants would have had some experience with representations. They are likely to have used numberlines in mathematics and timelines in history, and other diagrams such as mind maps. It is unlikely that had experience using representations in solving logic problems. Only about half of the groups used the tables to represent their thinking process, so it is not apparent that the choice to use a representation was obvious to our sample. In the third vignette, the teacher is seen to explicitly model the use of the table as a way to structure the group's process, leading the group to use the most appropriate circular structure for their representation. In contrast, Joshua, in the first vignette, uses a gesture to indicate swapping of items, which starts the group on the path of representing the solution using the clues. Research on group process indicates that collaborators develop practices to support their collaborations, through prior experiences or direct instruction (e.g., Mertl, 2009; Barron *et al*., 2009). In these two vignettes, we see that direct instruction from the teacher is one way in which a group developed the practice of using the multi-touch table as an external representation of their process, and eventually of their solution. We also see the red group from Shadbrook, develop the practice by negotiating a shared meaning of their gestures, the order of the clues and finally of their personal responsibility for the clues that were placed closest to them (in what has been referred to as the personal space of the territory of a table: Scott, 2004). Thus, it appears that the practices of using representations can be developed either by the group themselves, or through instruction from a more expert collaborator or teacher. Further research is necessary to investigate whether this practice is taken up by members of the group in future collaborations as a productive way of supporting joint cognition.

One aspect of this study, in contrast to many studies of collaborative learning, is that it took place in a lab-classroom, rather than just with individual groups, so the teacher had to adapt to the whole class, and provided different amounts of support to different groups within and across classes. The length of time that groups were given to work on tasks differed between the six classes, and the amount of support each group received differed between groups as the teacher could not be present with all groups during the task. As the study aimed to look at learning within a classroom situation, the decision was made for the teacher to support the students in their learning, rather than try to keep the experiences of each group constant. This was to enhance the ecological validity of the classroom and the pedagogical focus of the research project. It resulted in a dataset where there were three groups who were very close to the final answer when the teacher called the group time to an end. For the purposes of these analyses, we classified those groups as being successful, as they appeared to be on the correct path. Additionally, some groups received support from the teacher in solving the task, or, as was seen in the third vignette, were helped to develop a representation by the teacher. In a more controlled environment, all groups could have had the opportunity to complete the task and be given the same types of support by a teacher. However, we believe our study is similar to a typical school situation, and provides evidence for the possible value of multi-touch technology within school settings. It also indicates the necessity of preparing students to effectively use the tools that are available to them during collaborative learning activities, if these tools are to be implemented in a classroom setting.

The results from this study show the complex interaction between the tools that are available to groups, and how they interact with each other and the use of these tools in collaborative learning activities. It indicates the importance of supporting students in the creation of joint problem spaces and the use of external representations when engaging in collaborative problem solving, suggesting both the need for the provision of appropriate tools, such as interactive surfaces, but also the need to support representation of the problem-solving process externally and the use of prompts to develop such practices when necessary.

This study set out to explore the potential of multi-touch tables as a tool to support the use of joint representations by groups of students, in light of prior research that indicated that the use of this technology was associated with higher levels of task-focused talk, more interactive discussion and more joint interactions when compared with groups using paper, single-touch tables or traditional personal computers. Our results indicate that while the tables have potential to support joint representations, this depends on a learning context in which groups are supported in their collaborative process and helped to understand how external representations might help their group proceed. This suggests that multi-touch technology may have the potential to be used for more complex collaborative learning activities, with the appropriate classroom support and that existing tools that have been created to support, guide or monitor collaboration in classroom environments could be adapted for use with multi-touch tables to increase their value in the classroom.

Acknowledgements

The research described in this paper is funded through the UK's Teaching and Learning Research Programme (TLRP) Technology Enhanced Learning(TEL) Phase 5, funded jointly by the ESRC and EPSRC, grant number RES-139-25-0400. Any opinions, findings and conclusions expressed in the paper are those of the authors and do not necessarily reflect the views of the sponsoring agencies. The authors wish to acknowledge the schools and students who participated in this study. The authors also acknowledge the contribution of Louise Patterson and the SynergyNet project team in the development of work presented here.

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