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THE ROLE OF MOBILE DEVICES IN FACILITATING COLLABORATIVE INQUIRY *IN SITU*

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Mobile devices are increasingly being used to augment learning activities that occur outside of the classroom. In particular, they are being used to help students discover more about the environment they are visiting, be it a forest, museum or urban site. Our research is concerned with how they can be used to facilitate collaborative inquiry processes. We propose that they can provide contextually-relevant information, represented in a variety of media, that can be accessed and acted upon at opportune times leading to the integration of observations and ideas. Instructors and facilitators can also provide guidance: directing their questions and probes so that students can answer them through comparing what they are observing in the world and via the device. Two case studies are presented that illustrate how these forms of mobile learning happen *in situ*. The first is Ambient Wood, where young children explored a woodland to learn about habitats, and the second is LillyPad, where older students assessed the state of an environmental restoration site.

Keywords: Collaborative learning; mobile learning; mobile technologies; scientific inquiry.

1. Introduction

Mobile technologies are providing new opportunities for enhancing how learning takes place. Several economic and practical benefits have been identified; compared with PCs and laptops, mobile computers are lighter, cheaper, easier to interact with while on the move, more legible in different light settings and can be easily placed in and out of a person's clothing or bag (e.g. Roschelle & Pea, 2002). In addition, ubiquitous technologies, such as sensors, wi-fi and tangibles, can be integrated with mobile devices to allow digital information to be flexibly accessed, manipulated and shared.

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A range of applications has been developed to support mobile learning activities. These include sensing and recording aspects of the local environment while exploring it (e.g. measuring pollution levels); looking up information that is of relevant interest when wandering through a city center (e.g. historical sites) and texting and sending photos to others of what is being observed when in different parts of a physical environment. One benefit that has been found is increased motivation and engagement, promoting student's interest in their learning activities (e.g. Metcalf *et al.*, 2008; Wu *et al.*, 2008). However, there has been less research investigating how mobile devices can transform the learning process (Avraamidou, 2008; Price *et al.*, 2003; Zurita *et al.*, 2008). Debates continue as to whether mobile learning can encourage new forms of social interaction, discourse, meta-cognition or reflection (e.g. Pachler, 2007; Sharples, 2006).

The goal of our research is to investigate how scientific collaborative inquiry can be engendered through using mobile devices in the field. By collaborative inquiry we mean enabling students to play an active role in formulating research questions and pursuing them in collaboration with their peers, teachers or scientists (c.f. Edelson & O'Neill, 1994). We propose that contextually-relevant information, which is provided by the mobile device, will play a pivotal role, provided that this information can be integrated with prior knowledge and ongoing observations and actions in the physical environment.

Hence, a focus of our research is how the different ways of representing aspects of the physical world, using dynamic data, visualizations, graphs, sounds, textual descriptions and combinations of these — that are interacted with via mobile devices — enable students to switch between their observations and relevant information to promote inquiry activity. We suggest that having appropriate information at hand — that can be readily understood with respect to ongoing activities in the physical world — is central to whether the collaborative inquiry processes will be enhanced. This, in turn, will depend very much on the instructor's relationship with the students and, in particular, how they appropriate the mobile device to support them during their physical activities. The other focus of our research, therefore, is the changing role of instructor guidance. We examine how instructors also use the mobile devices, when remote or co-located, to pose contextually-relevant questions, provide probes and send relevant information that are intended to guide the students to make new observations, generate hypotheses and draw conclusions.

In this paper, we examine how collaborative inquiry was facilitated for two contrasting outdoor settings; first, an exploratory fieldtrip where pairs of children aged 10–12 were provided with novel mobile devices and reflection tools to discover and understand different woodland habitats, and second, a more formal assessment of an experimental riverbank restoration site, where university students measured tree growth for different planting methods, using both traditional measuring instruments and PDAs, that provided various functions, including data entry, access to previous measurements and a messaging facility.

The first case study showed how children used sounds, images and probe readings to initiate their own inquiry processes and subsequently aggregated visualizations to reflect upon them. It also examines how remote facilitators guided and encouraged them, through various forms of intervention. The second case study examines how the groups of students used text, numerical datasets and trend graphs on the mobile device to compare with their own observations and measurements, and the extent to which they reasoned and generated hypotheses about any patterns and anomalies. It also explores the changing role of the instructor — the scientists in each team — in the way they probed and supported the students.

2. Background

One of the earliest examples of a mobile learning tool designed to facilitate inquiry processes is Probeware (Layman & Krajcik, 1992). It comprises a combined simulation and measuring tool that enables students to perform hands-on scientific experiments, e.g. measuring parameters such as temperature and light, that they can subsequently view in real-time on a computer display in the form of graphical representations (e.g. Laws, 1997). Students' learning of complex and dynamic relationships has been found to improve through using this combination of sensor and PC technologies. For example, the TEEMMS project found that investigation, exploration, and reflection were enhanced (Metcalf & Tinker, 2003). Teachers also reported that students showed improved understanding of how the shape of graphs correlated with motion changes and that the direct experience helped the students confront their misconceptions.

Other kinds of scientific inquiry software developed for classroom learning have also been adapted and extended for use on handheld devices to be used outdoors, e.g. WISE — web-based inquiry science environment (Slotta *et al.*, 2002). Examples of outdoor activities originally based on web-based software include collecting mosquito larvae from a pond and examining them, and carrying out surveys at home (e.g. a GM foods survey). A benefit of this approach is that it enables students to ask questions within their own everyday environments and contexts as a basis for their scientific inquiry.

A number of mobile applications have been developed to enable students to collect scientific, environmental and geographical data, with a view to understanding the relevant subject matter in context (e.g. Gay *et al.*, 2002; Grant, 1993; Hine *et al.*, 2004; Rogers *et al.*, 2005; Sharples *et al.*, 2002; Soloway *et al.*, 1996, 2001; Roschelle & Pea, 2002; Yeh *et al.*, 2006; Wentzel *et al.*, 2005). Studies of fieldtrips have shown them to support the development of student's strategies and skills in science investigation (e.g. Loh *et al.*, 2001; Tinker & Krajcik, 2001; Rogers *et al.*, 2005). Other mobile applications have focused on enabling learners to create and share different forms of digital media, such as photos, audio or text, as part of their learning activity (e.g. Järvelä *et al.*, 2007; Rost & Holmquist, 2008; Spikol & Milrad, 2008). In such environments, the technology is primarily designed to support creativity and student production rather than the inquiry process itself.

Educators and teachers are also beginning to use mobile-based learning activities to change their pedagogical practices. For example, McFarlane *et al.* (2007) show how mobile technologies can change teachers' perspectives of their teaching role towards promoting more student autonomy and personalization. However, such a shift in pedagogical responsibility requires that the students have the appropriate skills to enable them to develop their own learning strategies. Another development is for instructors to view their role more as a facilitator whereby they ask the students to discover certain kinds of information or send them contextually-relevant material, via mobile devices, that the students can then compare, combine or apply to what they are doing.

A potential problem of using mobile devices during learning activities is that they can be distracting to those holding them. For example, it has been found that museum visitors provided with mobile devices tend to focus more on interacting with them at the expense of interacting less with hands-on exhibits and each other (Hsi, 2002). In another study, children without handheld devices were found to experience and work things out together, but when provided with PDAs, tended to read by themselves what was on them (Semper & Spasojevic, 2002). Children can also become more isolated from others around them, listening to or reading what is on the mobile device. To prevent mobile devices from becoming too distracting or isolating students, the information presented via them needs to be designed in ways that can be easily shared by groups in an ongoing task. This means making it relevant and lightweight in terms of the quality, timing, interactivity and form (Price *et al.*, 2003). Ideally, groups of students and their instructors should be able to switch fluidly between observing the physical world, accessing relevant information on the device and being able to communicate this with others in the group. Our research is concerned with investigating these parameters for facilitating collaborative inquiry processes.

3. Theoretical Approach

Our theoretical approach was informed by constructivist (Piaget, 1928) and socio-cultural theories of learning (Vygotsky, 1962). In constructivist theory learners are seen as central participants in their own learning process where "learning by doing or making" is instrumental (e.g. Papert, 1980; Rogoff, 1990; Wood & O'Malley, 1996). Learning is viewed as taking place during a person's experience of the world where they can discover what is "going on in their own heads" (Bruner, 1973, p. 72). Learners are assumed to actively construct knowledge through making sense of materials presented to them by selecting relevant information, organizing it into a coherent structure and subsequently integrating it with prior knowledge (Mayer, 2003). Such experiences are thought to encourage reflection, stimulating awareness (e.g. Ackermann, 1996), and the interpretation of content in context (Peterson *et al.*, 1996).

Of central importance in socio-cultural theory is the role social and collaborative interaction play in mediating learning. Thus, the concept of constructivism here is not purely discovery-based, but places an emphasis on meaningful learning through two primary forms of collaboration. Firstly, collaborative interactions, where two or more students work together to understand, make sense, solve problems and create objects of learning (Dillenbourg, 1999). A benefit is that they can learn more effectively through triggering certain learning mechanisms; the interaction among the students generates additional activities, such as explaining, arguing and regulating that can in turn trigger extra cognitive mechanisms, such as knowledge integration and internalization. Reflection can be promoted, as students are encouraged to express their opinions, seek clarification, interpret, explain, dispute, generate, test and elaborate ideas (e.g. Ackermann, 1996; Boud *et al.*, 1985; Scaife & Rogers, 2005). Moreover, by "self explaining" to themselves and others, learners become aware of their own discrepancies in understanding, enabling them to revise their knowledge (Chi, 1997). More recently, the process of collaborative learning has been considered as one of "coming to know through continuous conversations across multiple contexts amongst people and interactive technologies" (Sharples *et al.*, 2007). Secondly, collaborative interaction, where personal activity and engagement is still central, but where there is also some form of cognitive guidance (c.f. Mayer, 2004) by instructors, such as probing at various times. New conceptual frameworks of seamless learning (Chan *et al.*, 2006), mobile learning (e.g. Tatar *et al.*, 2003) and ubi-learning (Rogers *et al.*, 2005) have been proposed to explain how students can actively learn in this semi-guided way, when moving between overlapping physical, digital and communicative spaces, using mobile and ubiquitous technologies.

The practice of scientific inquiry is well suited to being grounded in collaborative and constructivist learning theories since students need opportunities to construct knowledge through direct experience in authentic environments, to ask and refine questions, to engage in collecting their own data, articulate their ideas and discoveries, and interpret their information. In addition they need opportunities to both collaborate and have autonomy and control over their investigation. They also need to be supported in reflective inquiry practice which combines the collecting and interpreting of data with metacognitive skills of monitoring and evaluating their progress and revising their plans (Loh *et al.*, 2001).

Mobile and ubiquitous technologies offer quite different forms of information flow (i.e. ways and means of accessing information) and information management (i.e. ways of storing, recording, and re-using information), compared with the conventional use of PCs, that can enable learning to be more active, collaborative, and explicitly integrated with everyday activities (Rogers & Price, 2006). The mobile learning tools that are described in the two case studies here were designed to be used during collaborative and constructivist activities, in the form of sharing, comparing, discussing, formulating of ideas and explaining. The collaborative inquiry processes that were engendered are discussed in terms of (i) how mobile devices are used *in situ*, (ii) the kind of collaborative inquiry processes that occurred and (iii) the role of the facilitator.

4. The Ambient Wood Project

The Ambient Wood project investigated how different forms, timing, and placement of digital information could facilitate collaborative scientific inquiry (Rogers *et al.*, 2004). A goal was to determine which of these would encourage children to initiate and follow up their own inquiries. A field trip was designed where children, aged 10–12, initially explored a physical woodland by itself, and then at certain times, accessed and received relevant sources of digital information about habitat distributions and interdependencies (Price *et al.*, 2003). Various mobile devices and ubiquitous computing technologies were constructed for this purpose. The digital information was chosen to provoke the children into making connections between what they were observing in the physical woodland. It comprised images and textual descriptions of organisms found in the woodland, animations and video clips of life cycles for some of the plants (e.g. bluebells) and sounds representing biological processes. It was presented via the devices depending on the children's location and activity; the children's movement and location triggered some digital information when exploring the woodland, other information was actively collected by the children by probing the environment, and others were aggregated and represented as composite information visualizations.

The mobile devices developed to present the digital information included a probing tool used in combination with a PDA and an ambient horn for listening to the sounds. Walkie-talkies were also provided to enable the children and remote facilitators to ask and answer questions and for the facilitators to guide the children in their explorations. The probing tool was designed to collect real time measurements of light and moisture in the woodland (see Figure 1(a)). Readings of the

(a) (b)

Figure 1. (a) Boy using probing tool and (b) a pair of boys discussing pinged image on PDA with a remote facilitator.

probes appeared on an accompanying PDA display as simple visualizations that varied in intensity of light or height of water to indicate their relative levels. Simple readings of data (showing relative high or low levels) were provided that could be easily read and communicated, with the intention of facilitating interpretation and meaning making *in situ*. The PDAs also transmitted the probe readings that the children took along with the location at which they were collected in the woodland to a mobile server. All of the readings were combined and re-represented as interactive data points on an aggregate visualization that showed a bird's eye view of the woodland areas visited by the children. These could be clicked on to bring up the same readings that had been seen on their respective PDAs. This tool was intended for the children to reflect upon and analyze their outdoor discoveries following their exploration but while still in the woodland. A makeshift classroom in the form of a tent (the den) was erected for this purpose that was located in another part of the woodland.

The PDAs were also used to present images of plants and animals to the students at pertinent times to draw their attention to particular aspects of the physical environment. Location-based pingers were situated at pre-determined places of interest in the woodland and when a pinger receiver was detected (carried in a backpack by the children) an image of an organism/s (e.g. thistle and butterfly) that could be found in that location was pinged to the PDA (see Figure 1(b)). The aim was to provoke the children into finding these, and being able to generate hypotheses as to why this was the case.

The Ambient Horn was a handheld device designed to transmit abstract sounds representing invisible ecological processes, e.g. root uptake (Randell *et al.*, 2004). The reason for using abstract sounds was again to provoke inquiry and meaning making, e.g. what does root uptake sound like and how is it achieved? The sounds, similar to the images that popped up on the PDAs, were triggered according to the children's location using location-based sensors placed in different parts of the woodland (see Figure 2). Questions and images could also be sent to the children by the remote facilitators while they explored various parts of the woodland.

4.1. *Studies and findings*

Two studies were carried out with 20 pairs of children, aged 10–12 years, taking part. Children of this age have been taught about habitats and eco-systems, but have very limited exposure to the practice of inquiry processes. The pairs of children were asked to discover and observe different aspects of the habitat and to generate hypotheses about their relationships and their interdependencies. To facilitate collaboration, the children talked with one another and a remote facilitator, via the use of the walkie-talkies, reporting on what they had discovered, what its significance was and what they planned to do next. The facilitators also probed the children to ask what they were observing and measuring, helping to guide their inquiry processes. The session lasted an hour. The pairs then came together in the

Figure 2. Listening to a pinged sound via the Ambient Horn.

den for approximately 30 minutes, to reflect on and share their explorations using the shared displays with the other children and remote facilitator.

Hence, the Ambient Wood provided the children with new opportunities to make connections between the knowledge they had been taught, the observations they were making in the woodland and the different forms of digital augmentation they were receiving; and with the guidance of remote facilitators begin to think about, question and generate hypotheses about these.

4.1.1. *Use of mobile devices in situ*

The findings from the two studies revealed how the mobile devices supported collaborative learning and the practice of inquiry processes (Rogers *et al.*, 2005). The pairs worked closely together, alternating between one child using the probing device and the other holding the PDA and using the walkie-talkie. Both looked at the information appearing on the PDA and took it in turns to listen to the sounds playing on the ambient horn. In this way the students contributed different, but equally important, components of the task, requiring them to take different roles in the activity, but at the same time to co-ordinate collective meanings.

Exploration of relevant aspects of the physical environment was also enriched through the digital information itself. Receiving digital information about invisible aspects of the physical environment not only drew attention to relevant concepts that were not clearly apparent, but also prompted the children to look for physical evidence of these features. For example, after hearing a "caterpillar eating" sound on the Ambient horn one pair looked for evidence of caterpillars in the vicinity of where they were through trying to find holes in leaves of the plants. The episodes of collaborative observation and integration of information also showed enhanced reasoning taking place, where the children abstracted from the digital information they received to what is around them in the physical world. For example, after hearing the sound of "photosynthesis", one pair of children related this specifically to the physical leaves on the trees, that subsequently led them to think about leaves from an ecological/biological perspective rather than merely as a "leaf" as a way of identifying a tree species.

The children also integrated the readings obtained from the probing devices with their own observations of the physical environment. For example, the excerpt below illustrates how one pair of girls used their observations of the woodland to direct their explorations and verification of the digital readings:

Girl A: "Shall we try a dry leaf?" <*she then puts the probe tool onto a leaf of the tree*>
Girl B: "That didn't do much at all – not very wet at all"
Girl A: "Try it in this grass"
Girl B: "That's much wetter"
Girl A: "This is really dry, shall I try it over here?"

There was also evidence of the children integrating their probe readings with their understanding of the habitat. For example, after taking a probe showing a dark reading under a tree, one boy observed that: "the grass grows where it is light and moist, but it is dry and leafy under the trees".

4.1.2. *Forms of collaborative inquiry processes*

There were numerous spontaneous conversations of the kind above suggesting that the use of the mobile devices and the information presented encouraged the children to initiate and practice inquiry. They often explained their readings to each other, by generating a hypothesis about that part of the woodland (e.g. it being wetter than another because of the environmental conditions); then suggesting another place to go to confirm or disconfirm their hypothesis. They also suggested where to take the most extreme readings, and again, this involved them generating and then testing predictions about the environment. The following example illustrates this, where two girls are having a discussion about a moisture reading they have just taken:

Girl B: "Its about half"
Girl A: "Shall we try the sunlight now?" <*She raises her arm and takes a moisture reading*>
Girl B: "So it likes a bit of moisture"

<*Both girls look at the sunlight reading*>

Girl B: "Quite high..."
Girl A: "It probably needs a lot of sunshine and... probably wet with a lot of sunlight."

These kinds of collaborative interactions were frequently observed. They were also found to provoke further exploration and supported successful collaborative learning, in particular, enabling the children to make predictions, generate hypotheses, analyze their data (c.f. De Jong & Van Joolingen, 1998), and to look for patterns and relationships between various instances of data (Novak *et al.*, 2002).

The children's understanding of the data they had collected, using the probing tool, was enhanced through re-visiting them as aggregate data via the visualization. Their explanations to one another in the den suggested they had integrated their knowledge of the moisture and light distributions in the different areas. In particular, they abstracted patterns from their set of personalized data points and made generalizations about the contrasting habitats as to why different types of organisms lived in each habitat and why they would not survive as well in the other. This learning effect was partially due to the children being able to do further analysis in the woodland with their exploratory experiences still fresh in their minds rather than waiting until they had returned back to school. Another reason was the personalized nature of the data, that they could readily make sense of, rather than interacting with depersonalized sets of abstract data points often presented as part of software simulation tools.

4.1.3. *Role of facilitator*

The teacher is an important player in mobile learning, helping to optimize the benefits of using the devices. In our studies, they played a central role in guiding tasks, helping access to relevant information, and in supporting reflection. Moreover, their role was very much seen as a facilitator, guiding the choices children made, both in terms of their activity and their use of devices through verbal collaboration using the walkie-talkie. They also sent relevant images or probes in response to the findings the children reported to them, enabling them to discuss further the information they were gathering, or providing guidance towards aspects they had not yet focused on.

The use of the walkie-talkies to communicate required that only one party spoke at a time. In order for this to work, the children's ideas and thoughts needed to be concise and coherent. The pairs of children would often discuss with each other what the one holding the walkie-talkie would say to the facilitator before reporting it over the walkie-talkie, forcing them to think collectively about their understanding and the meaning of their activity or the information. When the facilitator met up with the children later on in the den, they asked the pairs to explain to each other what they had discovered by interacting with their probe readings on the shared display. The children needed very little encouragement once they understood which set of readings was theirs. For example, they described the features of an area (e.g. whether there was lots of dead wood, near a pond, an open space) and showed their readings to confirm whether that region was mainly wet or dry.

4.2. *Discussion*

The studies showed the children readily switching between using the tools, exploring the woodland, and talking to each other and the facilitator. Moreover, they generated a number of hypotheses about the habitat from the observations they were making and then collected further data to refute or support them. This appears to be primarily through the devices enabling them to make connections between their concrete observations and digital information and abstract data. The novel mobile devices were also found to be highly engaging and enjoyable to use. This, too, may have played a role in the way the children initiated and followed through with their collaborative inquiry processes. At the same time, the children were not distracted when using them. If they were in the middle of doing something when a sound was pinged to the ambient horn or an image to the PDA they waited to listen or view them until after they had finished what they were doing. On other occasions, if they were completely engrossed in an activity, they simply ignored them. For example, when pinged information about blackberry bushes, one pair were more interested in the feathers from a dead bird they had just spotted, and hence paid little attention to the digital prompt.

Hence, it appears that the mobile tools were used to support a variety of social and collaborative interactions that led to knowledge integration. In particular, they were involved in mediating chains of them; the children moved from their experiences of observing instances in the woodland, to talking about them to one another, to re-representing them to the facilitators and finally explaining what they signified at a higher level to other children when re-presented to them in the abstracted visualization. The second case study builds on this analysis, by exploring how mobile devices enable the interlinking of observation, discourse and digital representations.

5. The LillyPad Project

Similar to Ambient Wood, the LillyPad project was concerned with how to facilitate collaborative inquiry processes during fieldwork, through providing various forms of digital information via a PDA, but for older learners, namely, university students, who worked in teams, rather than pairs. A difference was that the device was intended to augment an existing scientific practice, which was to participate in an environmental restoration project, where the data collected and analyzed were used to make predictions and inferences about the efficacy of different planting methods in a wetlands floodplain. Accordingly, the type of data collected, the tools used and the visualizations provided were more sophisticated, intended to be at an appropriate level for undergraduate students.

Of particular interest was how students contributed to the collaborative activity in terms of making connections between their observations, understandings, and analyses of aspects of the physical environment; comparing these with previously collected data stored on the mobile device; interpreting and making inferences at varying levels of abstraction using various graphical representations on the mobile device, and generating hypotheses and drawing conclusions (Rogers *et al.*, 2007). A further concern was how the scientists changed the way they guided, explained and probed the students when using the device *in situ*.

As part of the Lilly ARBOR project, an experiment was conducted to determine the best strategies for forest restoration along a riverbank in a floodplain, using three different tree planting methods. Over 1400 native trees of 12 different species were planted at the beginning of the project (2001) in six different plots (two for each planting method). Since then, the site has evolved into a wildflower meadow and shrub/sapling habitat. Twice a year, in the spring and fall, six teams, comprising 4–5 students and an environmental scientist who acted as team leader, assess the restoration site, measuring the survival and growth of the trees and noting, among other things, any predator damage and the impact of the recolonization of other trees and plants. The students in each team are assigned a role, whereby each is responsible for using a particular measuring tool (e.g. callipers, stadia rod) or a tree location map. Each team spends an entire day documenting the status of each tree, including locating, identifying and measuring the surviving trees for the different plots.

A problem that was noted by the team leaders during these student assessment days was that the students rarely engaged in any inquiry processes. While they located and measured the trees competently, they found it hard to draw conclusions from their measurement activities in relation to what was explained to them by the scientists about environmental restoration, such as the pros and cons of the different planting methods. It appeared they were unable to make connections between the data being collected, knowledge about reforestation and actual observations of the site.

LillyPad was developed for use on a PDA to address this concern, by allowing students to readily switch between data recording and analysis activities. The software provided five functions: (i) data entry page; (ii) information pages, showing descriptions of tree species together with photos of the most common parts used to identify them; (iii) "stats" pages showing the previous measurements recorded for each tree over the last five years; (iv) interactive graph pages visually depicting the growth rate for each tree and species for each of the measurements taken over that period and (v) a messaging facility enabling students to communicate their findings and ideas with other teams in different locations on the environmental restoration site. Pages for each one are shown in Figure 3.

5.1. *Studies and findings*

Details of the design and evaluation of the LillyPad application can be found in Rogers *et al.* (2007). Here, we summarize the findings from two separate studies that were conducted where the LillyPad application was used on two assessment days, one in the spring and one in the fall. In addition to the measuring instruments, each team was provided with two PDAs; one student was primarily responsible for data entry and the other for looking up information, data and sending messages. (A previous study had shown that it was too much work for one student to do both of these.) Throughout the day the students rotated using the different devices (see Figure 4).

5.1.1. *Use of mobile devices in situ*

The findings from the two studies showed the teams making frequent use of the different types of information and data on the mobile device. They also switched roles throughout the day, enabling each student to use the PDA and respective measuring tools. The students quickly learned how to use multiple representations

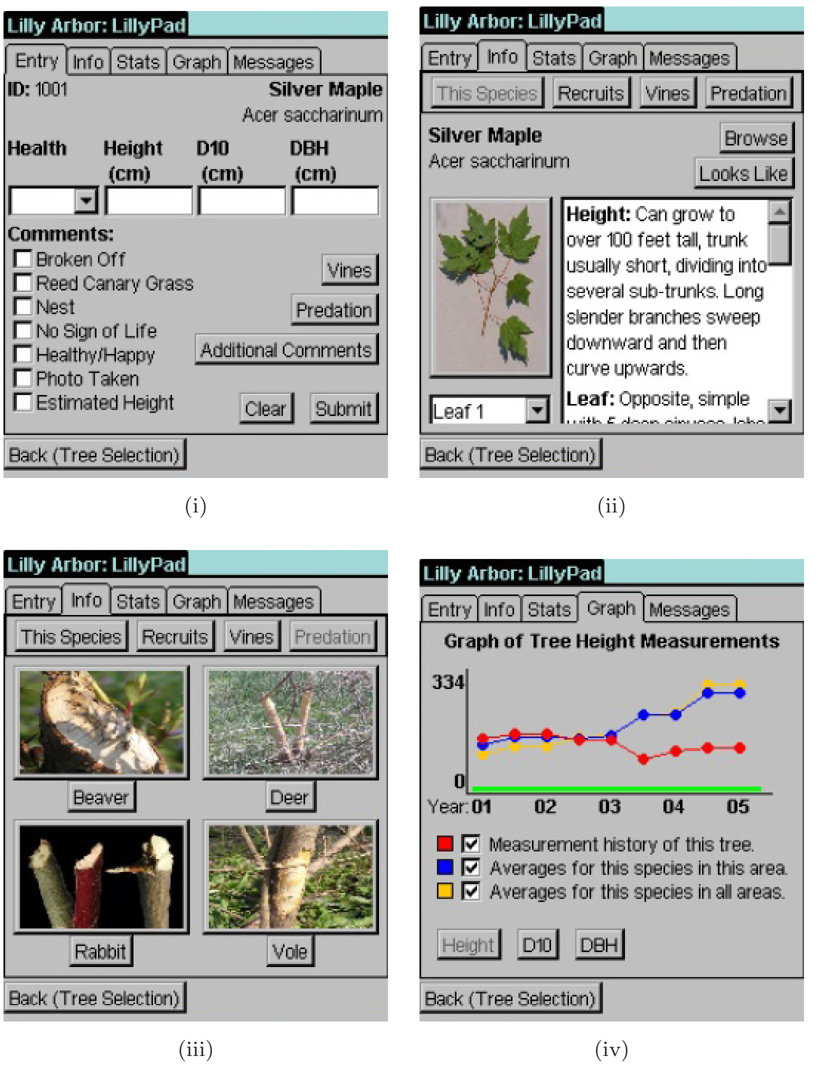
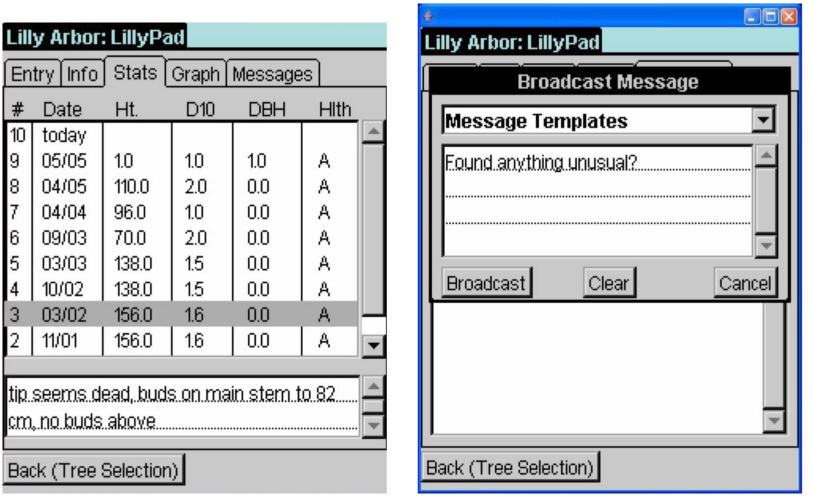


Figure 3. Pages of the LillyPad application: (i) data entry page for each tree (ii) information page for silver maple species, (iii) photos of the different predator's teeth marks typically found on tree trunks and branches, (iv) graph page showing trends for a particular tree, the species in the area and for all areas, (v) stats page showing measurements for a particular tree and (vi) messaging facility.



(v) (vi)

Figure 3. (*Continued*)

Figure 4. A team using the LillyPad application and other instruments to measure a tree.

to aid the team in explaining their observation and making hypotheses. For example, the PDA holders understood the benefit of switching between the numerical and graphical representations on the mobile device when locating and measuring trees. They would begin by looking at the stats page to help locate a tree by calling out details about it from the stats page to the others. When the others had found the tree and its measurements taken, the PDA holder would compare them with the stored data and if they were less than expected it triggered the team to try to work out why this was the case (since they should have increased). The PDA holder then switched to looking at the graph page for that tree to see if the anomaly was a one-off (e.g. top eaten by a beaver shown by the teeth marks) or as part of a growth pattern for that tree (e.g. smothered in vines causing it to not grow).

The one function that the students rarely used, however, was the messaging facility. The teams sent a total of 12 messages and then stopped. This excerpt shows a message being looked at while in the middle of measuring a tree:
Student A pulls up messaging window on her PDA
Student B peers over her shoulder: "Anything interesting on there?"
Student A: "ohhh boy, no, talking about, caterpillars, and bindweed" *[Returns quickly to graph page and does not send back a message.]*
One of the main reasons for its limited use appears to be that the teams were engrossed in their ongoing local activities. They commented on how messaging was too distracting in this context; the students interacting with the PDAs did not want to miss out on the discussions and activities happening in their own team. This finding resonates with those found in the Ambient Wood study, where the students decided themselves how to manage their time and which activities to pursue, so as not to get overloaded or distracted.

5.1.2. *Forms of collaborative inquiry processes*

As mentioned above, the students use of the various pages provided by LillyPad frequently led to further reasoning about the observations they were making in the environmental site. Between 15–25 extended inquiry–based conversations took place per team throughout the day, which had not occurred during the assessment days prior to the introduction of the LillyPad application. An example is shown in the excerpt below where a team is trying to work out why an oak tree has grown 100 cm in six months, which is most unusual, as oak trees grow very slowly. (A is the team leader, B and C are students with the PDAs and D is a student measuring the height of the tree with the stadia rod):

A: "This oak is doing well! For an oak, this thing is practically jumping out of the ground."
C: "It grew how much since last time?!"
B: "240... last time" <*she give the wrong reply, telling instead what its measurement "is*>
C: <*C realizes this and so asks in a different way*> "And that's from?"
D: "145"
C: "It grew a hundred centimeters?!"
B: "I didn't think oaks grew that fast."
C: "That was only like, 6 months ago wasn't it, Al?"
A: "Yup, if you can remember, it was nice weather too!"
D: <*pointing to the foliage*> "It's easier... you don't have all this stuff here growin' do ya, in April?"
C: "I don't know."

B: <*standing by herself with the PDA*> "Yeah, so... Then this tree in general is doing... is very happy."
C: "Yeah?"
B: "When you see it from the... with the..." <*Shows graph page to C*>
C: <*looking at PDA*> "mm-hmm... oh!, its better than... it's... yeah, it's better than all the averages, of this plot, and even of the entire site."
B: "Right, so then that makes you feel more comfortable that we're staying 100 cm. Because it's..."
C: "Oh yeah, that its less likely that they screwed up last time."
B: "Yup"
C: "That was my first thought actually, is I wondered if they... just measured it wrong last time."
B: "Yeah."

The excerpt also shows how the graphical representations enabled the students to make generalizations from the live data they were collecting relative to the data previously entered into the database. The trend graphs were used to reason about anomalous growths. They were also used at other times as evidence to generate hypotheses and to refute opposing hypotheses made by other students.

5.1.3. *The role of the facilitator*

As was found in Ambient Wood the facilitators — in this case the environmental scientists — were instrumental in the orchestration of the collaborative inquiry. They commented on how they found themselves changing the types of questions asked, knowing the students holding a PDA could look up certain kinds of information that could further the inquiry. Similar to Ambient Wood, they varied their amount of probing and explaining while at the same time encouraged the students to look, themselves, at the environment and reason from the two sources of evidence (information and observations) in front of them.

The success of the scientists in encouraging participation from the students in their team depended on their ability to act as a facilitator as well as an instructor. Some of the environmental scientists are more skilled at the former, drawing ideas out of the students, while others are better at the latter, explaining what they are seeing and doing. However, what the mobile device provided for all of them was a different way of guiding the students, through asking them questions they can answer by looking up the information and reading it out to the others.

5.2. *Discussion*

Similar to the Ambient Wood, the students were able to engage in collaborative inquiry processes when *in situ* through interlinking the information and data accessed via the mobile device in conjunction with the observations and measurements they were making. Being able to sequence these at the same location and time meant students did not have to "hold back" from pursuing further analysis until they had returned to the classroom — where they often forget what they have noted in the field — but could progress with making inferences using the combination of digital information and physical observations while still at the restoration site. Another finding was that as the measuring day progressed the students and scientists became practiced in making use of the information and data on the PDA to initiate and further their inquiries. Hence, knowledge was socially constructed through the teams making sense of the materials available to them; they selected relevant information, organized it into a structure that they were able to integrate with prior knowledge.

6. General Discussion and Conclusions

The two case studies have illustrated how mobile technologies can be designed to facilitate the practice of collaborative inquiry. One of the main benefits of using mobile devices for collaborative learning is how contextually-relevant information can be immediately accessed as evidence to support partially formed ideas and understandings. Central to both learning contexts was how the mobile devices enabled pairs and groups of students of different ages to collaborate through discovering and then sharing information. The groups were also able to integrate the accessed digital information with their observations and begin to make generalizations from them. Having pertinent digital information at hand during an ongoing physical activity was key to whether an inquiry process was triggered. If brought to the center of the students' attention at critical moments, it was used to formulate hypotheses. Sometimes, debates ensued where different students used the digital information to proffer alternative explanations of what they were collectively observing.

The types of digital information that were found to be most effective varied; simple images and abstract sounds were found to be effective at provoking and focusing young children on making connections; while having both numerical data and trend graphs provided a way of moving between the specifics of a single observation to a more abstracted level of understanding. Being able to switch between the different types of representation was found to be effective, helping them to make connections. Furthermore, being able to collect and analyze data in the same location allowed the changes they saw in numerical data to be connected with the changes they observed in the environment that lead to further inquiries.

The way the mobile devices, described in the two case studies, facilitated learning while outdoors was primarily through providing students with a form of cognitive augmentation. For the instructors, they provided them with a means of tailoring their intervention in the learning process; orienting towards certain kinds of questions and prompts as to what to do or look at. As a consequence, the students, guided by their facilitators, were able to generate hypotheses about what was being observed that could then be tested using the probing and other measuring tools.

Even though the mobile technologies were designed for single users, both studies showed them to be used in a distributed manner that did not result in isolation or distraction. The exception was the messaging facility which the PDA holders chose simply not to use after a short while because they did not want to miss out on what was happening locally. The other digital forms of information were viewed together by pairs or spoken aloud within a group, enabling a high level of awareness. More generally, the extent to which devices are shared raises the question of what is an optimal number of mobile devices per group relative to its size. Now that the price of mobile phones is much cheaper it is possible for every student to have one and hence all be able to interact with a particular mobile learning application. However, this approach might be counter-productive as it would mean the groups no longer need to share or request information. An alternative strategy is to design the learning activity to be explicitly structured so that each student takes on a specific role, requiring them to relay certain kinds of information or messages to the others at certain times. The role of remote (and even agent) facilitators could also be made more prescriptive, where they provide cues, prompts and feedback when it is deemed that the students need a particular kind of support. It remains to be seen, however, whether providing more or less structure in the learning activity and one mobile device per child results in enhanced collaborative interactions.

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