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A central challenge for science educators is to enable young people to act as scientists by gathering and assessing evidence, conducting experiments, and engaging in informed debate. We report the design of the nQuire toolkit, a system to support scripted personal inquiry learning, and a study of its use with school students ages 11–14. This differs from previous work on inquiry learning by its emphasis on learners investigating topics of personal significance supported by a computer-based toolkit to guide school pupils through an entire inquiry process that connects structured learning in the classroom with discovery and data collection at home or outdoors. Findings from the studies indicate that the toolkit was successfully adopted by teachers and pupils in contexts that included teacher-directed lessons, an after-school club, field trips, and learner-managed homework. It effectively supported the transition between individual, group, and whole-class activities and supported learning across formal and informal settings. We discuss issues raised by the intervention studies, including how the combination of technology and pedagogy provided support for the teacher despite difficulties in managing the technology and integrating field data into a classroom lesson. We also discuss the difficulty of altering young people's attitudes to science.

In a complex and uncertain world, in which major scientific issues are publically contested, it is essential for the well-being of society that young people better understand and engage in the science that affects their lives. There are two fundamental reasons for encouraging young people to engage in personally meaningful scientific inquiry. The first is to give them the experience of being scientists (Hodson, 1998). By engaging in scientific practices within and outside the classroom, young people can come to understand the nature of shared scientific investigation and the value of building their investigations on the findings of others (T. Bell, Urhahne, Schanze, & Ploetzner, 2010; Grandy & Duschl, 2007). With the Web providing easy access to conspiracy theories and pseudoscientific articles, there is more need than ever to enable young people to understand the practices of scientists, the need for scientific rigor, and valid interpretation of results (Anastopoulou et al., 2012). Such practices include generating their own research questions, selecting from many possible variables to investigate, designing procedures to explore questions, using multiple measures, questioning findings, and coordinating results from multiple studies (T. Bell et al., 2010; Chinn & Malhotra, 2002; Edelson, Gordin, & Pea, 1999). Young people can engage in a discursive process requiring forms of argumentation, presentation, and collaboration that have been established as part of a scientific culture (Board on Science Education, 2012; Latour, 1999), using a system of scientific language that has internal consistency and explanatory power (Dewey, 1938).

The second reason is that by undertaking meaningful and satisfying investigations of their locally accessible world, young people can feel the surprise and unease that are the foundations of scientific curiosity. Dewey (1910) referred to inquiry arising from a "felt difficulty" (p. 72), a vague feeling that something is out of place or an experience of unexpected response to a habitual action. This stimulates a need for resolution through reasoned investigation. Inquiry also arises from positive affect: a sense of wonder that leads to curiosity and a desire for explanation. It is this aspect of personal commitment to an inquiry that is often missing from school science (Chinn & Malhotra, 2002; Metz, 2011), and it cannot be assumed to drive science education outside the classroom in museums or discovery centers.

TEACHER ORCHESTRATION

The teacher is central to orchestrating the process of learning through inquiry in a school context: explaining its purpose and methods, locating it within the science curriculum, guiding the design and conduct of investigations, and coordinating the outcomes to reach a satisfying conclusion that helps learners understand the value of scientific inquiry. The teaching of science through inquiry is time consuming, hard to manage, and at odds with the ways in which science education is traditionally delivered (Edelson et al., 1999; Quintana et al., 2004). It is not feasible to take pupils outside the classroom to engage in scientific reasoning as part of a 40-min science lesson (Chinn & Malhotra, 2002). If pupils are asked to carry out the work in their own time, then the teacher is left with uncertainty over whether and how they have collected data and the possibility that a pupil might reach an impasse that cannot be resolved until he or she is back in the classroom. As a consequence, the teacher may have considerable difficulty creating common knowledge from fragmented practices (Edwards & Mercer, 1987). Additional demands are placed on the teacher to manage collaborative knowledge building (P. Bell, Reeve, & Zimmerman, 2007). For example, the teacher must act against established classroom practice by holding back answers in the interest of sustaining students' self-directed inquiry. This is a challenge that Driver (1983) identified as the "fallacy of induction" (p. 3) and was also discussed by Edwards and Mercer (1987) as the "teacher's dilemma" (p. 126). Furtak (2006) observed and documented a number of strategies that teachers adopt to manage this dilemma in science classes. However, she cautioned that

> in these guided scientific inquiry classrooms, the teachers did not fool their students. Years of in-school socialization have trained them to know that the teacher had the answer. Students went along with making observations for a while, but eventually asked for answers. (Furtak, 2006, p. 465)

Lakkala, Lallimo, and Hakkarainen (2005) described a study of 10 teachers in primary and secondary classes as they set up progressive inquiry collaboratively, with substantial professional training and supported by various Web-based tools. The teachers found the experience very demanding in managing the combination of new technology, unfamiliar pedagogy, and support for pupil collaboration, as well as interactions with project researchers.

THE PERSONAL INQUIRY PROJECT

Against this background, we report here the findings from a project recruiting mobile digital technology to support personally meaningful scientific inquiry. The Personal Inquiry project (http://www.pi-project.ac.uk) investigated the support of learning through a method of scripted personally meaningful inquiry. Its purpose was to investigate how technologies can be effectively used to enable inquiry learning and, in particular, how mobile technology offers the possibility of supporting evidence-based inquiry learning across formal (classroom) and informal (home and outdoors) settings. A toolkit was developed that included an inquiry learning framework and a dynamic inquiry guide. This consisted of a range of scientific data-gathering equipment, such as sensors and cameras, together with the nQuire software application, which supported students' progress through the phases of their inquiries.

The nQuire software provided scripts that guided the students and teachers through a process of gathering and assessing evidence and conducting experiments. The project ran eight sets of inquiries with young people ranging in age from 11 years to 16 years on a variety of topics. Each inquiry was about "myself," "my environment," or "my community." The motivation for this focus was to develop inquiries that engaged the young people in investigating their bodies and their local surroundings. The inquiries included investigations into healthy eating, diet, exercise, pollution, microclimates, and food packaging. They involved activities at home, in a nature reserve, and in a gym. Two of these investigations (healthy eating and microclimates) are reported in Anastopoulou et al. (2012) and Kerawalla et al. (2011). These studies led to further development of the toolkit, which was evaluated in another two intervention contexts reported in this article. The first was an investigation into the effect of noise pollution on bird feeding. The second was an activity conducted in an after-school club called the Sustainability Squad, which ran for 1 hr each week and focused on the food production cycle.

The overall research project addressed five broad concerns:

1. How should scripted personal technologies be designed to support effective learning between formal and informal settings?
2. How can teachers be enabled to author, orchestrate, and monitor successful learning activities aligned to curriculum topics?
3. How are such technologies appropriated as tools for learning?
4. How does the conduct and experience of scripted inquiry learning mediate and change learning activities?
5. In what ways do scripted inquiry learning activities develop young people's learning skills, including the abilities to work collaboratively, argue and debate from evidence, judge the veracity of source information, deal with noise in data, and construct and interpret appropriate visualizations of data?

Given the diversity of these concerns, and the overall aim of the project to understand the effects of introducing a combination of new technology and pedagogy, a generic summative evaluation of learning gains would have been inappropriate. The approach adopted within the project was to explore the impact and efficacy of a new educational method of scripted personally meaningful inquiry learning. In practice, this involved harnessing a range of theoretical constructs, methodologies, and analytic tools appropriate to the questions being asked. These included design-based research (Barab & Squire, 2004), critical incident analysis (Anastopoulou et al., 2008; Flanagan, 1954), and a test of children's knowledge of the inquiry process that was devised for the project based on Concept Cartoons™ (Keogh & Naylor, 1999).

Findings from earlier studies during the development of initial prototypes are reported elsewhere.[1] In this article we describe the design of the nQuire software as implemented at the end of the project and report findings from two evaluation studies in the final year of the project.

REPRESENTING PERSONALLY MEANINGFUL INQUIRY WITH nQUIRE

A central challenge for the project was to develop a representation of the inquiry learning process that both would serve to prompt and structure classroom discussion about the science inquiry and could also be implemented on personal technology as an interactive visual display that children could take home or outdoors to guide their progress through an investigation. Its design was informed by previous work on representing the science inquiry process.

White and Frederiksen (1998) created a cyclical representation of the inquiry process that informed the design and use of the ThinkerTools simulations and curriculum activities. Students carry out a sequence of activities that correspond to steps in the inquiry cycle. Following this, the SCI-WISE Inquiry Cycle engages students in a six-step inquiry (Question, Hypothesize, Investigate, Analyze, Model, and Evaluate) and introduces them to criteria for evaluating their reasoning. Each of the inquiry steps is presented on a separate page of their reflection-assessment tool called Project Journal, which augments the inquiry by unpacking the goals and subgoals associated with each step. It also gives general advice rather than step-by step procedures (Shimoda, White, & Frederiksen, 2002). Other depictions of a holistic inquiry process have been devised by Schwartz, Brophy, Lin, and Bransford (1999), Bruce and Bishop (2002), Llewellyn (2002), and T. Bell et al. (2010). These have all been designed as research tools, or for viewing and structuring inquiry in the classroom, not for extending inquiry learning outside of school.

We drew upon these representations to produce a generic depiction of the personally meaningful inquiry learning process shown in Figure 1. Our conceptual process of devising and refining this representational framework is described in Scanlon, Anastopoulou, Kerawalla, and Mulholland (2011).

The figure shows scientific inquiry as a cycle in the shape of an octagon, with each step building on understanding gained from previous activities. It involves finding an agreed-upon inquiry topic; deciding on a question or hypothesis to guide the investigation; planning the methods, activities, and equipment to be used; collecting evidential data; collating and analyzing those data; interpreting the evidence in relation to the original questions or hypothesis; sharing the results;

[1] See www.pi-project.ac.uk for a list of papers related to the program of research.

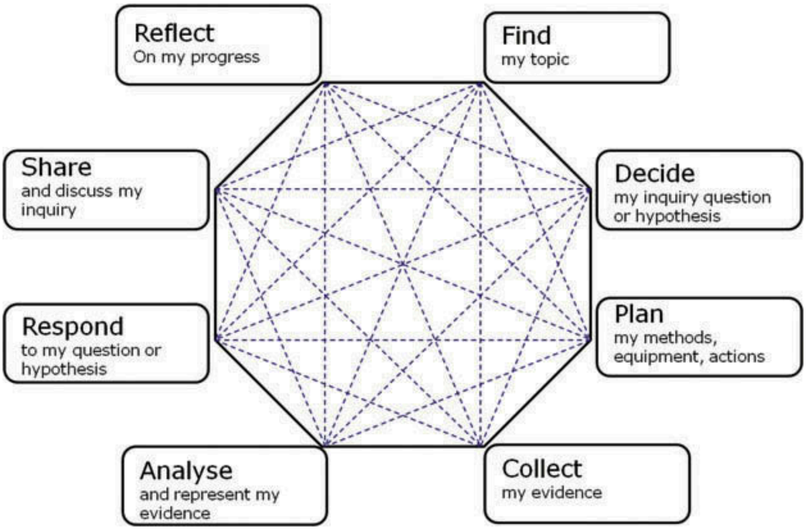

FIGURE 1 Depiction of the personal inquiry learning process (Scanlon et al., 2011).

and reflecting on the experience of conducting an inquiry (this leading to further curiosity, new topics to explore, or revised questions).

It is important to note, first, that the representational framework is intended to cover the range of methods of scientific inquiry from a controlled hypothesis–led experiment to an exploratory survey or discussion with an expert; second, that an investigation can begin at any step, for example, by collecting evidence to explore a question and plan already set by the teacher, or analyzing and discussing data collected from a previous inquiry, or debating whether there is sufficient evidence to answer a scientific question; and third, that an investigation initiated in the classroom can be continued in an informal setting by individuals or groups doing the data collection and initial analysis, assisted by the software, then either sharing the results back in the classroom or online.

A further challenge for representation is that the inquiry process is not necessarily linear. Depending on the result of current actions, learners and the teacher may decide to go back and revisit previous actions or jump forward to study the future effects of these actions. Therefore, constraints and dependencies between all elements of an inquiry are indicated through the hatched lines between the inquiry steps. For example, the Respond phase may involve revisiting the inquiry question in the knowledge of newly collected data, or the Reflect phase could result in a plan for a new cycle of inquiry.

The wording for the steps was based on the inquiry elements represented in previous approaches, particularly Llewellyn (2002), and the terms used in the Key Stage 3 English National Science curriculum for pupils ages 11 to 14 (Qualifications and Curriculum Authority, 2007). The steps are framed as personal activities (e.g., Collect My Evidence) to emphasize inquiry as a personally meaningful project. The concomitant problem is that this portrays inquiry as a solitary activity. So there is a clear role for a teacher in enabling each pupil to understand how personal meaning can be created through collaborative exploration. The goal is for each person to realize the scientific benefits of pooling data and be sufficiently engaged to want to share and compare findings.

IMPLEMENTING SCRIPTED INQUIRY LEARNING

As well as developing an interactive depiction of the inquiry process, we also implemented a dynamic representation of the structure and flow of activity across time and location. Unlike with a typical homework assignment, the pupils were not working outside the class to produce finished essays or reports but collecting data or resources that had to be integrated into a subsequent lesson.

Scardamalia and Bereiter (1991) described inquiry as an unpredictable, holistic process that involves the coordinated and creative development of ideas within a community. To organize such activity while allowing each learner sufficient control over process and outcomes so that he or she may experience the uncertainty of scientific experiment alongside the shared sense of progress might seem to correspond to scaffolding (Quintana et al., 2004; Wood, Bruner, & Ross, 1976). This is a pattern of teacher engagement that, through strategic intervention, allows the teacher to constrain specified aspects of freedom in a task, thus simplifying and structuring it. Scaffolding is a contingent activity. It is effective for learners insofar as the teacher can judge the appropriateness of an intervention, using the ongoing learner activity to decide when it is the right time to pull back from prompting and support, or when to increase it, as well as to determine the nature of that support. This form of judgment requires continual monitoring and interpreting of the learning activity in progress, which is not possible when work is extended across settings that are beyond the direct control of the teacher.

Software can assist in scaffolding inquiry learning by informing learners of their progress and next steps, offering hints and reminders, and encouraging them to articulate and reflect on their progress (Quintana et al., 2004). Although this may be feasible for prespecified topics and practices, it is beyond the scope of current computing to guide young people to devise personally relevant topics of inquiry, engage in productive collaboration, or choose where and how to collect and assess evidence. As Quintana et al. (2004) indicated, other kinds of support are essential, involving a judicious mix of teachers, peers, and curriculum materials.

An alternative approach of *scripted orchestration* has been used by educational researchers to refer to the planning, management, and guidance of a sequence of activities for individuals and groups to enable effective learning (Forman & Ansell, 2002; Littleton, Scanlon, & Sharples, 2012). It has been adopted by researchers in computer-supported collaborative learning to describe the management by a teacher, in real time, of a class of learners supported by interactive technology (Dillenbourg, Järvelä, & Fischer, 2009; Dillenbourg & Jermann, 2007; Roschelle & Pea, 2002). Unlike scaffolding, it does not require contingent support of individual learners but rather requires the enactment of a teaching script that schedules and prescribes the structure of activities and assignments while allowing flexibility in how these activities are ordered and conducted. For example, in the ManyScripts environment (Dillenbourg & Jermann, 2010) teachers can choose and edit a script such as ArgueGraph (to display students' answers to multiple-choice questions on a graph as a prompt for classroom discussion) that guides the flow of a lesson.

Scripted orchestration differs from lesson planning (Holtrop, 2010) in its abstraction away from the specifics of a particular school and teacher to provide a more generic pedagogic structure that embodies pedagogic principles. A script is designed to be enacted on computer technology that can assist the teacher in allocating resources, assigning students to groups, presenting materials, setting constraints, monitoring progress, enabling communication and shared activity, and integrating outcomes (Collins, Mulholland, & Gaved, 2012). The extension of scripted learning described in this article is to use personal mobile technology to orchestrate inquiry learning outside the classroom, so that the teacher initiates a structured activity with the mobile devices inside the classroom; then each pupil continues the investigation outdoors or at home with the technology providing the function of orchestration; and the results are then shared, discussed, and presented back in class.

Scripted inquiry learning has the potential to support and change inquiry learning activities by enabling a seamless transition between activities within and outside the classroom (Wong & Looi, 2011) and by giving learners a persistent and dynamic representation of the inquiry learning process that enables them to understand how the component activities (such as deciding an inquiry question, planning an inquiry, collecting and analyzing data, and sharing results) fit within and shape the process of scientific investigation over time (Littleton & Kerawalla, 2012). For example, they can come to understand how changing an inquiry question may invalidate data they have already collected, or that data must be collected in an appropriate form if they are to be shared, or that the conclusions must address the original inquiry questions.

Design of an Inquiry Learning Script

A challenge for orchestrating inquiry learning is to manage this flow of control and information between teacher, students, technology, and other resources, allowing learners the freedom to explore within a structure that guides understanding of the inquiry process and supports discussion and sharing of results (Sharples & Anastopoulou, 2012). One solution is to create a structured interactive representation of the task in the form of an inquiry learning script that can coordinate teacher-led planning and sense making in the classroom while also being implemented on personal devices to guide the out-of-school activity. To work successfully, this must

- Show how the specific inquiry fits within a generic inquiry process (T. Bell et al., 2010; Quintana et al., 2004);
- Represent both the process and the current inquiry in a visual form that guides interpretive knowing (Etkina et al., 2010);
- Integrate learning about personally meaningful topics, learning to do epistemically authentic science, and learning to be a scientist (Chinn & Malhotra, 2002; Hodson, 1998; Latour, 1999);
- Give the teacher a central role in modifying, monitoring, and supporting the activities (Puntambekar, Stylianou, & Goldstein, 2007);
- Be adaptable enough to preset an appropriate level of predictability and flexibility (T. Bell et al., 2010);
- Assist the learners in performing techniques for collection, visualization, sharing, and analysis of quantitative and qualitative data (T. Bell et al., 2010; Edelson et al., 1999);
- Enable the sharing of data and integration of knowledge gained during the inquiry (Linn, Clark, & Slotta, 2002); and
- Support assessment of the artifacts created by learners during an inquiry (Wasson, Vold, & de Jong, 2012).

It should be noted that this is not adaptive computer-based teaching (where contingent scaffolding is assigned to the computer) but rather coconstruction of meaning between learners, assisted by the teacher and classroom resources, within a shared visual framework instantiated through interaction with technology.

The nQuire technology described in this article provides software tools for a teacher to choose a pre-prepared inquiry and then make changes to the inquiry script so as to align it with the curriculum or a sequence of timetabled lessons. For example, a teacher can modify which phases of the inquiry should be visible and available for editing by the students during each lesson, change the textual labels to describe phases or activities, add new locations for data collection, or prime the inquiry with initial questions or hypotheses. The aim is to enable scripting and orchestration of learning activities within and outside the classroom. Students would normally begin by framing a problem within the class led by the teacher; continue the investigation in the playground, at home, or in an outside location; then return to the classroom to share, analyze, interpret, and present their results.

A typical sequence is as follows:

1. The teacher introduces the inquiry topic, showing the inquiry cycle on a classroom display and working with the whole class to agree on a wording for Find My Topic.
2. Students work in groups to propose inquiry questions or hypotheses, which are discussed and agreed upon with the teacher.
3. In groups, the students plan their methods and set up the investigation.
4. Students work individually outside the classroom to collect data. Each student can see data from other students either as they are entered (if there is a network connection) or back in class (if not).
5. In a classroom lesson, groups of students analyze their shared data and reach conclusions, referring back to their initial questions.
6. Each group prepares and presents its work for a class discussion.

For the studies reported here, members of the research team created scripts for each study based on design requirements developed with teachers and pupils. They showed the teachers how to script and operate the nQuire toolkit. If the software and approach is to be more widely adopted, teachers will need to be offered not only operating instructions but also professional development in methods of scripting and supporting inquiry learning.

COMPARISON WITH RECENT PROJECTS FOR SCRIPTED PERSONALLY MEANINGFUL INQUIRY

Similar projects have taken complementary approaches to the research and development of technology-mediated inquiry learning. Savannah (Facer et al., 2004), Environmental Detectives (Squire & Klopfer, 2007), and Bird Watching Learning (Chen, Kao, & Sheu, 2003) investigated inquiry-based learning outdoors supported by handheld technologies. The Learning Ecology with Technologies from Science for Global Outcomes (LETS GO) project, a collaboration between Linnaeus University (Sweden) and Stanford University (United States), designed and evaluated collaborative learning for outdoor science inquiry in environmental and ecological sciences (Pea et al., 2012). The Science Created by You (SCY) project involving the Universities of Duisburg-Essen and Twente designed support for students to engage in the interactive design and creation of science learning objects, including interactive models, in the field (de Jong et al., 2010). A team at the National Institute of Education, Nanyang Technological University, developed tools for seamless inquiry learning between formal and informal settings (Looi, Zhang, Chen, Seow, & Chia, 2011). Although these projects have supported aspects of inquiry learning across indoor and outdoor settings, such as collecting, sharing, and visualizing data, they have not been based on an interactive visual representation of the complete inquiry process. The Inquiry Island software (Eslinger, White, Frederiksen, & Brobst, 2008) provides tabs to step through the Inquiry Cycle, but the cycle is not the guiding visual representation.

The distinctive contributions of the Personal Inquiry project are the development of a modifiable toolkit based on explicit representation and orchestration of the entire inquiry learning process; its implementation on mobile devices, enabling the inquiry to be conducted within and outside the classroom; its focus on learning through scripted personally meaningful inquiry; and an extended codesign and evaluation process with teachers and pupils in schools to ensure that the technology and inquiry activities are aligned with the curriculum, classroom practices, and pupils' interests.

DESIGN-BASED RESEARCH APPROACH

We adopted a design-based research approach (Barab & Squire, 2004) to developing the nQuire toolkit, in which the pedagogy and technology were developed, evaluated, and refined in concert, producing recommendations for design improvements and insights into effective learning that informed further cycles of research and development. In the early stages of the project a series of scenarios for inquiry learning were devised in partnership with teachers and subject experts. These were designed to address broad areas of the school science curriculum, such as personal health, while being relevant to the everyday lives of school students and feasible to enact with existing equipment owned by the school or university. The most promising scenarios were then evaluated through expert usability testing and pilot studies in schools that involved technology from previous research projects. In partnership with teachers, and through discussion with pupils, we then created further inquiry science scenarios and implemented these as software to author, modify, and deploy inquiry learning scripts. The nQuire software, implemented in an extension of the Drupal open source content management environment, runs on mobile devices and desktop computers to support and orchestrate the learning. Prototypes of nQuire were combined with data probes, global positioning system devices, and cameras to form the Personal Inquiry Toolkit, which was evaluated in studies with schools at Nottingham and Milton Keynes, followed by a further cycle of development and testing involving school, outdoor, and home settings. Mulholland et al. (2011) gives a more detailed account of the software design and technology implementation of the toolkit.

We took a lifecycle approach to evaluation (Meek, 2006), whereby evaluation formed part of the development process and the outcomes of each evaluation session informed the next stage of the system development or fed into an iteration of an earlier stage. The early evaluations comprised formative assessments of usability of the prototype system by experts in human–computer interaction, along with first-year trials of existing technologies, including a heart-rate monitor, with teachers and pupils to inform the design of personally meaningful inquiries. Evaluations in the second and third years of the project consisted of intervention studies in schools involving video-recorded observations; interviews with teachers and students; analyses of computer log files; and pre- and postintervention studies of changes in domain knowledge, knowledge of the inquiry process, and attitudes to science. We were fortunate to work with enthusiastic teachers and pupils willing to share their ideas throughout the project. The teachers acted as design partners in shaping the lesson plans and design of the studies as well as orchestrating the teaching sessions.

THE nQUIRE SOFTWARE

Here we describe the final version of nQuire implemented for this project. The intervention studies used an earlier version of the nQuire software containing the essential functionality of the current version but with minor differences in interface and interactivity.

On starting nQuire, the home screen gives an interactive depiction of the inquiry process, with each box being a button that links to the associated phase (see Figure 2). The software can be configured with other visualizations and labels to align with curricula or to support different types of inquiry. The inquiry is constructed from a sequence of phases that correspond to elements of the inquiry

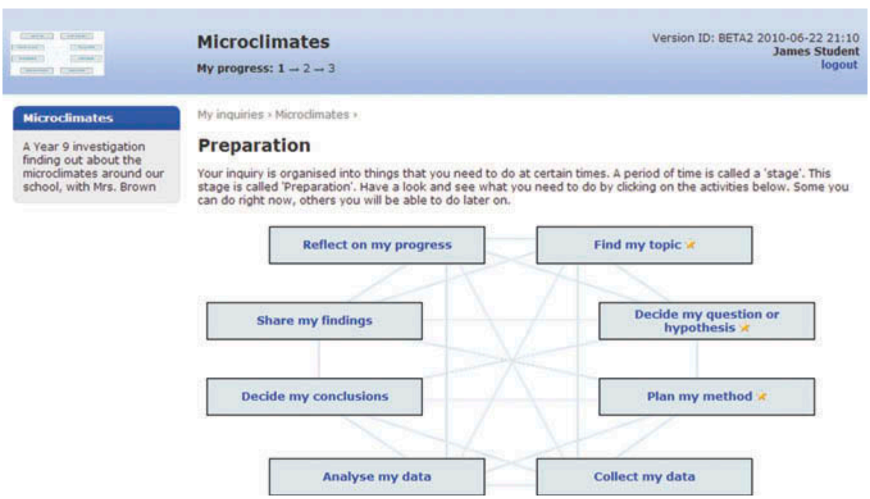

FIGURE 2 Home screen for nQuire.

process, such as Find My Topic. An investigation can begin at any phase (e.g., it could start with analyzing data collected by another group and use those data to frame a new inquiry question), and each phase builds on knowledge gained from previous activities.

Within each phase, there are activities to be viewed or enacted, such as writing an inquiry question, conducting a survey, asking questions of an expert, or presenting conclusions. For each activity, the teacher or inquiry author can specify which individual or group can perform the activity and who will be able to view its result. For example, the class could be allocated to groups, each of which forms an inquiry question that is then shared with members of the other groups, or individual students in a group may collect data at home and then share the findings with group members before presenting a combined analysis to the class.

To manage the activities, each inquiry is enacted as a sequence of temporal stages, of any duration, that could correspond to classroom lessons, field studies, or home experiments. A stage can be associated with any number of phases, and by default this means that the activities in that phase are available for the students to start or revise. Previous activities from phases not associated with the current stage can be viewed and edited; future activities are unavailable. These default settings can be changed, for example, to allow students to begin work on a final report or presentation while carrying out the investigation.

Figure 3 shows a typical display from nQuire during the Healthy Eating investigation. The octagon representation of the inquiry process provides a link from

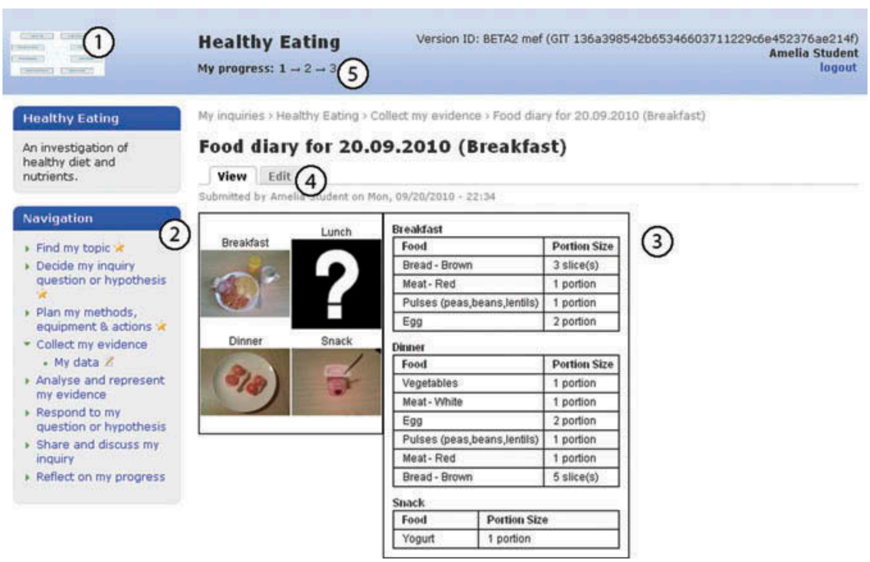

FIGURE 3 nQuire screenshot showing an activity from the Healthy Eating investigation.

each screen to the home page, with a visual reminder of the inquiry process (1). This is linearized on each screen to provide a hierarchical navigation panel (2) with phases as top-level items and activities as subitems. To the user, this navigation panel functions like a dynamic to-do list, providing an ordering of phases, with each phase associated with one or more activities specific to the inquiry. The current activity is displayed in the main area of the screen (3); in this example, the user is engaged in the Food Diary activity of the Collect My Evidence phase. The user can move between viewing and editing an activity (4) and so can view the results of an activity before adding and editing new material. The temporal stages of the inquiry process are shown as a progression, with the current stage in bold (5).

Typically, during the planning phase, the student must select appropriate measures. The measures may have been created in advance using the authoring tool, and new ones can be added as the inquiry progresses. Each is designated as a key measure (equivalent to an independent variable), a selected measure (a chosen dependent variable), or unused. Each measure can be continuous, discrete, pictorial, or textual, with the type of value and method of input being specified. By dragging the measures on the screen, the student can decide which measures to take and how they are organized (e.g., in Figure 4 by dragging "Windspeed" into the "Selected Measures" area).

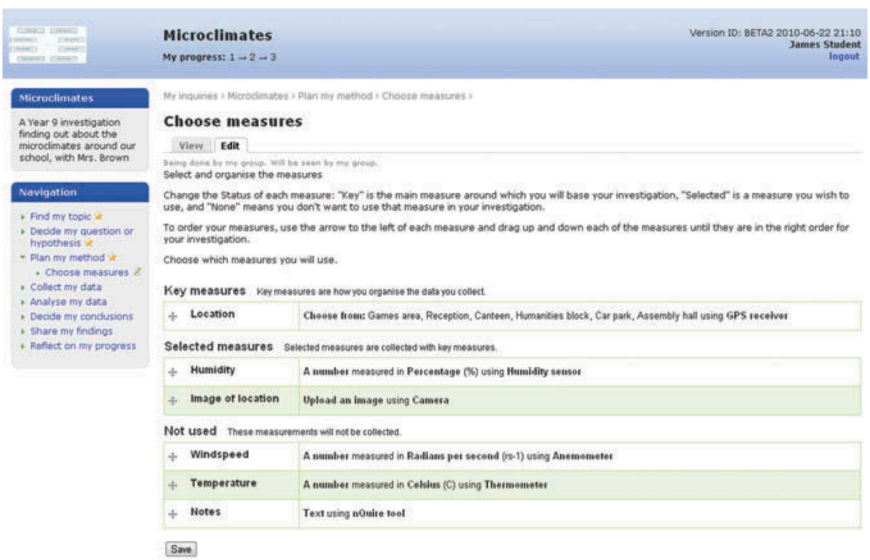

FIGURE 4 Selecting measures in nQuire for the Microclimates investigation.

Our ambition has been to recruit scripted personal technologies into the support of effective learning between formal and informal settings. The nQuire software application addresses this aim. It was developed through a process of design-based research to implement a dynamic representation of the inquiry process. The representation can be used by a teacher to describe scientific inquiry and contextualize classroom discussion. It also provides the macrostructure for a scripted inquiry guide and support system. This presents and structures activities through phases of inquiry across temporal stages. Implementation on mobile devices, including netbooks and tablet computers, and synchronization of data across devices enable the toolkit to be accessed at home or outdoors and also across classroom technologies, including pupils' devices and the teacher's electronic whiteboard.

TWO INTERVENTIONS FOR PERSONALLY MEANINGFUL INQUIRY

In this section we give a descriptive account of the design and findings for two intervention studies conducted in schools at Milton Keynes and Nottingham with the final version of the nQuire software. We frame the findings in relation to two questions:

1. How was the Personal Inquiry approach to curriculum-related science investigations adopted and orchestrated by teachers and learners?
2. How did engaging in the scripted personally meaningful inquiry influence children's science-related activity and attitudes toward science?

By *adopted* in Question 1, we mean the ways in which the teacher integrated the technology and approach into the classroom lessons and the students took up the technology to support personal inquiry within and outside the classroom.

The objective of the studies was to build on findings from our previous interventions in designing effective technology-enabled personal inquiries that connect learning in and beyond the classroom. Both teams, at Milton Keynes and Nottingham, engaged the students more fully in the design of the inquiries, alongside the teachers and subject experts, so as to examine tensions and opportunities related to personal relevance to individual students, collective engagement, match to the school curriculum, and support required by the teacher and technology. The topics developed through this collaborative design process were (a) effects of noise pollution on bird feeding and (b) sustainability and food packaging. The two studies were intended to be complementary, with one connecting classroom and playground activity orchestrated by a teacher and the other connecting projects initiated by young people in an after-school club with experiments and data collection at home. Together, they provide a rich picture of the inquiry activities and examine issues raised by the previous studies, relating particularly to involvement of students in the design of the investigations and to orchestration of activity outside the classroom. Consequently, we first describe the design of each study and then integrate their findings to address the research questions.

Effects of Noise Pollution on Bird Feeding

Design. A participatory design session was conducted at the Nottingham school with Year 8 students (ages 12–13) and the teacher, who had collaborated in our previous studies. An initial discussion between the class teacher and researchers resulted in the topic of ecology being selected as being relevant to the school curriculum. A design workshop was then arranged with eight children from the teacher's class as an after-class activity. The pupils were shown a temperature sensor as an example of a data probe. They were asked to suggest words relating to ecology and then were asked what aspects of ecology interested them the most, which were environment, habitats, and animals. Then, through group discussion, the children proposed questions to investigate. These were "How does noise pollution affect the way birds eat and live?" "Would we find the same organisms in a pond in winter compared to summer?" and "What do chickens eat; what do they survive on?" The children were also asked to reflect on the session, giving positive and negative comments. The most frequent positive comments related to their being able to choose how the experiment would go. The most frequent negative one was that only one piece of equipment was shown to the group. Subsequent discussions among the researchers, an expert on animal behavior who offered guidance on what was feasible to study, and the teacher refined the question to "What is the effect of noise pollution on bird feeding?"

Methods. The teacher and researchers together devised three methods for the pupils to investigate the question, to fit with the school science curriculum:

1. An observational study by the pupils of bird habitats at a local nature reserve.
2. An opportunistic comparison of bird feeding at three locations around the school grounds, chosen to have differing levels and types of noise.
3. A fair test comparison of bird feeding at two locations in a large garden owned by one of the researchers, with noise artificially generated at one of the locations. The data were collected by the researcher, with results presented to the class.

The dependent variable for the pupils to investigate during the second and third comparisons was the weight of the seed eaten by the birds. Noise sensors were put next to each bird feeder in the school grounds to capture the level of noise in the specific place. A webcam was also set up for some of the bird feeders in the school grounds to give an indication of the type and frequency of bird feeding. For the fair test comparison bird feeders were placed on similar trees at identical heights. A radio was placed on one tree to generate noise.

The inquiry question was presented by the teacher at the first lesson, with the equipment already available and configured to support the investigation. During the first lesson the teacher discussed with the pupils the practicalities of investigating pollution and how this question represented a generic set of inquiries. The teacher introduced the pupils to the three types of inquiry investigation and guided them through iterations of an inquiry learning cycle. A sequence of 10 lessons to cover the three investigations was prepared jointly by the research team and the teacher (see Anastopoulou et al., 2010, for further details).

The processes and experiences of inquiry learning were examined by four main methods: recordings of classroom interactions from three cameras (one located at the rear of the class focused on the teacher and two covering small groups of pupils), videotaped observations of the pupils at the nature reserve, interviews with the teacher and with groups of pupils during and after the study (11 in total) covering their positive and negative experiences and issues that might be addressed if the study were to be repeated, and log files from the computers.

The videotapes of interactions in the classroom and nature reserve were analyzed to identify critical incidents (Flanagan, 1954) corresponding to breakthroughs and breakdowns of regular and expected activity, where we characterize breakthroughs as observable incidents that appear to be initiating productive new forms of learning or conceptual change and breakdowns as observable incidents in which a learner is struggling with technology or is exhibiting a misunderstanding or confusion (Anastopoulou et al., 2008). Each videotape sequence (for the classroom, captured from three camera angles) was viewed by three researchers working separately to identify irregular events that might constitute a critical incident. The events logged with video timecodes were then viewed and discussed by the three researchers and a consensus was reached as to whether each constituted a breakdown, breakthrough, or routine event. The breakthrough and breakdown events were described in brief nontechnical language. When the incident seemed ambiguous or unusual, its video was shown to a focus group of students and the teacher, and they were asked to recall and describe the event. The outcome of this analysis was a series of catalogued incidents with associated descriptions.

In addition to the recorded observations, structured interviews were held with the teacher and students to explore their perceptions of what aspects of the intervention were most successful, what were least successful, and what they would like to change if the study were repeated. All of the interviews were transcribed and then examined by at least two researchers, who selected extracts that addressed the framing questions in relation to the children's and teacher's perceptions of successes, limitations, and aspects of the studies that could be improved.

The computer log files included textual and numeric data collected by the pupils with the nQuire toolkit during the inquiry activity, including their initial written hypotheses, their specific inquiry questions, their analysis of data, their answers to the inquiry questions, and their reflections on what they learned from the study. These provided additional evidence of inquiry activity, in particular how the children had revisited and changed their hypotheses.

We could find no test of inquiry knowledge that was directly relevant to the personally meaningful inquiry skills we hoped students would develop; consequently we developed our own based upon a comic format. The Inquiry Comics test was partly inspired by Concept Cartoons™ (Keogh & Naylor, 1999) in that it depicts cartoon characters engaged in scientific activities using minimal text, visual representation, familiar everyday settings, and correct and incorrect statements. It presents a character's inquiry process from the early stages of choosing a topic to investigate, through to selecting appropriate methods, collecting data, presenting the data, and drawing appropriate conclusions. At each stage in the process, the character makes decisions about aspects of scientific investigations that are known to be difficult for learners, such as judging the veracity of source information, the collection of data, controlling variables, hypothesis testing, and drawing appropriate inferences from data (e.g., Schauble, Glaser, Duschl, Schulze, & John, 1995). For example, the learner is asked "What did you think of his action—was it a good thing to decide?" and must select "yes," "no," or "maybe" and justify the response by providing a short written answer.

In this study, we created two parallel versions of the comic that followed the same sequence of inquiry: One was concerned with where spiders spin webs (see Figure 5) and the other with where wasps build nests. The cartoon character researches a question, conducts observations, develops hypotheses, designs an experiment, designs a better experiment, collects data, draws inferences from the data, and presents a report of the findings. In total, the students were asked

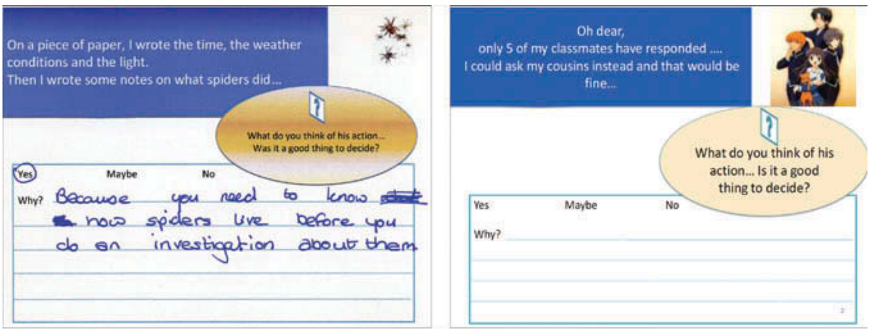

FIGURE 5 Sample pages from the Inquiry Comics.

to judge 14 decisions. To provide a comparison, we also administered the test to a nonintervention control group of children from the same year group who undertook normal class activities.

Sustainability and Food Packaging

Design. The study was conducted with students of a similar age (12–14) as those in the noise pollution study but in the less formal setting of an after-school club, called the Sustainability Squad, at a secondary school in Milton Keynes. Jones, Blake, and Petrou (2012) provide further detail on the design and conduct of this study. The club ran for 1 hr a week with a focus on the sustainability of food production and consumption. The number of students each week fluctuated (maximum = 30, minimum = 8), as attendance was not compulsory. Two teachers ran the club, overseen by a third. They introduced the broad topic of food sustainability. The children at the club collectively decided to explore how food rots and designed investigations into the rate of food decay. They divided into groups, with each group choosing a different food product and plan of investigation.

Following consultation with the teachers, the research team used large posters that represented Kellett's (2005) think sheet approach to inquiry planning that the students annotated during early club sessions to help them define their own question prior to putting their plans into action at home. Because this was a collaborative room-based activity involving visual design, it was considered more appropriate to use paper rather than computer technology.

Methods. We focused on two of the groups for our study, having secured consent to monitor their progress and outcomes. One group compared the decay of organic packaged, organic unpackaged, and value packaged (i.e., supermarket-branded low-price) bananas kept in one participant's house. The other group investigated cheese stored in a box, in the open air, and in a fridge across three different houses.

During the club, the students also carried out a 20-min inquiry into packaging in which they inspected boxes with value, organic, free range, and locally produced eggs and voted on which eggs they thought would taste the best. The teachers then cooked the eggs and the students observed their appearance (consent issues meant that they could not taste them). Other activities included watching YouTube videos concerned with food production. The students also had the opportunity to create interview questions within nQuire to ask family and friends at home about food sustainability issues.

Their conversations during the club sessions were video-recorded and transcribed and field notes were taken. In addition, we have drawn on interviews with students, parents, and teachers about their experiences participating in, or supporting, the inquiry activities as well examination of the log files of text that the students typed into nQuire.

RESULTS AND DISCUSSION

How Was the Personal Inquiry Approach to Curriculum-Related Science Investigations Adopted and Orchestrated by Teachers and Learners?

Adoption of the technology by students. In both studies, the critical incident analysis, the teacher interviews, and the log files showed no substantial usability problems with pupils operating the devices in school or at home, despite the small keyboard and screen and the Linux operating system. However, some minor technical issues were observed in the studies. It was noted that nQuire running on netbook computers had a slow speed of response compared to some home computers, but this did not seem to substantially inhibit its use. The critical incident analysis by the three reviewers of videos captured in the nature reserve and classroom during the noise pollution study identified 51 notable incidents, of which 44 were agreed to be breakdowns in routine activity and the remainder categorized as breakthroughs. The main category of incident (30 instances) was "minor technical problem." Examples included a temporary loss of Internet connection and the teacher's lack of familiarity with the nQuire interface. The technological aspects were summed by one teacher [NP[2]] as follows: "The good moments were that [. . .] the students could easily access the computers, they didn't find it difficult to work them, or they didn't seem to find it that complicated."

Ownership of the technology. Ownership was a central issue of technology adoption by the students, mentioned repeatedly in the interviews. Students were able to distinguish ownership of the data from ownership and use of the physical device on which results were stored, but they sometimes needed help to do so. In the teacher interview that follows, the researcher refers to a breakdown in which students were working in class on a computer they had borrowed temporarily because a pupil had left the loaned computer at home.

> Researcher [NP]: They were working together there and they were using one of the computers that—they hadn't got one of their own so they made the document and then they called me over and said, "What do we do? This isn't our computer, it's not going to be here next week. What can we do about it?" I said, "You can upload it

[2]Quotations are extracted from interviews with individual teachers or focus group interviews with pupils. NP refers to the noise pollution study and SS to the Sustainability Squad study.

> and save it on the toolkit" and so I showed them how to do that and they uploaded it and saved it but I was impressed that they were proactive enough to ask and not just go "whatever."
>
> Teacher: Yes, they bothered about the ownership.

In interviews, students often referred negatively to their inability to connect the netbook running the Linux operating system to the Internet at home and the lack of games or entertainment software. Here, constraints of the technology may have brought immediate benefit by restricting its use to the task at hand. But it is necessary to balance short-term focus on the task against long-term issues that might arise from young people having to own and operate different computer tools for work and leisure, reinforcing a conception of schoolwork as separated from informal social learning outside the classroom.

Adoption of the technology by teachers. From the teachers' perspective, they were required to introduce each pupil to the possibility of learning with new personal technology, alongside the constraints of adapting their teaching to accommodate a method of personally meaningful inquiry learning that connected learning within and outside the classroom. In particular, the teacher needed to manage a combination of student-with-technology through the phases of inquiries that started in the classroom, continued outside, and concluded back in the classroom. That the technology introduction was successful (as indicated by a lack of any major usability problems identified from the critical incident analysis and observer notes) may be due to a combination of ease of use of the equipment, willingness of the teachers to engage with new technology, competence of the students, and availability of a technical team to offer support.

Adoption of the pedagogy. There is evidence that the Nottingham teacher adopted the pedagogy of personally meaningful inquiry into the school curriculum. For example, she created a modified version of the inquiry diagram as a permanent classroom display to illustrate the inquiry process and frame discussion in science lessons (see Figure 6).

An interview after Lesson 6 of the noise pollution study indicates how the teacher had begun to adopt the scripted inquiry phases to coordinate classroom activity:

> Researcher [NP]: Did you find yourself being able to support the pupils using the technology?
>
> Teacher: Yes, I think now I feel more confident that I can find them. . . . If you know what phase you're on, then you're all right. And maybe it's making sure that titles are obvious [as to] what things are, on the toolkit, making sure those are obvious for the children to easily tell it's this one, this one.

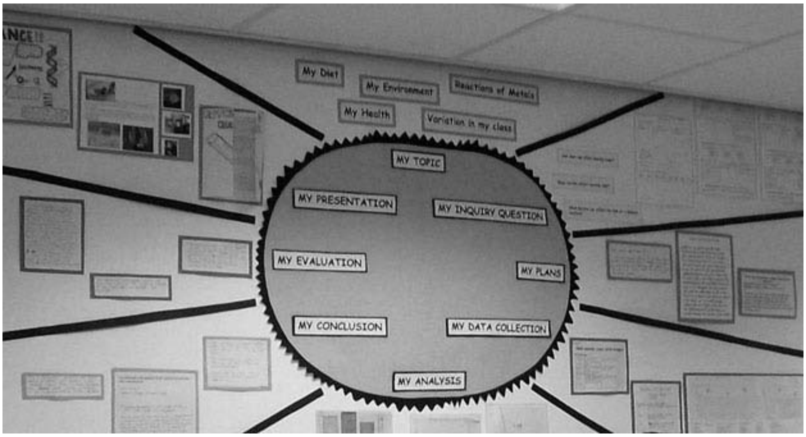

FIGURE 6 A depiction of the inquiry framework designed by the teacher, displayed on the classroom wall.

The teacher also indicated that the children had successfully appropriated the pedagogy alongside the technology.

> Teacher [NP]: . . . they were measuring it, that was their data and no one else in the school was doing it. It was a unique trial and I think they understood why the feeders had been put in the places that they had done. I think that the study made sense to them.

Orchestration of the inquiry activity. A critical incident analysis of the noise pollution inquiry identified six negative classroom orchestration incidents, most due to the children being overoccupied with their computers and ignoring the teacher's instructions. Six further pedagogical incidents related to children being confused about what activity to perform next or to the teacher failing to exploit a learning opportunity.

A particular problem faced by the teachers was in lessons in which the results from investigations conducted outside the school had to be integrated back into the classroom activity. Not only were there technical breakdowns with merging and sharing data, but the teacher needed to improvise the teaching around the emerging findings. She did that by organizing the students into groups, asking them to share and discuss their data in relation to their hypotheses, then having each group present its findings to the class. Such disciplined improvisation presents a challenge to a teacher to build a teaching session around the students' experience (Sawyer, 2004).

In summary, our interviews with teachers and students showed that they were able to adopt the netbook technology and nQuire software in school settings, outdoors, and at home despite minor technical difficulties. But it would not be feasible for a school to provide such special-purpose devices, so ownership and configuration of technology for inquiry learning is an issue to be explored. Our personally meaningful inquiry method was also adopted and understood by both teachers, with the teacher in the noise pollution study producing a poster of our inquiry process for use in science lessons throughout the year. The teachers and students understood and appropriated the pedagogy of personally meaningful inquiry, but orchestrating the activities placed additional demands on the teacher, especially in merging, interpreting, and integrating data collected by the children into a coherent classroom lesson.

How Did Engaging in the Scripted Personally Meaningful Inquiry Influence Children's Science-Related Activity and Attitudes Toward Science?

Progression through the inquiry cycle. The diagram shown in Figure 1 depicts the inquiry process as nonlinear, with links or dependencies between phases. Its presentation as both an interactive visual display and a to-do list on the computer screen was designed to guide users in a progression through the eight phases while indicating possibilities to revise questions (or hypotheses) and measures. To find out whether the children did revisit earlier phases, we examined the computer log files for each of the groups in the Sustainability Squad study (six groups in total, including the two that were the focus of detailed study). This study had the least teacher direction and so provides the best indication of whether learners went beyond the linear sequence of phases in following the science inquiry process. Of the six groups, three returned to revise their hypotheses after they had inputted proposed measures. Of these, the first group just made changes to the spelling of the question; the second added an additional hypothesis; and the third made six revisions over 4 weeks, changing the decaying fruit from peaches to bananas, then forming more precise and testable hypotheses and rationale.

Science activity outside the classroom. An important benefit of the nQuire technology is that it set up complementary sites of inquiry, with the classroom as a location for framing the problem and analyzing results and the home or outdoors as a place of investigation. The opportunity for learning through activity outside the classroom was explored by devising inquiry topics that did not have predicted outcomes and by having the children collect data individually and then compare results to discuss inconsistencies. One teacher [NP] said, "I think it's quite nice when you don't know what the outcome of something is going to be and things aren't obvious."

During the Collect My Evidence phase of the noise pollution inquiry the teacher examined data that the pupils had collected in the school grounds and discussed how they appeared to contradict the initial hypothesis. The participants went out into the grounds to recheck their findings. Similar checking points were added during the inquiry so that unexpected findings might become opportunities for learning. In this study, the data students collected from locations in the school grounds contradicted their initial expectations by indicating that more food was eaten from containers in noisy areas. After further observation, the pupils found that a greedy pigeon was eating large quantities of the bird food and, unlike smaller birds, it appeared to prefer the noisy location. The computer log files show that most participants were able to provide explanations that might account for the unexpected findings:

> Student log file [NP]: Nothing because the noisy yard had more food eaten but the birds where [*sic*] mainly pigeons which et [*sic*] a lot. Whereas the quiet yard had mainly small birds like sparrows and robins. The quiet yard might of [*sic*] had more visited but they don't eat as much.

A more difficult issue is to learn from inconclusive results. For example, the fair test study of bird feeding conducted in the garden of a member of the research team showed no clear difference in recorded sound levels between the noisy tree where a radio had been placed and the quiet tree. When the results were presented in class, teacher took the initiative to provide feedback on the difficulty of conducting authentic experiments.

> Teacher [NP]: Unfortunately, I think the results we got in practice will have just confused them more . . . if it had been set up so that one tree was a lot noisier than the other, then I think we would have got certain results and I think that would have just helped to embed some of the learning, but because—it was difficult to explain on a lot of levels, wasn't it? And you could just say, "We didn't find anything out" but it wasn't because any of their ideas were wrong, it was just because we hadn't been able to implement their ideas properly.

The software enables evidence to be evaluated in the field. Where a wireless Internet connection is available, data from other students appear whenever they are entered and can be viewed as graphs or charts within the Analyze and Represent My Evidence phase to show trends or outliers. However, the nQuire software does not provide immediate feedback. Missing or incorrectly entered data might only be identified back in the classroom, requiring another round of data collection. Because the home activities are beyond the supervision of a teacher, it would require a sophisticated intelligent tutoring system to diagnose immediate problems in data collection or measurement. Instead, this was addressed by providing immediate visual representations of the data as bar charts or scatterplots to reveal outliers or missing data. When data were missing, the teacher turned this into a discussion on the need for reliable data collection.

> Teacher [NP]: And the lessons learned with collecting data, those groups have to go out and make some more measurements. I think some of them—was it last lesson when they were turning round "Why haven't you done that?" and then you're "Whoa" but they realize the value of doing that properly.

This places an onus on the teacher to respond quickly to uncertainties and opportunities during the classroom lesson following the out-of-school activity, when pupils may return with inconsistent or missing data, unexpected findings, or broken equipment.

Attitudes toward science. An aspect of learning to be a scientist is whether students identify with the process and outcomes of their investigation. A quote from an interview with a parent indicates identification with the topic of sustainability:

> Parent: I tell you one thing, whenever we go anywhere, and anybody says do you want a bag, [my daughter] says no.
>
> Researcher [SS]: Is that new [since she has been attending the club]?
>
> Parent: Is it new? Yes . . . if we go to any other shops, [my daughter] now wants to take any bags we have at home . . . and today we went shopping, in [a card shop], and they asked if we wanted a bag, and I said no. It's obviously rubbing off somewhere.

The pupils also contrasted the compulsion of work in class with the freedom and personal control over the technology and the experimental process outside:

> Students (intermingled voices) [SS]: in school you have to learn, but when you choose to do something it's meant to be a bit fun . . . In normal lessons you are just copying off the board into your books . . . here you get more freedom . . . one of the best things about doing the experiments at home was that we did it for ourselves.

For the Sustainability Squad, the participants undertook their own fair test studies (unlike those for noise pollution, which for practical reasons had to be carried out in the garden of a researcher) to examine change in observed variables (color, smell) over time. One group, for example, investigated the visual decay of packaged versus unpackaged and organic versus value bananas to test its prediction that packaged organic bananas would last the longest because these were better quality products and the packaging minimized damage during transportation. There is evidence from interviews that some of the pupils developed skills to argue from evidence and that the activity resulted in increased awareness of relations between local decisions and broader environmental and scientific issues:

> Student [SS]: We're more sustainable now. We don't buy bananas in packaging . . . when you go into a shop you just buy what's best for your budget, people don't think about the packaging and how far it's travelled, they just think about what suits them . . . think before you buy.

Thus, there are indications from the interviews that some participants learned to become more like scientists in adopting scientific methods into their daily lives.

Children's inquiry skills. We also conducted a pre-/postintervention test of the participants' changes in scientific inquiry skills as a result of engaging in the activity, including their ability to select appropriate methods, assess the reliability of evidence, interpret results, and draw appropriate conclusions. In this study we used the Inquiry Comics instrument described earlier.

The test was administered to the intervention class for the noise pollution study and to the nonintervention control class. Because of absences from school, some students missed either the pretest or posttest, and so data are included only from students who took both tests, resulting in 28 students from the intervention class and 15 students from the control class. The written responses were analyzed by two independent markers blind to condition and time, using a hierarchical coding scheme devised by the researchers. Each response was first classified as correct or incorrect, then a code was assigned to indicate whether the response correctly indicated the inquiry conception being tested, and lastly a mark between 1 and 3 was given for the depth of insight shown in the written response. For example, when the character decides to collect data about spiders from a shed when he cannot get access to attics (where the rest of the data are collected), typical responses that were scored as incorrect included "Yes because more spiders are found in a shed than an attic" and "Yes because you can try it in more then one place," as they showed no sensitivity to systematicity in data collection. In contrast, the response "No because it is a different place not in a attic where [*sic*] all the others were it makes it a not fair test" was coded as correct and given the maximum score of 3. Any disagreements in scores were resolved by discussion.

As can be seen in Table 1, there were significant differences in prior inquiry skills between the two school classes (accuracy, $t = 2.52$, $p < .02$; insight, $t = 2.53$, $p < .015$). Consequently, analysis by analyses of variance is uninterpretable, and the sample size precluded the use of hierarchical linear modeling. We can report that the intervention group significantly improved its accuracy scores over time ($t = 2.31$, $df = 27$, $p < .05$) and tended to increase its insight scores ($t = 1.73$, $df = 27$, $p < .1$) whereas the control group did not (accuracy, $t = 0.60$,

TABLE 1
Mean (*SD*) Accuracy of Inquiry Knowledge and Depth of Insight by Time and Condition

	Accuracy/12[a]		*Depth of Insight/36*[b]	
Time	*Intervention (*N = *28)*	*Control (*N = *15)*	*Intervention (*N = *28)*	*Control (*N = *15)*
Pretest	8.11 (2.30)	6.00 (3.14)	14.11 (6.15)	9.27 (5.61)
Posttest	9.25 (1.69)	6.53 (2.92)	16.25 (4.90)	10.2 (5.56)

[a]Out of a maximum score of 12. [b]Out of a maximum score of 36.

df = 14; insight, $t = 0.93$, *df* = 14), but we cannot conclude with certainty that the improvement for the intervention group was due only to the effects of the intervention.

To summarize, children and teachers in both studies collaborated on framing inquiry questions, and children were actively involved in proposing topics of personal meaning. The children mostly progressed in a linear way through the eight phases of the inquiry process, but an examination of the computer log files for the six groups in the Sustainability Squad study showed that three groups returned to revise their hypotheses after they had inputted proposed measures. In the data collection phase, the children gathered authentic data at home or in the playground, and the teachers in both studies guided them to interpret their data, understand the consequences of missing items, and discuss unexpected findings.

Evidence of the ability to do science inquiry came from classroom observations of the noise pollution study, which showed that although the children had produced findings that were contrary to their initial hypothesis, some were able to provide an appropriate explanation for the data. This is supplemented by evidence from log files in which children accounted for the unexpected findings and from an interview with the teacher.

We have evidence from interviews that some of the students gained increased awareness of issues related to sustainability. We also saw from classroom observations that children were engaging in scientific methods, including framing appropriate questions, planning investigations, selecting measures, and collecting and comparing data. But we have no evidence that these resulted in lasting change in attitudes to science or in the adoption of scientific methods in students' everyday lives. A controlled test of the children's scientific inquiry skills showed that students in the intervention group made a significant improvement in the accuracy of their decisions from pretest to posttest.

CONCLUSIONS

We now return to the five concerns that were introduced at the start of the article. We have shown how a process of codesign of technology and pedagogy, in partnership with two schools, was instantiated in a representation of the inquiry process and implemented in the nQuire toolkit, which enables a teacher or instructional designer to create scripts that structure the progress of learners through inquiry phases and provides relevant tools and activities for each phase. The phases can be organized by the teacher into time periods, and the software can allocate learners to individual or group activities, enabling sharing of data. The nQuire toolkit has been developed further since this project ended to support self-directed online learning, and the latest version can be accessed at www.nquire.info.

The teacher has a central role in helping learners to frame inquiry questions, select appropriate measures, and plan their investigations. The lesson that integrates data collected outside the classroom and supports the pupils in sharing and interpreting findings is particularly demanding, and if this method of personally meaningful inquiry learning is to be more widely adopted, then teachers will require professional training and development to manage the new pedagogy.

The clearest indication of appropriation of the technologies as tools for learning, from observations and interviews, was that the participants were able to engage in a pattern of learning in which they started in the classroom under the guidance of a teacher; then continued at home or outside, guided by the phases of scripted inquiry on nQuire; and then integrated their findings into a subsequent classroom lesson, repeating this process through one or more iterations. No substantial problems were reported with operating the equipment or engaging with the computer representation of phased inquiry. The teacher at the Nottingham site expressed concern at having to cope with new releases of the toolkit, but the lessons were never abandoned through technical failure. The main concern of the teacher was to refocus the attention of pupils away from their computer screens.

As regards the conduct and experience of scripted inquiry learning, the setting of an after-school science club allowed the teacher and pupils to work as coinvestigators, constructing fair test experiments that could be undertaken at home without the constraints of curriculum and individual assessment. The research project was able to provide technical support in scripting these investigations for the nQuire toolkit.

The participants successfully conducted a range of scientific explorations, including fair test experiments at home, with multiple observations over time, to compare the decay of food; comparison studies in the school playground to explore microclimates and to examine the effect of noise on bird feeding habits; observation and recording of bird habitats in a nature reserve; systematic collection of data on daily meals and their content; and e-mailing questions to a nutrition expert.

For the noise pollution study, some participants experienced difficulty in integrating findings from multiple studies and in interpreting inconclusive results. The interviews and log files indicated that most pupils could construct an explanation of findings that countered an initial hypothesis, providing the explanation was observable and compelling (e.g., "A pigeon ate most of the food and it isn't affected by noise"). More difficult is accounting for inconclusive results. These might arise from technology problems (e.g., low signal-to-noise ratio in the measuring equipment), small sample size, inaccurate data, or incorrect analysis. Or the study may be well designed but show no significant differences between conditions. Finding and overcoming inadequate or inaccurate data, and interpreting whether a hypothesis has been falsified, are essential aspects of being a scientist, but these take time and skill to acquire. Young people may be left with feelings of confusion that confirm their views of science as being vague and unsatisfying.

As with many educational innovations, there are no straightforward conclusions as to whether scripted inquiry learning changed the young people's inquiry skills and attitudes to science. We have no evidence that young people came to identify more strongly with science and scientists as a result of engaging with the inquiry activities. It is difficult to change young people's attitudes toward a profession by modeling its practices and even more difficult to alter behavior. However, interviews with the pupils after the Sustainability Squad sessions did suggest that after exploring food decay and packaging some young people had changed, or persuaded their parents to change, their buying habits in supermarkets.

The wider issues of altering attitudes to science might be addressed by embedding inquiry practices within a science curriculum that encourages empathy with scientific practices and builds a broad understanding of science and society. Knowledge about topics in health, environment, and society that affect us all must be built by engaging in rational debate and making informed choices among contested sources of evidence. The program of research reported here suggests that if they are to realize their personal potential, learners need to participate in a variety of critical scientific activities that enable them to make appropriate connections between everyday experiences and formal education. New technology could assist this process by offering a set of interconnected tools to shape the ways in which learners make meaning and develop scientific understanding.

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REFERENCES

Anastopoulou, S., Sharples, M., Ainsworth, S., Crook, C., O'Malley, C., & Wright, M. (2012). Creating personal meaning through technology-supported science inquiry learning across formal and informal settings. *International Journal of Science Education*, *34*(2), 251–273.

Anastopoulou, S., Sharples, M., Wright, M., Martin, H., Ainsworth, S., Benford, S., . . . O'Malley, C. (2008). Learning 21st century science in context with mobile technologies. In J. Traxler, B. Riordan, & C. Dennett (Eds.), *Proceedings of the mLearn 2008 conference: The bridge from text to context* (pp. 296–303). Wolverhampton, England: University of Wolverhampton.

Anastopoulou, S., Yang, Y., Paxton, M., Sharples, M., Crook, C., Ainsworth, S., & O'Malley, C. (2010). Maintaining continuity of inquiry learning experiences across contexts: Teacher's management strategies and the role of technology. In M. Wolpers, P. A. Kirschner, M. Scheffell, S. Lindstaedt, & V. Dimitrova (Eds.), *Sustaining TEL: From innovation to learning and practice. Proceedings of 5th European Conference on Technology Enhanced Learning, Barcelona*, *Spain*, *September/October 2010* (pp. 17–29). Heidelberg, Germany: Springer-Verlag.

Barab, S., & Squire, K. (2004). Design-based research: Putting a stake in the ground. *Journal of the Learning Sciences*, *13*, 1–14.

Bell, P., Reeve, S., & Zimmerman, H. T. (2007, August). *Understanding children's everyday science learning through analysis of home science kit activity*. Paper presented at the European Science Education Research Association annual meeting, Malmö, Sweden.

Bell, T., Urhahne, D., Schanze, S., & Ploetzner, R. (2010). Collaborative inquiry learning: Models, tools, and challenges. *International Journal of Science Education*, *32*(3), 349–377.

Board on Science Education. (2012). *A framework for K-12 science education: Practices, crosscutting concepts and core ideas*. Washington, DC: National Academies Press.

Bruce, B. C., & Bishop, A. P. (2002). Using the Web to support inquiry-based literacy development. *Journal of Adolescent & Adult Literacy*, *45*(8), 706–714.

Chen, Y. S., Kao, T. C., & Sheu, J. P. (2003). A mobile learning system for scaffolding bird watching learning. *Journal of Computer Assisted Learning*, *19*(3), 347–359.

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education*, *86*(2), 175–218.

Collins, T., Mulholland, P., & Gaved, M. (2012). Scripting personal inquiry. In K. Littleton, E. Scanlon, & M. Sharples (Eds.), *Orchestrating inquiry learning* (pp. 87–104). Abingdon, England: Routledge.

de Jong, T., van Joolingen, W. R., Giemza, A., Girault, I., Hoppe, U., Kindermann, J., & the SCY Team. (2010). Learning by creating and exchanging objects: The SCY experience. *British Journal of Educational Technology, 41*, 909–921.

Dewey, J. (1910). *How we think*. Boston, MA: D. C. Heath & Co.

Dewey, J. (1938). *Logic: The theory of inquiry*. New York, NY: Holt, Rinehart & Winston.

Dillenbourg, P., Järvelä, S., & Fischer, F. (2009). The evolution of research on computer-supported collaborative learning: From design to orchestration. In N. Balacheff, S. Ludvigsen, T. Jong, A. Lazonder, & S. Barnes (Eds.), *Technology-enhanced learning* (pp. 3–19). New York, NY: Springer.
Dillenbourg, P., & Jermann, P. (2007). Designing integrative scripts—Scripting computer-supported collaborative learning. In F. Fischer, I. Kollar, H. Mandl, & J. M. Haake (Eds.), *Scripting computer-supported collaborative learning: Cognitive, computational and educational perspectives* (pp. 275–301). New York, NY: Springer.
Dillenbourg, P., & Jermann, P. (2010). Technology for classroom orchestration. In M. S. Khine & I. M. Saleh (Eds.), *New science of learning: Cognition, computers and collaboration in education* (pp. 525–552). New York, NY: Springer.
Driver, R. (1983). *The pupil as scientist?* Milton Keynes, England: Open University Press.
Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences*, *8*, 391–450.
Edwards, D., & Mercer, N. (1987). *Common knowledge: The development of understanding in the classroom*. London, England: Routledge.
Eslinger, E., White, B., Frederiksen, J., & Brobst, J. (2008). Supporting inquiry processes with an interactive learning environment: Inquiry Island. *Journal of Science Education and Technology*, *17*, 610–617.
Etkina, E., Karelina, A., Ruibal-Villasenor, M., Rosengrant, D., Jordan, R., & Hmelo-Silver, C. E. (2010). Design and reflection help students develop scientific abilities: Learning in introductory physics laboratories. *Journal of the Learning Sciences*, *19*, 54–98.
Facer, K., Joiner, R., Stanton, D., Reid, J., Hull, R., & Kirk, D. (2004). Savannah: Mobile gaming and learning? *Journal of Computer Assisted Learning*, *20*, 399–409.
Flanagan, J. C. (1954). The critical incident technique. *Psychological Bulletin*, *51*(4), 327–358.
Forman, E. A., & Ansell, E. (2002). Orchestrating the multiple voices and inscriptions of a mathematics classroom. *Journal of the Learning Sciences*, *11*, 251–274.
Furtak, E. M. (2006). The problem with answers: An exploration of guided scientific inquiry teaching. *Science Education*, *90*, 453–467.
Grandy, R., & Duschl, R. (2007). Reconsidering the character and role of inquiry in school science: Analysis of a conference. *Science and Education*, *16*(2), 141–166.
Hodson, D. (1998). *Teaching and learning science: Towards a personalized approach* (1st ed.). Buckingham, England: Open University Press.
Holtrop, S. D. (2010). *Writing lesson plans: An introductory page*. Retrieved from http://www.huntington.edu/dept_interior.aspx?id=2217
Jones, A., Blake, C., & Petrou, M. (2012). Inquiry learning in semi-formal contexts. In K. Littleton, E. Scanlon, & M. Sharples (Eds.), *Orchestrating inquiry learning* (pp. 192–213). Abingdon, England: Routledge.
Kellett, M. (2005). *How to develop children as researchers*. London, England: Paul Chapman Educational Publishing.
Keogh, B., & Naylor, S. (1999). Concept Cartoons, teaching and learning in science: An evaluation. *International Journal of Science Education*, *21*, 431–446.
Kerawalla, L., Littleton, K., Scanlon, E., Jones, A., Gaved, M., Collins, T., . . . Petrou, M. (2011). Personal inquiry learning trajectories in geography: Technological support across contexts. *Interactive Learning Environments*, *21*, 497–515.
Lakkala, M., Lallimo, J., & Hakkarainen, K. (2005). Teachers' pedagogical designs for technology-supported collective inquiry: A national case study. *Computers and Education*, *45*(3), 337–356.
Latour, B. (1999). *Pandora's hope: Essays on the reality of science studies*. Cambridge, MA: Harvard University Press.
Linn, M. C., Clark, D., & Slotta, J. D. (2002). WISE design for knowledge integration. *Science Education*, *87*, 517–538.

Littleton, K., & Kerawalla, L. (2012). Trajectories of inquiry learning. In K. Littleton, E. Scanlon, & M. Sharples (Eds.), *Orchestrating inquiry learning* (pp. 31–47). Abingdon, England: Routledge.

Littleton, K., Scanlon, E., & Sharples, M. (Eds.). (2012). *Orchestrating inquiry learning*. Abingdon, England: Routledge.

Llewellyn, D. (2002). *Inquire within: Implementing inquiry-based science standards*. Thousand Oaks, CA: Corwin Press.

Looi, C.-K., Zhang, B. H., Chen, W., Seow, P., & Chia, G. (2011). 1:1 mobile inquiry learning experience for primary science students: A study of learning effectiveness. *Journal of Computer Assisted Learning*, *27*(3), 269–287.

Meek, J. (2006). *Evaluation of computer-assisted learning* (Unpublished doctoral dissertation). University of Birmingham, Birmingham, England.

Metz, K. E. (2011). Disentangling robust developmental constraints from the instructionally mutable: Young children's epistemic reasoning about a study of their own design. *Journal of the Learning Sciences*, *20*, 50–110.

Mulholland, P., Anastopoulou, S., Collins, T., Feißt, M., Gaved, M., Kerawalla, L., . . . Wright, M. (2011). nQuire: Technological support for personal inquiry learning. *IEEE Transactions on Learning Technologies*, *5*(2), 157–169.

Pea, R., Milrad, M., Maldonado, H., Vogel, B., Kurti, A., & Spikol, D. (2012). Learning and technological designs for mobile science inquiry collaboratories. In K. Littleton, E. Scanlon, & M. Sharples (Eds.), *Orchestrating inquiry learning* (pp. 105–127). Abingdon, England: Routledge.

Puntambekar, S., Stylianou, A., & Goldstein, J. (2007). Comparing classroom enactments of an inquiry curriculum: Lessons learned from two teachers. *Journal of the Learning Sciences*, *16*, 81–130.

Qualifications and Curriculum Authority. (2007). *Science: Programme of study for the key stage 3 and attainment targets*. London, England: Author.

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., . . . Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences*, *13*, 337–386.

Roschelle, J., & Pea, R. (2002). A walk on the WILD side: How wireless handhelds may change computer-supported collaborative learning. *International Journal of Cognition and Technology*, *1*(1), 145–168.

Sawyer, K. R. (2004). Creative teaching: Collaborative discussion as disciplined improvisation. *Educational Researcher*, *33*(1), 189–201.

Scanlon, E., Anastopoulou, S., Kerawalla, L., & Mulholland, P. (2011). How technology resources can be used to represent personal inquiry and support students' understanding of it across contexts. *Journal of Computer Assisted Learning*, *27*, 516–529.

Scardamalia, M., & Bereiter, C. (1991). Higher levels of agency for children in knowledge building: A challenge for the design of new knowledge media. *Journal of the Learning Sciences*, *1*, 37–68.

Schauble, L., Glaser, R., Duschl, R. A., Schulze, S., & John, J. (1995). Students' understanding of the objectives and procedures of experimentation in the science classroom. *Journal of the Learning Sciences*, *4*, 131–166.

Schwartz, D. L., Brophy, S., Lin, X., & Bransford, J. D. (1999). Software for managing complex learning: Examples from an educational psychology course. *Educational Technology Research & Development*, *47*(2), 39–59.

Sharples, M., & Anastopoulou, S. (2012). Designing orchestration for inquiry learning. In K. Littleton, E. Scanlon, & M. Sharples (Eds.), *Orchestrating inquiry learning* (pp. 69–85). Abingdon, England: Routledge.

Shimoda, T. A., White, B. Y., & Frederiksen, J. R. (2002). Student goal orientation in learning inquiry skills with modifiable software advisors. *Science Education*, *86*(2), 244–263.

Squire, K., & Klopfer, E. (2007). Augmented reality simulations on handheld computers. *Journal of the Learning Sciences*, *16*, 371–413.

Wasson, B., Vold, V., & de Jong, T. (2012). Orchestration of assessment: Assessing emerging learning objects. In K. Littleton, E. Scanlon, & M. Sharples (Eds.), *Orchestrating inquiry learning* (pp. 175–192). Abingdon, England: Routledge.

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

Wong, L.-H., & Looi, C.-K. (2011). What seams do we remove in mobile assisted seamless learning? A critical review of the literature. *Computers and Education*, *57*, 2364–2381.

Wood, D., Bruner, J. S., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of Child Psychology and Psychiatry*, *17*(2), 89–100.