Learning 21st Century Science in Context with Mobile Technologies

Stamatina Anastopoulou Mike Sharples, Michael Wright, Hazel Martin, Shaaron Ainsworth, Steve Benford, Charles Crook, Chris Greenhalgh, Claire O'Malley
Learning Sciences Research Institute, University of Nottingham,
Jubilee Campus, Wollaton Road, Nottingham, NG8 1BB, UK
{stamatina.anastopoulou; mike.sharples ...}@nottingham.ac.uk

ABSTRACT

The paper describes a project to support personal inquiry learning with handheld and desktop technology between formal and informal settings. It presents a trial of the technology and learning across a school classroom, sports hall, and library. The main aim of the study was to incorporate inquiry learning activities within an extended school science environment in order to investigate opportunities for technological mediations and to extract initial recommendations for the design of mobile technology to link inquiry learning across different contexts. A critical incident analysis was carried out to identify learning breakdowns and breakthroughs that led to design implications. The main findings are the opportunities that a combination of mobile and fixed technology bring to: manage the formation of groups, display live visualisations of student and teacher data on a shared screen to facilitate motivation and personal relevance, incorporate broader technical support, provide context-specific guidance on the sequence, reasons and aims of learning activities, offer opportunities to micro-sites for reflection and learning in the field, to explicitly support appropriation of data within inquiry and show the relation between specific activities and the general inquiry process.

Author Keywords

Inquiry learning, 21st century science, contextual learning

BACKGROUND

The Personal Inquiry (PI) project is a three-year collaboration between the University of Nottingham and the Open University, UK, to help young people aged 11-14 to understand themselves and their world through a scientific process of active inquiry across formal and informal settings. The children use new methods of Scripted Inquiry Learning, implemented on handheld and classroom computers, to gather and assess evidence, conduct experiments and engage in informed debate. Their activities are based around topic themes – Myself, My Environment, My Community – that engage young learners in investigating their health, diet and fitness, their immediate environment and their wider surroundings. These topics are key elements of the new 21st century science curriculum (Millar & Osborne, 1998) that requires children to reason about the natural sciences as a complex system and to explore how people relate to the physical world.

The technology under development is in the form of an Inquiry Learning Toolkit running on small touch screen computer-phones, with integral cameras and keyboards, plus connected data probes, to enable learners to investigate personally-relevant questions outside the classroom, by gathering and communicating evidence. The Toolkit is designed to support scripted inquiry learning, where scripts are software structures, like dynamic lesson plans, that generate teacher and learner interfaces. These orchestrate the learners through an inquiry learning process providing a sequence of activities, collaborators, software tools and hardware devices, while allowing the teacher to monitor and guide student activity.

The children and their teachers will be able to monitor their learning activity, and to visualize, share, discuss and present the results, through a review tool accessible through a standard web browser running on a desktop or portable computer in the home or school. Teachers will also have a script authoring tool to create and modify the scripts, to support the learning of specific curriculum topics.

The PI project builds on other inquiry projects with mobile devices, such as Savannah (Facer, et al., 2004) and Environmental Detectives (Squire & Klopfer, 2007), but differs in its emphasis on linking formal classroom activities to informal settings such as sports halls and the home.

The paper gives an introduction to current research in inquiry learning and it can be supported by scripted technology. This is followed by the design methodology for the PI project. A case study is then described that incorporates inquiry learning activities into school science classes. The study is described in terms of its science learning content and the technology to support it. A critical incident analysis is presented, as a means to provide design recommendations for the Inquiry Learning Toolkit.

THEORY

Learning by inquiry is a potentially effective strategy when supported appropriately (e.g. Chinn & Malhotra, 2001; White & Frederiksen, 1998) and is an essential tool of the professional scientist. However, de Jong (2006) indicate specific difficulties children have in engaging with inquiry learning, in addition to general metacognitive problems in failing to regulate their behaviour or plan effectively. Based on their findings, children need specific support in:

– designing appropriate experiments (e.g. what variables to chose, how many variables to change, how to state and test hypotheses),

– implementation of experiments (e.g. making predictions, avoiding being fixated with achieving particular results rather than testing hypotheses),

– interpreting results (e.g. children can misinterpret data and representations).

Such support should also be combined with support for argumentation and debate (McAlister et al., 2004).

The approach of 'scripted' collaboration and inquiry has been used in previous research in computer supported collaborative learning (O'Donnell & Dansereau, 1992; Dillenbourg, 2002). Drawing on research in learning design, scaffolding, and guided discovery learning, such scripts are dynamic templates that guide how students should interact and collaborate in addressing a problem. They differ from lesson plans in that they structure and support individual and group learning across different settings. They are implemented as tools and interfaces for technology to support students through a sequence of activities including investigation, debate, inquiry and presentation.

One example of a general script for inquiry-based learning might be:

1. The teacher poses an open question to prompt debate (for example, 'How can I reduce waste?').
2. Students use their handheld devices linked to a classroom data projector to generate initial responses, which the teacher can cluster and display along different dimensions (such as 'importance to me', 'effect on the environment', 'cost').
3. The software selects teams of students whose answers differ along the dimensions and sets them the challenge to move closer in agreement through inquiry and debate.
4. Each team chooses one or more methods of inquiry, such as 'debate with expert' or 'run experiments outdoors'.
5. Software running on their mobile devices provides tailored tools and curriculum materials to structure their investigations as they move between locations, and to transmit the results to a team website.
6. The script-based system guides the students at home and in school to share data, analyse the evidence, and try to reach consensus.
7. Their results, and changes in response to the initial question, are presented and compared in the classroom through a discussion mediated by the teacher.

Other general scripts will support different sequences of inquiry learning activities including: observations; posing questions; examining sources; planning an investigation; data collection; data analysis, visualization and interpretation; resolving differences; proposing answers; presenting and communicating results. Central to the investigation is the question of whether it is possible to identify generic scripts appropriate to inquiry science learning and whether these can be supported through the linking of desktop and mobile technologies. In order to investigate these issues we held pilot trials in a partner school to develop a set of scripted inquiry lessons supported by technology and to describe and analyse critical incidents arising from the trials. Results from the initial school trial are reported in this paper. These are currently informing design of the personal Inquiry Learning Toolkit and the development of scripts to orchestrate science inquiry activities.

METHODOLOGY

We are designing the pedagogy and technology in concert, through an approach to human-centred systems design based on socio-cognitive engineering (Sharples et al., 2002). Like user-centred design, this draws on the knowledge of potential users and other stakeholders and involves them in the design process. But it extends beyond individual users to analyse the activity systems of people and their interaction with technology, building a composite picture of human knowledge and activity that informs the design of the socio-technical systems.

By adopting this design approach, user participation in design decisions becomes critical. Initially this was achieved through focus groups with stakeholders (including teachers, interpretation officers of museums, local authority advisors, qualifications and curriculum authority advisors, business partners and associated academics) to create the learning scenarios, followed by structured interviews that provide requirements for the technology and content design. The next stage is to undertake an initial test of the scripted inquiry learning method, using existing technology. A decision was taken to carry out this trial in a school rather than a research lab so as to test the learning in context. Since the scripted inquiry system had not been implemented, orchestration of the teaching and technology was done by the teacher, assisted by the researchers. This required development, in close cooperation with the teacher, of a detailed lesson plan that could guide not only traditional classroom activities, but also the children's interaction with the technology, inside and outside the classroom. For future trials, orchestration of learning outside the classroom will be progressively managed by software on the children's handheld computers, enabling the children to engage in a structured inquiry process away from the teacher, for example in the school grounds or at home.

METHOD OF THE STUDY

The aim of the school trial was to investigate how children can be helped to engage in a process of scientific inquiry learning across formal and more informal contexts. The formal setting was a science classroom of an inner city secondary school. The less formal setting was the sports hall of a leisure centre which was close to the school. Over a two-week period (5 science lessons), 30 students of Year 9 (age 14) planned a scientific investigation (lesson 1) which they first explored in the relatively controlled environment of the classroom (lesson 2), then extended through a more active engagement with the inquiry process in the leisure centre (lesson 3), and concluded the work in the school library as they analysed the results (lesson 4) and created presentations (lesson 5). All the teaching sessions were videotaped with three cameras: one fixed camera giving an overview of the lesson and two others to record closer views on the classroom or group activity. Radio microphones were used to provide good sound quality. The two cameras recording group activity focused on groups that the teacher had indicated as containing the most and the least able pupils that had given their consent to video capture and analyse their activities.

Science learning

The scientific topic that the research team, in cooperation with the teacher, chose for investigation was the relation between heart rate and fitness. The heart and fitness are topics covered in the UK KeyStage 3 curriculum, fitness is also a topic of personal interest to most children, heart rate can be measured with relatively simple equipment. 'Recovery heart rate' is a measure of how long it takes the heart rate to return to normal (baseline) heart rate after stopping a period of exercise. In general, a fast recovery heart rate is an indication of general fitness and, conversely, people with a slower recovery are at higher risk of sudden death (Cole et al, 1999).

Lesson plans were developed to enable the children to investigate questions about the relation between heart rate and fitness. Five science lessons were planned as shown in Table 1 that took place over a period of two weeks.

Lesson 1	Set up an inquiry question, make predictions	Introduction to the study, familiarisation with scientific enquiry vocabulary and processes, discussion on the inquiry questions to investigate, predictions of possible answers to these inquiry questions. Children are formed into groups of four, with an Exerciser, Note Taker, Photographer, and Computer Handler.
Lesson 2	Carry out an investigation	Introduction to technology. Collection of baseline heart rate in the classroom. In groups, children measure the resting heart rate of the Exerciser. The Notetaker records the results. The Photographer photographs the process. Children elaborate the answer to Question 1. The groups compete over a maze activity and see the effects of excitement and mental activity on their heart rate.
Lesson 3	Carry out an investigation	After walking to the leisure centre, the children in teams collect data for the Resting Heart rate and Recovery Heart Rate of the Exerciser. The Notetaker records the results. The Photographer photographs the process. Children in groups elaborate the answer to Question 2
Lesson 4	Analyse data and conclude findings	In the classroom, the children view, analyse their data and discuss the answer to Question 3.
Lesson 5	Summarise and present the process	The children have access to all their collected data and produce posters to reflect on aspects of the scientific inquiry process

Table 1. Sequence of lessons.

Technology

The technology forms a bridge between contexts, in a similar manner to the MyArtSpace service (Vavoula et al., 2007) but with tighter orchestration of the learning activities. Two sets of technology were developed for the trial: the mobile data collector (which was adapted to project needs by the third author) and visualisation tool and the web-based analysis tool developed by the third author.

The data collection tool comprised a Sunto heart-rate chest strap connected wirelessly to a box that generates a stream of heart-rate data. The box is connected to the USB port on a Samsung Q1 tablet computer running a custom Java program to continuously generate the heart rate as a graph (Figure 1). It also sampled the heart rate every 0.25 seconds to produce a comma-separated stream of data.

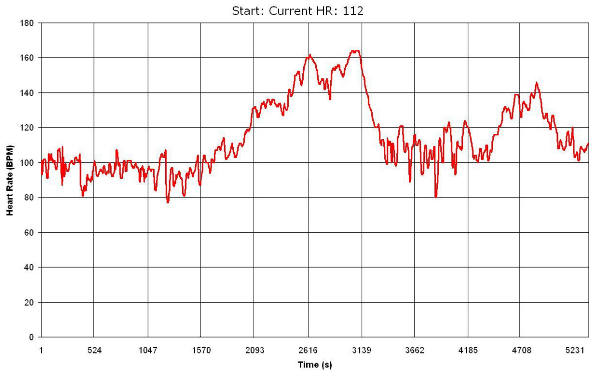

Figure 1: An example graph generated from the heart-rate monitor on the tablet computer.

The web-based teaching, running on desktop computers in the classroom, enables each group of students to see the heart rate data collected for the group and by other groups in the class, along with photos taken by the group (Figure 2). It takes the students through a sequence of steps to view and then analyse the data in order to answer Inquiry Questions 2 and 3 (What happens to heart rate with exercise? and What is the relation between heart rate and fitness?).

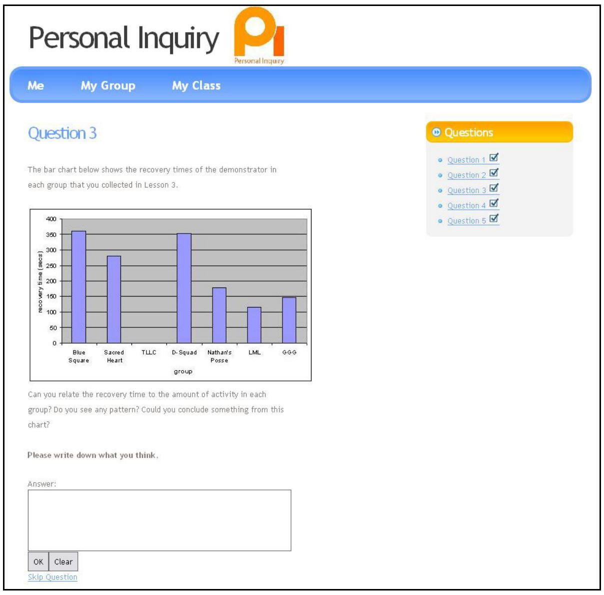

Figure 2. A screen from the web-based activity showing the recovery time recorded by each group (one group failed to make a measurement), ordered by level of self-reported fitness activity.

Results

The children's science teacher successfully interpreted the lesson plans to guide the children through a sequence of inquiry science activities that connected learning in the classroom and the leisure centre. The lessons were sequenced to first orient the children towards a science inquiry process, and then progressively move from a tightly controlled data collection activity in the classroom, to more self-coordinated groupwork in the leisure centre, and then personal and group reflection and presentation. The teacher reported that time was barely sufficient to complete the first lesson and that the children were somewhat bored in that lesson by the teacher-led work. Once they began to use the heart-rate devices the children were fully engaged with the activity.

The Recovery Heart Rates (RHR) did not show the expected results, in that the children's self-reported levels of fitness did not correlate at all with the RHR: children who reported a high level of weekly fitness activity did not have heart rates that returned more quickly to normal after exercise than those who reported being less generally active. There are many possible reasons for this – including unreliable self reporting of fitness activity, and errors by the children in recording the time taken to recover to base level heart rate – but unexpected results are to be expected from a science inquiry investigation. Interpreting their results and proposing reasons why the data did not match expectations were a learning activity for the children. Nevertheless, the children had enjoyed collecting their own heart rate changes and being able to see and analyse this data in different ways.

In the final lesson, the children produced group posters on each of the three inquiry questions plus a poster on evaluating their experience. The group producing the Evaluation poster were asked to list five things they liked the most and the least during all the lessons. They were also asked to show what they learned about scientific inquiry and how to make things better. What they wrote on the poster is shown below.

Likes: Exercises, Equipment, Different from normal lessons

Dislikes: Disruption [other students disrupting the class]. Wanted more time. Not everyone goes on all equipment.

Things we learnt: Heart rates of different people. How to work as a team. More or less the amount of activities you do the healthier you are. The fitter you are the lower your resting heart rate is. Also the fitter you are the faster your heart rate returns after exercising.

The last is despite their own experiments showing no relation between self-reported level of fitness and measured RHR.

How to make things better: have a whole day working on the subject, have more practicals, more preparation.

CRITICAL INCIDENT ANALYSIS

The main purpose for the evaluation of the initial trials is to provide design recommendations for the next stage of the PI project. More generally, it offers guidelines for the design of mobile technology to link learning between formal and informal contexts such as classrooms and museums, or training centres and workplaces. An evaluation of learning gains is inappropriate for a pilot study intended to explore the effects of introducing a combination of new learning and new technology, so we carried out a critical incident analysis to identify specific learning breakthroughs and breakdowns (Sharples, 1993). Breakthroughs are observable critical incidents which appear to be initiating productive new forms of learning or important conceptual change. Breakdowns are observable critical incidents where a learner is struggling with the technology, is asking for help, or appears to be labouring under a clear misunderstanding. They may either be predictable (e.g. the intervention may be aimed at producing conceptual change) or unpredicted (e.g. a child uses the technology in novel ways, or makes an unforeseen connection or conceptual leap).

The critical incident analysis was conducted as follows. The videotapes were separately viewed by three researchers to identify obvious and informative breakdowns or breakthroughs (for example, where there is some activity and discussion on the video to indicate causes or solutions to the problem, or that suggest the nature of the learning). The identified critical incidents were then compared to reach an agreed set of incidents that might inform design. These are listed here.

Incident 1. Breakdown. (Lesson 1, 18 minutes after start of the lesson) *Allocating children to groups*

Context: Teacher at the front of the class.

Teacher: "I need 6 groups with 4 pupils in, and 2 groups with 3 pupils in. Now go and sit in a group. Take account of people who are away but will be back next lesson."

This somewhat complicated instruction to form into groups needed to be further modified when the children whose parents had not given permission for them to be videoed needed to be formed into a separate group.

Design implication: Group formation is a complex and contingent process, so simplistic automation may cause more problems than it solves. However, if each child has a personal device, then the teacher could develop or inform a scripting software that allocates children to groups according to specified criteria, including: friendship group, mixed ability, similar ability, or special provision.

Incident 2. Breakdown. (Lesson 1, 42 minutes after start of the lesson) *Participation in groups*

Context: Teacher in the classroom talking to a child in a group of three who have been asked to produce a list of factors that influence heart rate.

Teacher: "Why can't you add your thoughts to this – because you have plenty of good thoughts – why don't you put some of your ideas down here?"

Design implication: Zurita et al. (2003) have indicated the opportunity for personal handheld devices to coordinate and synchronise group activity in the classroom, so that the group members all work collaboratively to achieve a shared goal. In this case, it could enable and motivate the children simultaneously to propose factors that they could then combine and discuss.

Incident 3. Breakthrough. (Lesson 2, 17 minutes after the start of the lesson) *Displaying teacher's heart-rate to the class*

Context: The teacher put on a heart-monitoring chest strap that was connected wirelessly to the classroom PC linked to an electronic whiteboard. With this, the teacher could walk round the class while the screen continuously generated a graph of her heart-rate (as in Figure 1).

Teacher: “This is me. … This is beats per minute, so at the moment – look at that, I’m doing quite well. … This [points to a section of the display with a raised heart rate] is where I started to shout, you see. … Do you see what you do to my heart rate? Every time I have to shout.

Design implication: This activity illustrated issues of timeliness and personal relevance in data capture and measurement. Providing a shared display for the teacher, or any of the children, to show and discuss the data as it is being generated can be beneficial. It could provide a means to compare data, show trends, and indicate abnormalities. It can, however, raise social and ethical issues, e.g. showing abnormalities in a person’s data. There may also be an opportunity to link large displays already available outside the classroom, for example in a fitness centre or a science museum, to the children’s computers.

Incident 4. Breakdown. (Lesson 2, 28 minutes after start of the lesson) *Do we have to draw the graph?*
Context: The teacher has given instructions to the class to draw the graph they are seeing on their tablet computer displays, but one group has lost the image due to battery failure. This technology failure gives the teacher an opportunity to tell students why they need to carry out the particular drawing activity.

Pupil 1: “Miss, do we have to draw the graph, what it says?”

Teacher: “Yes, just sketch it.”

Pupil 2: “How can we sketch it, we haven’t got it?”

Teacher: “Have you got an idea what it looked like?”

Pupil 3: “At least we know what it looked like.”

Pupil 1: “Yes, it’s wiggly, like that..<draws it in the air>.”

Teacher: “Then it shows you, you know, after we say the Heart Rate is 80 beats per minute which would indicate you’d get a flat line, wouldn’t you. But it’s not, what it’s showing you is that heart rate fluctuates.”

Design implication: The computer failure raises technical issues relating to data persistence strategies and policies, design of contingencies and fallbacks and consideration of the broader technical support context (e.g. administration, trouble shooting, charging, and networking). From an educational perspective, students need to be aware of the reasons for carrying out specific learning activities and personal technology could provide context-specific guidance, for those occasions where the teacher is not available.

Incident 5. Breakthrough. (Lesson 2, 42 minutes after start of the lesson) *Do something to increase your heart rate*
Context: A group wants to run a little experiment and see the effects of the heart rate.

Pupil 1: “Do kneels, run on the spot, oh please just run on the spot…Do something, anything to get you heart rate up..

Pupil 2: <pinches the Exerciser> … “Sorry… that took the heart rate up, look!”

Having completed the tasks of the class, this group wants to try something further. Since the Exerciser refuses to carry out an activity himself, one of his group mates tries the effect of pain in heart rate.

Design implication: The system could provide an adaptive ToDo list of extra activities for those students that want to try something further. It could also provide support for students to abstract related information from those activities, through a retrospective ‘diary’ entry or annotation, e.g. make a note that a specific jump in the graph was when we pinched the person. Such design feature could complement the plan-driven activities with more exploratory inquiry.

Incident 6. Breakdown. (Lesson 3 (sports hall), 11 minutes after start of the lesson) *We’re not doing it yet*
Context: The children have arrived in the sports hall and are standing around the fitness equipment. One child gets onto the equipment and starts exercising.

Teacher: “No, we’re not doing it yet. We’ve got to do our resting heart rate. We’re doing the resting heart rate first – we don’t want to do any exercise for two minutes.”

Design implication: The sequencing of some activities is important, while other activities can be conducted in any order. The technology could indicate, e.g. through an adaptive and context-sensitive ToDo list, which activities *must* be done next and which are optional or could be carried out in any order. For sequential activities managed by the system, it could only make the data entry form and equipment available once the previous activity has been fully completed. From an educational perspective, students would need to understand and technology could remind them the reasons for the specific sequencing of activities.

Incident 7. Breakthrough and breakdown. (Lesson 3 (sports hall), 32 minutes after start of the lesson) *Let's have a look at your graph*

Context: The children have collected data on resting heart rate, exercise to target heart rate, and recovery heart rate. The teacher is discussing the results with one group.

Teacher: "Did she get to her target heart rate? Did she get to 145."

Child: "Yeah."

Teacher: "Time taken to get to 145?"

Child 1: "Five minutes."

Teacher: "It wouldn't have taken her five minutes to get to 145 would, it?"

Child 2 (Exerciser): "Miss, it might have, because I was going at my normal walking speed."

Teacher: "Let's have a look at your graph. What have you got. 145 is here. That's 630 seconds."

The teacher calls over the researcher and they have a discussion about the interpretation of the graph generated from the exercise activity.

Teacher: "So she starts her exercise here?"

Researcher: "Probably somewhere about here."

Design implication: The graphs generated in the field can offer 'micro sites' for reflection and learning. In this example, it provides a means for the teacher and children together to validate the child's assertion that it had taken her five minutes to reach the target heart rate. A problem with the current system is that it does not indicate on the graph where the exercise started and ended. This could be solved by having 'start exercise' and 'end exercise' buttons that automatically add labels to the graph, to assist the children in interpreting the data and calculating the results.

Incident 8. Breakthrough. (Lesson 4 (library), 27 minutes after start of the lesson) *Answering the third inquiry question*

Context: A group tries to answer the question and they seek advice from the teacher.

Teacher: "That [group] doesn't have any data [in the chart] because it didn't get any data in lesson 3"

The teacher explains what the chart meant for the particular data point and she further facilitated them in deciding whether there was a trend in their data or not.

Design implication: Students may not be aware of the consequences of not collecting data over the course of an investigation. This indicates the importance of explicitly supporting data appropriation i.e. filtering, selecting and managing the data – within the scientific inquiry process. The technology could also indicate how the data they are collecting fits with the inquiry process as a whole, leading to higher-level understanding. This incident also supports the need for iteration of students' activities across the lessons, which technically might include linking to 'situations like this' or 'this stage' in other experiments or activities done in the past by other students.

Summary of recommendations

The critical incidents have informed recommendations of when and how technology can mediate students' inquiry activities. One recommendation, now being implemented in the Toolkit, is for a 'Dynamic ToDo List' that can display a personal inquiry plan, giving a broad overview of the whole inquiry process that unfolds into a hierarchy of necessary and optional activities. The aim is for students not only to visualise where each activity fits into the inquiry as a whole but also to appreciate how current actions can influence future ones. Another recommendation is for the Toolkit to provide 'micro-sites' for learners to reflect in the field on their actions, for example through simple visualisations of the data collected so far. It can also offer them the possibility to re-visit activities that they missed or ignored and to allow different organising perspectives, through their own, their group's or their class's data. Script authoring software can support the teacher in allocating children to groups according to specified criteria.

CONCLUSION

The Personal Inquiry (PI) project is providing children with new methods of scripted inquiry learning, implemented on handheld and classroom computers, to gather and assess evidence, conduct experiments and engage in informed debate. Pedagogical activities and technological functionalities are being developed in parallel, through socio-cognitive engineering and participatory design approaches to develop a set of inquiry learning scenarios. These will illustrate how new combinations of technology and pedagogy may be deployed across contexts: connecting learners in and between different locations.

The study described in this paper investigated opportunities for technological mediations and extracted initial recommendations for the design of mobile technology to link learning across different settings. The technology used in the current study consisted of a mobile data-probe and a handheld visualisation tool to collect and reflect on data on a group basis as well as of a web-based tool to support analysis of data as a class. A critical incident analysis was carried out to identify learning breakdowns and breakthroughs that led to design implications. The main implications relate to the need to support group formation, facilitate motivation and personal relevance, incorporate broader technical support, provide reasons for carrying out activities and their sequence, offer micro-sites for learning in the field, and explicitly support appropriation of data within inquiry and link specific activities to the broader picture of the inquiry process. The next stage of the project will develop the Inquiry Learning Toolkit to guide children in personal and group investigations with mobile technology in school grounds, homes and science centres.

ACKNOWLEDGMENTS

The project acknowledges support from the Economic and Social Research Council and the Engineering and Physical Sciences Research Council UK Teaching and Learning Research Programme. We are grateful for the support and engagement of Liz Booth and children of Harvey Park High School, Nottingham who participated in this study. The project is a collaboration between the University of Nottingham and the Open University, UK.

REFERENCES

Chinn, C.A., & Malhotra, B.A. (2001). Epistemologically authentic scientific reasoning. In K. Crowley, C. D. Schunn, & T. Okada (Eds.), *Designing for science: Implications from everyday, classroom, and professional settings*, (pp. 351-392). Mahwah, NJ: Erlbaum.

Cole C.R, Blackstone E.H, Pashkow F.J, Snader C.E, & Lauer MS. (1999) Heart-rate recovery immediately after exercise as a predictor of mortality. *N Engl J Med*, 341:1351-1357.

de Jong, T. (2006). Computer simulations - Technological advances in inquiry learning. *Science*, 312(5773), 532-533.

Dillenbourg, P. (2002) Over-scripting CSCL: The risks of blending collaborative learning with instructional design. In P. A. Kirschner (Ed.), *Three worlds of CSCL: Can we support CSCL?* (pp. 61-91). Heerlen: Open University of the Netherlands.

Facer, K., Joiner, R., Stanton, D., Reidz, J., Hullz, R. & Kirk, D. (2004) Savannah: mobile gaming and learning*? Journal of Computer Assisted Learning*, 20, pp399–409

McAlister, S., Ravenscroft, A. & Scanlon, E. (2004) Combining interaction and context design to support collaborative argumentation using a tool for synchronous CMC, *Journal of Computer Assisted Learning*: Special Issue: Developing dialogue for learning, Vol. 20, No 3, pp. 194-204.

Millar, R and Osborne, J (Eds.) (1998) *Beyond 2000: Science education for the future*, King's College, University of London.

O'Donnell, A. M. & Dansereau, D. F. (1992) Scripted cooperation in student dyads: A method for analyzing and enhancing academic learning and performance. In R. Hertz-Lazarowitz and N. Miller (Eds.), *Interaction in cooperative groups: The theoretical anatomy of group learning* (pp. 120-141). London: CUP.

Sharples, M., Jeffery, N., du Boulay, J.B.H., Teather, D., Teather, B., & du Boulay, G.H. (2002) Socio-cognitive engineering: a methodology for the design of human-centred technology. *European Journal of Operational Research* 136, 2, pp. 310-323.

Sharples, M. (1993) A Study of Breakdowns and Repairs in a Computer Mediated Communication System, *Interacting with Computers*, 5, 1, pp. 61 – 77.

Squire, K., & Klopfer, E. (2007). Augmented Reality Simulations on Handheld Computers. *Journal of the Learning Sciences*, 16(3), 371 - 413.

Vavoula, G., Sharples, M., Rudman, P., Lonsdale, P., Meek, J. (2007) Learning Bridges: a role for mobile technologies in education. *Educational Technology*,Vol. XLVII, No. 3, May-June 2007, pp. 33-37.

White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction*, 16(1), 3-118.

Zurita, G., Nussbaum, M. and Sharples, M. (2003) Encouraging face-to-face collaborative learning through the use of handheld computers in the classroom. In L. Chittaro (Ed.) *Proceedings of Mobile HCI 2003*, Berlin: Springer-Verlag, pp. 193-208.