Remote experiments, re-versioning and re-thinking science learning

Eileen Scanlon a, Chetz Colwell a,*, Martyn Cooper a, Terry Di Paolo b

a Institute of Educational Technology, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK
b School of Health and Social Welfare, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK

Abstract

Science and engineering students’ involvement in practical work contributes to the development of their understanding of the concepts and processes of science. The Practical Experimentation by Accessible Remote Learning (PEARL) project aimed to develop a system to enable students to conduct real-world experiments at a distance using a computer. We explored methods of extending the flexibility of laboratory teaching in terms of time and location, and of meeting the requirements of students with special needs. This involved the development of remote experiments at four Universities. This paper uses one of the four experiments, spectroscopy for introductory science in a distance learning setting, to illustrate the process of developing remote experiments. We describe the evaluation work leading to refinement of the design, and an assessment of the learning experience for students. This paper presents the findings of the validation phases of the project which have established the feasibility of the remote experiment approach.

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1. Introduction

Our concern in this paper is to reflect on the provision of practical work in higher distance education. This is informed by our experience of working on the Practical Experimentation by Accessible Remote Learning (PEARL) project aimed to develop a system to provide remote access to laboratory work over the Internet. We describe the rationale for the project and present
a case study of the use of the system in one experimental setting. We present the work carried out to inform the design of the system, and the evaluation work carried out to assess the future utility of such systems.

1.1. Remote and simulated experiments in science learning

Information technology offers a number of ways in which learners’ experiences in science can be augmented. Simulations and multimedia presentations have been demonstrated to provide useful learning experiences in science for many years (see e.g. Ross & Scanlon, 1995). More specifically, simulations have been used to support practical work. Our review of the pedagogical (Scanlon, Morris, Di Paolo, & Cooper, 2002) and technological (Cooper, 2000) requirements for remote experimentation established the potential of providing collaborative working at a distance on simulated, or real, experimental work. There are a number of dimensions on which experiments mediated by technologies can differ. One dimension is real vs. simulated, while another is remote vs. co-located. The distinction between remote experiments and remote simulations is that the former involves the manipulation or control of real apparatus at a distance, whereas the latter involves control of simulations of the apparatus. The trend towards sharing sophisticated instruments on the Internet is growing. Our estimate is that in the four years we have been working in this area the number of remote experiments has tripled (see e.g. Scanlon, 2004). This increased interest in remote working may be related to the developments in collaborative working both by scientists, and between universities. Wulf, for example writes of the modern university.

Some disciplines that do need shared physical facilities – say a telescope – suggest the need of a ‘place’. But large scientific instruments such as telescopes and accelerators are already run by consortia and are shared by faculty from many universities, and many of these facilities do not require the physical presence of investigators. They could be ‘online’ and accessible via the network (Wulf, 2003, p. 20).

For any experiment the sense of reality can be influenced by whether real experimental equipment is being manipulated but also by being remote from the full sensory experience of the laboratory. In some instances, therefore a remote experiment may not reproduce the gestalt of working on real experiments in the laboratory. However a feasible design aim is to use all available means of increasing the impression of “presence”. For example, a video feed from the laboratory can provide a reasonable view of equipment and feedback on the use of controls, but video cannot replace the smells of the chemistry laboratory or the feel of manipulating of a soldering iron.

2. The PEARL project

The aims of the PEARL project were to develop a system to enable students to conduct real-world experiments at a distance, and to assess the educational potential of such a system. Students with disabilities are under-represented in science and engineering in higher education and it was hypothesised that remote experimentation could help to increase their participation in practical work. Underlying our approach is a model of collaborative working in remote experimental work.
In this model feedback to students on their experiences is provided by tutor comments and by working with peers. Our starting point was to explore how current technologies could provide the appropriate technical infrastructure to allow the necessary interactions between students, tutor and apparatus. The pedagogical requirements of the system were established by means of a literature review on practical work, and research on the views of teachers in higher education about their requirements for such systems. The work of the Labwork in Science Education project (see e.g. Psillos & Niedderer, 1998) was invaluable. It provided information on how laboratory work in higher education in science is organised. It was also the source of recommendations for improving laboratory work by clarifying the purpose and the learning objectives of such work. We also found the conversational model developed by Laurillard (1993) helpful in thinking about the interactions between students, tutor and learning environments.

2.1. Range of PEARL experiments and partners

The design of the PEARL system was reported in detail in Colwell, Scanlon, and Cooper (2002). In brief, it includes network, server, and interface technologies, equipment control and streaming media technologies, and video cameras. Collaboration tools are also included for some of the experiments (described below). Students can conduct experiments in the remote laboratory from their computer. They can see the laboratory equipment being controlled via video feeds, and can communicate with their peers about doing the experiment. The system thereby allows students to collaborate remotely while conducting experiments, which is a significant development on current distance learning models.

Experiments were developed at four universities, the University of Dundee (UD), Trinity College Dublin (TCD), the University of Porto (UP) and the Open University (OU). These offered activities for students at different levels in different disciplines. In each case there were particular advantages in the remote version of the experiment over the laboratory-based experiment. At UD third year undergraduates in cellular biology were shown samples by a lecturer who demonstrated the use of an electron microscope to investigate the content and behaviour of biological cells. The PEARL system allows students to use the microscope themselves, remotely. At TCD students investigated and programmed a computer based vision inspection system. This was of a type used in the automated inspection of printed circuit boards in a manufacturing plant. They set up and controlled cameras, lighting heads, lenses and computer vision processors in a laboratory at the University. With the PEARL system they can do this remotely, thus enabling practical work in manufacturing engineering courses to be offered at a distance. At UP first year undergraduate students use a digital electronic bench to design and test digital circuits. These are implemented on programmable integrated circuits and students submit their designs and then tested them. This experiment is integrated with a web based course and conducted remotely via the PEARL system.

The OU has a long history of teaching science at a distance. At the OU experiments are mostly performed at residential schools in traditional laboratories. The experiment we chose to implement was part of an introductory science course. In this experiment students carry out flame tests, use optical spectrometers and colorimeters in the analyses of substances. They use this apparatus to make and record observations, and analyse and interpret data. The PEARL system allows students to work in pairs and to communicate with each other and their tutor while working
together at a distance. We were interested in the feasibility of providing laboratory experiences for students who were unable to attend residential schools. Examples include students with caring responsibilities and students with disabilities. We examined the effectiveness of this approach by conducting validations of these developments in different higher educational contexts and subject areas in science. In this paper we will focus on the OU experiment as a case study to illustrate the processes we went through in the development and evaluation of the remote experiment approach.

2.2. Re-versioning of the OU experiment for remote implementation

The experiment consists of a set of tasks that offer an introduction to the physics of light spectra, and their use in chemical analysis. In the first activity students examine the different responses of four chemicals when placed in a flame. This flame test procedure comprises three main steps: cleaning a nichrome wire using hydrochloric acid and a Bunsen flame; dipping the clean wire into the acid and then into the salt and introducing the wire into the hottest part of the flame. Students then observe the flames with both the naked eye and a hand-held spectroscope.

The original intention was to implement the flame test activity as a remote activity but we did not find a cost-effective robotic solution to what is actually a relatively simple procedure. Instead, a series of video clips were produced, which demonstrate the flame test procedure described above, including the view of the flames through a spectroscope. The clips were embedded in web pages, which outlined the purpose of this part of the activity, and provided the student with details of how the procedures would be carried out in a laboratory.

In the second activity, students set up and calibrate the grating spectrometer and then perform two experimental tasks. In the first task, the students observe the spectral signature of a sodium lamp. In the second task they identify unknown metal ions by observing their spectral signatures in flames. These tasks are linked to the key learning objectives of the experiment, i.e. appreciating that there are qualitative and quantitative differences between light spectra.

Although the intention was to make the remote activity exactly the same as the laboratory activity we found that this was not feasible and two aspects of the setup and calibration were not implemented for remote control. Firstly, the focusing of the spectrometer telescope was not implemented because this required the telescope to be pointed at a distant object and this was difficult to automate. Secondly, the insertion of the diffraction grating into its mount proved to be too costly to automate. The focusing of the telescope and the insertion of the grating do relate to another objective of the task: that students become familiar with setting up and the operation of the spectrometer. However, it was decided that the telescope should be focused and the grating inserted in advance by a technician, and that the students should be given additional written information about the setting up and operation of the spectrometer in the labscript. It was thought that these were acceptable alternative methods for the students to achieve this objective because they were not central to the main activity. The key issue here is that the process of implementing the remote activity resulted in a number of changes to the activity.

It can be difficult to clearly establish the aims and objectives of practical work. We were able to use the survey conducted by Millar, Le Maréchal, and Tiberghien (1999) of science educators of
the learning objectives commonly associated with university level practical work. A number of common objectives were identified: some involving the process of doing experimental work; some linked to the conceptual content of the practical work. We combined these common objectives with an analysis of the activity to be carried out with the flame tests and spectrometer.

2.3. The remote controlled spectrometer

The spectrometer was adapted for remote operation by the fifth project partner, Zenon SA (Greece). This is shown in the annotated photograph in Fig. 1. The adaptations included control of the collimator focus and slit width, and the position of the telescope. The spectrometer was mounted on a movable table which was in turn mounted on a platform. Also mounted on the platform were the two light sources (sodium lamp and Bunsen burner) and three solution containers (through which air was bubbled before being blown through the Bunsen flame). Collectively, the platform, movable table, light sources and bubblers are referred to as the 'spectrometer jig'. For the student trials, which are described in the following sections, the spectrometer jig was located in a laboratory on campus, which was remote from the students' location.

To support the remote operation of the jig, two video cameras were attached to the spectrometer. One was attached to the telescope eyepiece to transmit the view through the telescope. Another was mounted above the Vernier scale that gave the angular position of the telescope, to allow the scale to be read remotely. (For the main validation trials a third camera was located in the laboratory to provide the students with an overview of the whole spectrometer jig.) The user interface (UI) application which was developed to enable students to control the spectrometer remotely is shown in Fig. 2. The UI included buttons for controlling the different parts of the spectrometer jig, and displayed the feeds from the video cameras attached to the spectrometer. It was designed to be easy to use, and accessible to students with disabilities.
3. The validation phases of the project

There were two phases in the project’s lifecycle in which evaluation activities were undertaken. Firstly, an interim validation was carried out during the technology development phase. In this phase prototypes of the remote experimental activities were tested to ensure that the educational and remote experiment facilities were in place, and that the design of the remote system was workable. The tests also examined the usability of the user interface design. Secondly, the main validation was conducted when the system was complete, and assessed the effects of undertaking the experiments remotely on students’ learning experience.

At both stages a number of student trials were conducted with the experiments at all four Universities. At the OU 12 volunteer students took part; six in each validation phase. This number allowed us to focus in detail on the video records of their interaction with the system. Their experiences were compared with those of a group of students who were observed and interviewed when they performed the light spectra experiment at the residential school the previous summer.
3.1. Interim validation

The aims of the interim validation trials (conducted January–May 2002) were to:

- Validate the technical aspects of the system: establish that the equipment could be controlled remotely via the user interface application, and that the video was transmitted from the laboratory,
- Evaluate the usability of the user interface, i.e. the extent to which students found it easy to use,
- Evaluate the effectiveness of the labscript in guiding students through the task.

At the OU six students took part in these trials (three male, three female; average age 28 years), who were drawn from the population of PhD students studying natural sciences.

The students conducted the experiment in pairs, as they would have done in the traditional laboratory. They were located in separate rooms to simulate working together online from home. The students communicated with each other using the video conferencing facility of Microsoft NetMeeting in conjunction with web-cams and headsets, which allowed them to see and hear each other. A tutor was located in the laboratory with the spectrometer jig to assist the students when necessary. The students used the text chat facility of NetMeeting to communicate with the tutor. The students worked through a paper based labscript that directed them through the activities. Each pair took approximately one hour to complete the task. The system allowed more than one student to operating the spectrometer at the same time, and therefore they had to negotiate who was to have control and take turns. Each student was observed by one of three evaluators who made notes on any problems experienced by the students, or with the software. 1

A questionnaire, interview schedule and video records were used to collect data. The questionnaire collected data on the students’ opinions on using and learning with the PEARL system (its usefulness, how easy it was to learn how to use, and attitudes towards using the system) and the use of the collaboration tools. The interview schedule covered students’ opinions on their experience of performing the activity remotely, the usability of the controls, and the utility of the video feeds. The video records allowed observations of the students’ actual use of the system.

3.1.1. Results of interim validation

Overall the students were able to successfully conduct the remote experiment and the students’ response to the system was generally positive. They reported that they enjoyed doing the task and found it interesting. They found the collaborative aspect useful and the collaboration tools usable. The students found that the ‘affordance’ of the user interface controls and their ‘ease of use’ could be improved. Most students found the quality, size and detail of the video feeds acceptable, although the video feed needed to be improved for reading the Vernier scale. The students found that the written instructions were adequate, although there were some suggestions for additional information. Half the students had used a spectrometer before, but none had done this particular task before. Most of the students said they were either “very” or “fairly” confident that having done this task they could use the equipment in a laboratory in future. When students reported that they encountered problems using the system they believed these to be negligible and could

1 The evaluators agreed in advance as to the types of issue that should be noted. The observation data was intended to complement that from the interviews and to serve as an overview of the student session and therefore a formal observation schedule was not required.
overcome them easily. The two key findings from these student trials in relation to the remote control aspect of the experiment were (a) a need for additional feedback on what was happening in the laboratory; and (b) that confusion sometimes occurred caused by delays between initiating an action in the laboratory and the execution of that action.

As a direct result of these findings of the interim trials, a number of changes were made to the user interface, including the provision of:

- A third video camera to provide an overview of the laboratory,
- A facility for changing the size of the video feeds to allow students to see more detail when required,
- Additional feedback on the progress of commands using visual progress bars, auditory feedback, and a status field.

3.2. Main validation

The main validation of the system was conducted in December 2002. The main aims of this validation phase were to examine:

- How the experience of conducting the experiment remotely impacts on students’ learning and motivation,
- How this experience compares with traditional laboratory work and simulations,
- The opinions of students with disabilities on the accessibility of the user interface and the remote experiment experience,
- The views of academics on the potential of the system.

We compared the experiences of students using the system with those of students who had been observed and interviewed at a residential school the previous summer. Our original intention was to conduct a fairly direct comparison of the experiences of those using the PEARL system with those of residential school students. However, as noted above, changes to the activity were made in the process of making it available remotely, and this should be borne in mind when comparing the responses.

Six students (one female and five male; average age 35 years) were observed using the modified spectrometer jig, under the same conditions as described for the interim trials. Three of these students were registered with the OU as having a disability; two had mobility impairments, one had a hearing impairment. An interview schedule was used to collect data in relation to the above aims of this validation phase, and the sessions were video recorded.

3.2.1. Results of the main validation

The responses of the students who conducted the experiment remotely (referred to as the PEARL students) were compared with those of 12 students who attended the residential school and performed the experiment in the laboratory (referred to as the residential school students). In general, both groups reported that they enjoyed the activity, particularly doing or viewing the flame tests, and using the spectrometer to measure wavelengths. In addition both groups found the task of locating the spectral lines rather frustrating. Further findings are presented below in terms of three aspects of the student experience: how they managed the tasks; what evidence we had of their learning; and the extent to which the UI was accessible to students with disabilities.
3.2.2. Managing the tasks

A number of management aspects were considered: completing the tasks in the allocated time; the role of the tutor; working with another student; and working in a laboratory. The residential school students felt they had enough time to carry out the task whilst the PEARL students felt they needed more time, mainly because of the extra time needed to communicate with their partner. Both groups of students were positive about the role of tutor and about working in pairs. One disadvantage identified by the PEARL students of working in a pair was disparity in skill and rate of reading/comprehension. However this could also be the case when working in pairs in a laboratory. The residential school students enjoyed the experience of a larger support network of students in the laboratory.

One significant way in which the groups differed was that some PEARL students felt they could have benefited from clearer instructions and more help from the tutor. Our decision to provide only text chat communication between the students and tutor may have been responsible for this response. Interestingly some students held the view that they preferred the tutor to be at a distance.

3.2.3. Learning outcomes

Both groups of students were asked to consider how the activity related to the objectives that we had identified from Millar et al. (1999) and our own analysis. They were also asked about their perceptions of how far they had achieved these objectives. While both groups of students had learnt how set up and use laboratory equipment involved, both groups also had some gaps in their achievement of the other objectives. Both groups of students reported that they had learnt a key objective of the activity (that elements have differing spectral signatures) but both groups were less clear on understanding the grating relationship (the mathematical relationship between the angle at which the spectra were observed and their wavelength). More PEARL students than residential school students were able to comment on the expected outcome of becoming familiar with spectral lines. The PEARL group took longer to complete the task than students in the conventional laboratory, partly because of the need to communicate with their partner about what to do. Several students from both groups had reservations about whether the system could fully replace the traditional laboratory experience if they were to achieve all the objectives. However, all the students were convinced that remote experimentation was more effective than working with a simulation. One student commented:

I think this is better [than a simulation] to be honest with you. . . because it’s actually happening. I know it’s hard to explain, but I know what I mean. When you’re doing it on CD, it’s doing what it’s supposed to be doing isn’t it.

3.2.4. Accessibility

The three students with disabilities found the user interface was accessible to them. They all thought that the PEARL approach would be useful for those people who cannot attend a residential school. One student said:

I definitely see a place for it for people that cannot do their residential schools and can’t do the hands-on. It’s a good substitute . . . at least you’re doing something. You’ll never replace the hands-on but as I said it’s a good substitute.
However, the students with mobility impairments said that students with disabilities should still be encouraged to attend residential schools and be supported at them. In addition, the hearing impaired student said he thought the PEARL approach was excellent for supporting those aspects of a residential school that are difficult for deaf students, such as communication. This student said:

Had it [the PEARL system] been available I might have opted not to go on the residential course.

3.2.5. Future prospects

As part of the main validation we also explored the future potential of the PEARL approach with academics. Two focus group discussions were organised which involved 15 staff who taught science and engineering at a number of Universities. One group concentrated on the potential advantages of remote experiments from the students’ perspective. The second reviewed the type of practical work that might be suitable for remote implementation. Both groups were enthusiastic about the prospects for remote experiment systems but were also concerned about the resources necessary to invest in such systems. In addition, the participants expressed concerns about the lack of physical handling of equipment, particularly for those students who wish to have a career in science of engineering. One participant commented:

The student who wants to work as a chemist needs more hands on than people who need to learn principles.

The academics appreciated that the system could allow experiences to be offered that would otherwise be unavailable, and the motivating effects of this for students. The group identified several aspects of practical work which lend themselves to remote implementation. These included the development of basic observation skills, data collection and recording skills, and process skills, and areas where health and safety is an issue. Aspects that were identified as not necessarily suitable for remote implementations included some subjects in chemistry, and subjects where video cameras would not be able to provide a sufficient image or view of an artefact.

3.2.6. Conclusion on the main validation

The validation trials found that students were able to use the remote laboratory with a partner to demonstrate their ability to use a spectrometer and to achieve the learning goals set for them such as measuring the wavelength of spectral lines, and processing data. Our findings from the small sample of students suggest a real potential and opportunity for remote experimentation to provide an alternative to practical work in the traditional laboratory setting. This potential has also been reported by academics to whom we have demonstrated the system.

4. Conclusions

In the PEARL project we were seeking to establish the feasibility of the remote experiment approach and to establish what kind of learning experience is offered by the four remote experiments. We developed the idea of practical experimentation based on a model of collaborative working based round experimental work in a remote laboratory setting with feedback to students on their experiences provided by tutor comments and peer interaction. Our experiences, reported
here in relation to one of our experiments, demonstrated this approach is feasible and workable. The findings of the validations at the three other sites (not reported here) are consistent with this view. One key finding from the OU experiment is that the process of implementing remote experiments can require changes to the learning and teaching objectives, and it is therefore not necessarily possible to compare a traditional laboratory experiment with its remote equivalent. However, in one of our four experimental settings, the OU experiment, we have described above how there was sufficient equivalence between the original laboratory experiment and its remote implementation for some comparison of students’ perceptions. In the validation of the system students rated the remote experiment as a useful contributor to their overall learning, although with some reservations. The students with disabilities who used the PEARL system found significant improvements in their experience of laboratory work in the remote setting. However, these students were also concerned that existing provision for disabled students at residential schools should not be reduced. Science teachers in higher education who reviewed the system were also positive about its potential. Finally, we have demonstrated the role that formative and summative evaluation can play in the development of such systems.

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