

REMOTE LABORATORIES IN THE CURRICULUM

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ABSTRACT

Remote laboratories are increasingly being developed to provide students with web-based access to real laboratory experiments. The demonstrable advantages (e.g. increased accessibility) are tempered by concerns that remote access will be substituted for “hands-on” practical work, and reduce interaction between students. We argue that these concerns can be avoided if remote labs are used appropriately, as with any other pedagogical method, making the best use of their many beneficial affordances.

We review studies that have made direct comparisons between remote and hands-on labs, and analyse the two methods' important similarities and differences by considering the students' physical and psychological experiences. Then, the characteristic properties of remote-access labs are investigated from a pedagogical perspective, including results from focus groups of students' opinions and experiences with hands-on and remote labs.

We find that the only necessary difference between hands-on and remote-labs is the physical separation of student and apparatus. Other differences and similarities between the modalities are controllable factors, to greater or lesser extents. Remote labs have potential to offer some valuable educational advantages which have not been possible with traditional labs. To achieve the technique's full potential, it is important that its abilities and limitations are widely understood.

1. Introduction

In the disciplines of Engineering and Physical Sciences, laboratory work is considered to be “at the heart” of learning^[1] and has a strong impact on students' learning outcomes^[2,3]. Laboratory-based sessions are widely used in order to provide physical evidence of theoretical principles and to teach practical skills. When used appropriately they can enthuse, motivate and inspire students.

Laboratory teaching requires commitments of time, space and finance to purchase, install and maintain equipment,

and then to host the students. As the size and diversity of cohorts increase, so does the pressure on resources; that has been one factor driving research into technological alternatives to the traditional methods of laboratory teaching. Simulations of the lab experience have been created, using computer interfaces and pre-recorded data, however the technique has sometimes received a critical response from students and educationalists^[4]. Simulations certainly have value (e.g. in providing animations of dynamic physical processes), when they are provided *supplementary* to existing teaching, as originally intended^[5]. However, if simulations are used in place of experimental work, where uncertainties (“serendipity”^[6]) occur, then the method is philosophically flawed since the simulation's results are pre-determined and unvarying. Simulations are not discussed in detail in this paper.

An alternative approach to laboratory-based teaching is to provide remote access to real laboratory experiments. Proponents of this technique are keen that it is distinguished from simulated experiments so it is important that we define our terms. Figure 1 shows the general structure of a remote-lab, comprising:

- Real experimental equipment (**apparatus**),
 - from which data (measurements) can be recorded
- A **remote link** for bi-directional transmission
- An **interface** that allows students to
 - submit requests for a particular experiment
 - receive data (measurements)

Three vital components are indicated in bold type. The specific implementation of these three is left undefined.

Remote-labs have been applied in a range of disciplines including environmental and ecological science^[7] but are mainly found in engineering departments: chemical (e.g.^[8]), electrical (e.g.^[9]), mechanical (e.g.^[10]). The technology is being developed in an increasing number of higher education institutions and is visibly branching out to new subjects and to other levels of education.

Some remote-labs can already be accessed by anyone with conventional web-browser software^[10]; this feature could provide a huge opportunity for resource-limited

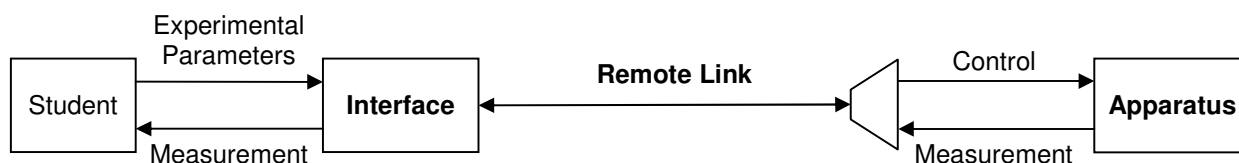


Fig 1: An instance of a remote laboratory

institutions across the world to access high-quality experimental equipment. Remote labs have great potential for providing access to developing nations, often at very little additional cost to the host organisation. However there has been little or no published assessment of the specific educational needs of developing countries and how remote labs might be of benefit. This paper unfortunately makes no advancement in that area but the authors would recommend that the issue is kept alive within remote lab discussions.

To date some small user-groups have formed, providing evidence of successful collaboration and sharing of resources over international boundaries^[11]. Before remote-laboratories can become more widely used and achieve their potential, several fundamental logistical issues still require urgent attention: how will facilities be funded and maintained? Who will have access and when? In order to resolve these issues debate is required to reach a consensus on the strengths and weaknesses of the remote-lab modality, and its place in the curriculum. Currently, there is not even an agreement on the technique's name: "Weblabs, virtual labs, distributed learning labs"^[6].

There exist ongoing disputes over the effectiveness of different modalities (hands-on vs. remote) at delivering learning outcomes, and their overall effects on students' experience. Most examples to date are simply remote versions of traditional labs and some researchers have attempted to make direct comparisons between learning outcomes with hands-on vs. remote labs. However, there has been little work that addresses how the specific characteristics of the remote modality can be exploited to reinforce learning. Now that the technical feasibilities of various approaches are being increasingly understood and proven, it is timely to consider the best use of the remote lab modality from an educational perspective.

2. Making Comparisons Between Remote and Hands-On Labs

Presence and Learning Context:

The fundamental difference presented by remote operation is the physical separation of student and apparatus. This, by definition means that it is impossible for students to perform tactile, physical interaction with the remote device. In this respect, remote labs have very limited ability to teach a physical skill or craft.

In hands-on labs, students may work individually or in groups, using one piece of apparatus or several duplicated sets, and the lab may be led by one teacher or he/she may be assisted. In each case the ratio of student : apparatus : teacher is fixed before the lab, and during the experiment the teacher will be in control of the learning environment. For remote labs, that is not necessarily the case: if a teacher is not actually present with a student then the

physical environment in which the student conducts the lab is not guaranteed.

Physical presence however is only one element in the perception of reality, a student's "subjective mental reality"^[12, 13]. Though physically remote, a student can still feel a sense of immersion within the concepts and themes of a lab: a "psychological presence". This suspension of disbelief can be enhanced with a high-fidelity interface^[14].

This concept of presence has relevance to the issue of the "environmental context of learning" (see e.g.^[15], for a review). Studies have indicated that a same-context advantage is observed for recall of information: information received in a classroom may be more easily recalled within that same classroom. As with presence though, physical context is not all: the "internal context" is perhaps more relevant for a student who is engaged in introspective study. "Same context" can then be applied to any situation where a student is studying that particular subject, depending on the depth of their psychological "immersion" in the concepts and theories.

A student is not necessarily more psychologically "immersed" in a subject during a lab session; there can be any number of other distractions (this point is discussed later). Physical presence does not guarantee psychological presence when concentration lapses: "Are you *with us*?" Thus, depending on the cognitive nature of the experiment, the degree of psychological immersion is not necessarily greater in either remote or hands-on labs. The degree of psychological presence with either modality is very hard to quantify or control. Therefore, attempts to directly compare remote and hands-on modalities may actually have several uncontrolled degrees of freedom.

Assessment of Effectiveness:

The ability to perform direct comparison between modalities is further limited by the lack of standard criteria with which to evaluate the effectiveness of lab work^[6]. The traditional method of assessment of performance in laboratory work is to grade a student's report. However it has been pointed out that in many cases the resulting grade represents to a large extent the student's ability to write a report, rather than their grasp of a particular concept or development of a skill^[11].

Lang et. al.^[9] attempted to quantify learning outcomes by applying a knowledge test of 120 true/false questions to students before and after carrying out an experiment. One group of students participated in a traditional lab (on electric circuits) and the other experienced an online version. The researchers thus attempted to investigate any difference in learning outcome attributable to delivery method. The knowledge test did not show any practically significant differences, however all the measured differences in knowledge were very small and in some

cases knowledge level was found to be higher *before* participating in the experiment.

Lindsay & Good ^[16] canvassed students who had taken either a hands-on experiment or simulated or remote-access versions of the same experiment and found several differences in their perceptions and experiences. The experiment had several learning outcomes which were assessed individually through systematic grading of the students' written reports on their work. After a series of detailed studies, Lindsay & Good concluded that it was not possible to conclude that any access mode was ultimately superior to any other, because the modes exhibited multiple differences across different learning outcomes.

After reviewing remote-lab technology, Ma & Nickerson ^[6], also questioned the validity of like-for-like comparisons and noted that controlled trials are not possible when there's no way to standardise instructor ability. Furthermore it would not be relevant to compare across different disciplines. In reviewing published studies of the effectiveness of remote technologies vs. hands-on labs, we observed that research has very rarely been conducted by workers without a strong allegiance for either method.

In conclusion, the two modalities are fundamentally and significantly different, thus direct comparison between the two is not appropriate or productive. No matter how lifelike the remote lab, they are not appropriate as a direct like-for-like replacement for practical hands-on (tactile) work since there is always physical separation, by definition. Instead, the differences can be acknowledged, accepted and exploited in order to make the most appropriate use of each different teaching method.

3. Remote Lab Learning and Teaching

In this section, we concentrate on the characteristics of remote-labs, and discuss their relevance to learning and teaching. Included in our analysis are results from independent focus group studies of students*, as verbatim quotes.

Accessibility

Remote access offers tremendous benefits for those students who are physically unable to attend a conventional laboratory (due to limited mobility or other medical restrictions, for example). In many cases, the process of automating an experiment for remote access –

* Conducted by Royal Academy of Engineering (UK), March 2008. Groups of 5-6 engineering students at University of Leeds and University College London (UK) were interviewed in an informal setting: a facilitator asked open-ended questions on the students' experiences with hands-on labs and remote-labs. Interviews were recorded and later transcribed.

removing the need for human operators – results in an experiment that can be accessed 24 hours a day. This provides further support for students who are unable to attend a particular timetabled lab session due to other commitments, for example child-care, or religious holidays. Read et. al. ^[17] presented evidence of students accessing a lab from many different countries, during religious festivals and at all 24 hours of the day. Students from a focus group at Leeds University unanimously appreciated the 24/7 access:

"I live a long way from Uni...I was using it between lectures"

"It was nice being able to do the work when you wanted"

In traditional labs, it is generally not possible for students to return to repeat data measurements if they realise later that they have made a mistake. Remote access can provide the opportunity to repeat whenever necessary. This mode would apply less pressure to record data correctly within a given time-frame. This is seen as beneficial by many students; flexible access provides them freedom to carry out work at their own pace (discussed later in this paper). This access mode may be less suitable for students who are poorer at governing and planning their study time. If that is a concern, it should be remembered then that remote labs are equally capable of being run in a time-restricted, strictly-scheduled timetable just as with hands-on labs, and that if required, the students' individual access logs can be observed by teachers.

Standards of Education

In general, homogenising the students' experiences is not viewed in a positive light by educationalists ^[4] who feel that education is a personal process of development, and that a learner's motivation is dependent on their feeling individually recognised and valued ^[18]. If remote-labs are applied arbitrarily, the learning process could suffer. However that is by no means necessary, and if used appropriately – as frequently reported – student motivation and interest has been maintained and often increased through the use of remote technology.

Providing remote access for many students to one identical piece of apparatus has some potential gains: e.g. students could have the ability to perform collaborative experiments to produce an emergent result when their data are combined ^[11]. As the Bologna process is applied across Europe, the remote delivery method could allow widely-dispersed students to share the same laboratory experience and develop links across international boundaries, if the infrastructure is supported. Of course, proper guidance must be provided locally, where teaching style and course content would vary according to local requirements.

Rather than presenting the students with an identical experience, Levesley et. al. ^[11] demonstrated deliberate differentiation of their experiences. Personal IDs and

automation of lab operation enabled students to be presented with individualised experimental parameters when they logged-in.

Human Interaction

While the student is physically separated from the laboratory, that does not necessarily mean that they must perform the experiment in isolation. Remote delivery affords several strategies for learning environments. The physical environment may be a student's dorm-room or internet café, but it need not be: remote labs can still be conducted in a classroom with computers. There is greater scope for variation of the virtual (psychological) environment. The degree of virtual presence of peers and of teachers are also controllable factors, through optional provision of online chat-rooms, email support or video links.

In traditional hands-on labs, various ratios of student:apparatus:teacher are encountered, depending on the total number of students, the nature of the experiment, and the resources (time, financial, space, staffing) of the institution. Therefore, unfortunately the teaching environment is frequently determined by logistical and resource limitations instead of educational requirements.

Remote lab experience has shown that students have the option to select a working mode that best suits their learning style, be that working alone or in small groups in a computer room^[17]. This flexibility has been seen as advantageous in supporting the needs of increasingly diverse cohorts of students where peer group dynamics can impinge on individual learning.

"I worked with my housemate who was on the same course, that was really helpful"

"It really helps to bounce ideas off each other"

The opposite case is also possible: the working mode can be enforced if that is suitable: Read & Sarmiento^[19] presented a technique to develop modern communication skills by requiring that groups of students only conducted their meetings online, in a professional manner.

Focused Learning Outcomes

Prior to running a hands-on lab, it is necessary to ensure that the starting conditions for the equipment are always returned to a consistent state, as far as possible. Depending on the laboratory in question, many experimental setups will have their own peculiarities and teachers might be familiar with explaining that "Where the lab instruction sheet says 'connect the blue wire' instead you should connect the red wire". These realities, while being a non-trivial, valuable part of the student's overall experience, should not be allowed to interfere with the designed learning outcomes. Students offered mixed opinions on their hands-on labs experiences:

"In real life things go wrong and you don't get to learn that experience if you just use [the remote lab]"

"...having to set it up and then being frustrated that it didn't work"

"As an engineer do we need to operate all the kit in a workshop?"

"All the setting up wasn't assessed ... I thought it was a waste of time"

Magin & Kanapathipillai^[3] report of a degree course which has completely separated the teaching of practical lab skills into a year-long module "engineering experimentation" to ensure that students have hands-on experience. This option may not be suitable for other courses though, where lab experiments are perhaps more fundamental to the understanding of theories.

Learning Psychology: Motivation

The situations in hands-on labs described above can be stressing, de-motivating and counterproductive for learning.

"...you go into the lab with the focus being on the assessment and because of that you are not really thinking about the engineering side of it, you are just thinking 'I need to get written down what I need for my lab report'"

"Trying to cram everything into two hours is too much concentration and stress"

Elton^[18] recommended that to enhance the intrinsic motivation of students they should be:

- Treated as individuals;
- Expected to show individuality, originality, creativity;
- Allowed choices and preferences in their learning;
- Allowed to negotiate the means by which they are assessed."

These recommendations were made before remote-labs became available, however each point is certainly attainable using remote access. The ability to individualise experiments has been reported^[11], as has the provision of choice in their learning method^[17].

Any experiment can promote motivation of students through these routes, if it is thoughtfully designed in the first instance and then kept up-to-date.

"Lecturers that use practical up to date examples are the most popular"

Maintenance of a lab is facilitated through remote-access:

- Updating apparatus and instructions documents only needs to be performed once (as opposed to many duplicated sets of apparatus)
- The 24/7 accessibility offers increased opportunity for a teacher to test and update the protocol.

Learning Psychology: Student Independence

The degree of control provided to a student will influence their motivation, and it will fundamentally affect their

learning^[18]. With a tightly-prescribed laboratory protocol, students may simply follow instructions robotically and gain very little deep understanding.

“following the lab procedure... you are almost doing it without thinking what is happening until afterwards”

Conversely, open-ended structures allow more-interested students to investigate to a deeper level, and to learn about effective experimental design.

In some ways remote labs are more prescribed – for example students cannot accidentally connect up the apparatus incorrectly. Also, the lack of the immediate presence of an instructor (in some cases) could mean that written instructions have to be more specific. However, in other ways remote access provides much greater freedom to explore, to make mistakes without embarrassment, to repeat experiments and to proceed at their chosen pace. An interesting result from the focus groups was that students did not always see hands-on labs as providing valuable practical experience:

“[the hands-on labs] are not teaching us the engineering as we do not get the opportunity to play with the equipment and take it to extremes”

While remote-access can offer a greater degree of student liberation, this must be supported by a teacher to avoid independence turning to isolation. Two alternate views:

“..when you get it right it is just awesome, I get really geeked out when I get things right without any help”

“[to] have the instructors there in the lab that can answer your questions, that helps a lot”

Learning Psychology: Reflective Cycles

The traditional method of providing feedback on students' performance in a laboratory has been the submission of reports which are then graded and returned. Apart from the time required to grade these reports, there exists a necessary further delay in that no reports can be returned until the whole class has completed the laboratory (some schedules can run over months). This severely limits laboratories as a tool for providing formative feedback within a course, impinging on student learning and motivation.

Laboratories are often used to demonstrate theoretical concepts in practice. To link theory and practice, the student should have access to theoretical material while carrying out the experiment; here “access” means physical access to books and notes, and also cognitive access – that the relevant concepts are “fresh in the mind”. Due to scheduling restrictions of hands-on labs, it is often not possible to coincide the teaching of a particular concept with the relevant laboratory. This can lead to the laboratory work being seen as conceptually separate from the theory.

The more flexible access options afforded by remote-labs mean that students can learn in reflection cycles: referring to the theory, performing an experiment, comparing and then repeating this cycle as required. They can even return to the experiment while writing a report, for example to check a particular detail or verify an unusual/unexpected result.

“[the online lab] helps you to understand things better as ... you can think about what is going on in the system while you are doing it and how that relates to what you have learnt [in lectures]”

We suggest that this learning method could promote deeper, better-linked understanding, making more effective use of the laboratory experiment.

4. Recommendations for Best Practice

We have proposed that remote labs are fundamentally different from hands-on labs and should therefore not be directly substituted for hands-on laboratory work. Instead, we have illustrated several specific affordances provided by the remote laboratory format:

- Personalised experiments
- Collaborative work
 - Ability to learn from peers' results
 - Anonymous if desired
- Flexible access (often 24/7)
- Immediate feedback, which can be either
 - purely formative
 - assessed
- Flexibility of learning environments:
 - physical environment
 - social environment

These can be exploited to promote:

- Deeper learning for interested students
- Greater student control and ownership of their learning
- More inclusive and accessible teaching environments
- Better linking of practical and theoretical work

Since each educational discipline and course will have its own learning objectives, with different priorities, the incorporation of the technology will have to be tailored to each specific laboratory. The “best practice” is to recognise that there is no universally-suitable approach to the use of remote labs. The means to ensure the labs are applied appropriately in every situation is “reflective practice”^[20]: the practice of continually evaluating and reflecting on features of the course which are successful, and those which need addressing. Learning and research are linked by the common theme of “enquiry”^[21], and teachers should continually evaluate and refine their teaching methods.

5. Conclusions

The only *necessary* difference between hands-on and remote-labs is the physical separation of student and apparatus. Other differences and similarities between the modalities are controllable factors, to greater or lesser extents. Remote labs have potential to offer some valuable educational advantages if, like any other teaching technique, they are used appropriately within the curriculum and not advocated purely on a cost-saving basis.

Now is the time to debate and to reach conclusions on the use of remote labs in education. Researchers have made remarkable achievements in demonstrating the efficacy of technologies, and if predictions are correct, the technology will begin to be marketed on a wide scale in the coming years. It is important that, as consumers of this technology, we are well-informed.

Acknowledgements

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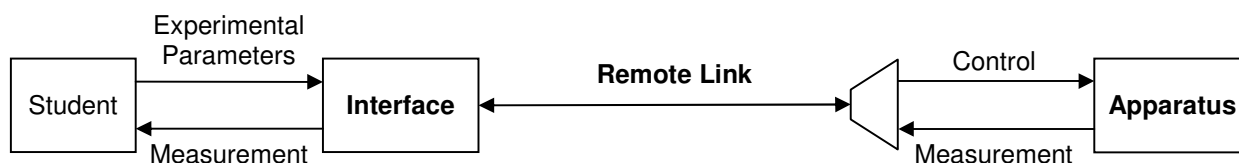


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Physical presence however is only one element in the perception of reality, a student's "subjective mental reality"^[12, 13]. Though physically remote, a student can still feel a sense of immersion within the concepts and themes of a lab: a "psychological presence". This suspension of disbelief can be enhanced with a high-fidelity interface^[14].

This concept of presence has relevance to the issue of the "environmental context of learning" (see e.g.^[15], for a review). Studies have indicated that a same-context advantage is observed for recall of information: information received in a classroom may be more easily recalled within that same classroom. As with presence though, physical context is not all: the "internal context" is perhaps more relevant for a student who is engaged in introspective study. "Same context" can then be applied to any situation where a student is studying that particular subject, depending on the depth of their psychological "immersion" in the concepts and theories.

A student is not necessarily more psychologically "immersed" in a subject during a lab session; there can be any number of other distractions (this point is discussed later). Physical presence does not guarantee psychological presence when concentration lapses: "Are you *with us*?" Thus, depending on the cognitive nature of the experiment, the degree of psychological immersion is not necessarily greater in either remote or hands-on labs. The degree of psychological presence with either modality is very hard to quantify or control. Therefore, attempts to directly compare remote and hands-on modalities may actually have several uncontrolled degrees of freedom.

Assessment of Effectiveness:

The ability to perform direct comparison between modalities is further limited by the lack of standard criteria with which to evaluate the effectiveness of lab work^[6]. The traditional method of assessment of performance in laboratory work is to grade a student's report. However it has been pointed out that in many cases the resulting grade represents to a large extent the student's ability to write a report, rather than their grasp of a particular concept or development of a skill^[11].

Lang et. al.^[9] attempted to quantify learning outcomes by applying a knowledge test of 120 true/false questions to students before and after carrying out an experiment. One group of students participated in a traditional lab (on electric circuits) and the other experienced an online version. The researchers thus attempted to investigate any difference in learning outcome attributable to delivery method. The knowledge test did not show any practically significant differences, however all the measured differences in knowledge were very small and in some

cases knowledge level was found to be higher *before* participating in the experiment.

Lindsay & Good ^[16] canvassed students who had taken either a hands-on experiment or simulated or remote-access versions of the same experiment and found several differences in their perceptions and experiences. The experiment had several learning outcomes which were assessed individually through systematic grading of the students' written reports on their work. After a series of detailed studies, Lindsay & Good concluded that it was not possible to conclude that any access mode was ultimately superior to any other, because the modes exhibited multiple differences across different learning outcomes.

After reviewing remote-lab technology, Ma & Nickerson ^[6], also questioned the validity of like-for-like comparisons and noted that controlled trials are not possible when there's no way to standardise instructor ability. Furthermore it would not be relevant to compare across different disciplines. In reviewing published studies of the effectiveness of remote technologies vs. hands-on labs, we observed that research has very rarely been conducted by workers without a strong allegiance for either method.

In conclusion, the two modalities are fundamentally and significantly different, thus direct comparison between the two is not appropriate or productive. No matter how lifelike the remote lab, they are not appropriate as a direct like-for-like replacement for practical hands-on (tactile) work since there is always physical separation, by definition. Instead, the differences can be acknowledged, accepted and exploited in order to make the most appropriate use of each different teaching method.

3. Remote Lab Learning and Teaching

In this section, we concentrate on the characteristics of remote-labs, and discuss their relevance to learning and teaching. Included in our analysis are results from independent focus group studies of students*, as verbatim quotes.

Accessibility

Remote access offers tremendous benefits for those students who are physically unable to attend a conventional laboratory (due to limited mobility or other medical restrictions, for example). In many cases, the process of automating an experiment for remote access –

* Conducted by Royal Academy of Engineering (UK), March 2008. Groups of 5-6 engineering students at University of Leeds and University College London (UK) were interviewed in an informal setting: a facilitator asked open-ended questions on the students' experiences with hands-on labs and remote-labs. Interviews were recorded and later transcribed.

removing the need for human operators – results in an experiment that can be accessed 24 hours a day. This provides further support for students who are unable to attend a particular timetabled lab session due to other commitments, for example child-care, or religious holidays. Read et. al. ^[17] presented evidence of students accessing a lab from many different countries, during religious festivals and at all 24 hours of the day. Students from a focus group at Leeds University unanimously appreciated the 24/7 access:

"I live a long way from Uni...I was using it between lectures"

"It was nice being able to do the work when you wanted"

In traditional labs, it is generally not possible for students to return to repeat data measurements if they realise later that they have made a mistake. Remote access can provide the opportunity to repeat whenever necessary. This mode would apply less pressure to record data correctly within a given time-frame. This is seen as beneficial by many students; flexible access provides them freedom to carry out work at their own pace (discussed later in this paper). This access mode may be less suitable for students who are poorer at governing and planning their study time. If that is a concern, it should be remembered then that remote labs are equally capable of being run in a time-restricted, strictly-scheduled timetable just as with hands-on labs, and that if required, the students' individual access logs can be observed by teachers.

Standards of Education

In general, homogenising the students' experiences is not viewed in a positive light by educationalists ^[4] who feel that education is a personal process of development, and that a learner's motivation is dependent on their feeling individually recognised and valued ^[18]. If remote-labs are applied arbitrarily, the learning process could suffer. However that is by no means necessary, and if used appropriately – as frequently reported – student motivation and interest has been maintained and often increased through the use of remote technology.

Providing remote access for many students to one identical piece of apparatus has some potential gains: e.g. students could have the ability to perform collaborative experiments to produce an emergent result when their data are combined ^[11]. As the Bologna process is applied across Europe, the remote delivery method could allow widely-dispersed students to share the same laboratory experience and develop links across international boundaries, if the infrastructure is supported. Of course, proper guidance must be provided locally, where teaching style and course content would vary according to local requirements.

Rather than presenting the students with an identical experience, Levesley et. al. ^[11] demonstrated deliberate differentiation of their experiences. Personal IDs and

automation of lab operation enabled students to be presented with individualised experimental parameters when they logged-in.

Human Interaction

While the student is physically separated from the laboratory, that does not necessarily mean that they must perform the experiment in isolation. Remote delivery affords several strategies for learning environments. The physical environment may be a student's dorm-room or internet café, but it need not be: remote labs can still be conducted in a classroom with computers. There is greater scope for variation of the virtual (psychological) environment. The degree of virtual presence of peers and of teachers are also controllable factors, through optional provision of online chat-rooms, email support or video links.

In traditional hands-on labs, various ratios of student:apparatus:teacher are encountered, depending on the total number of students, the nature of the experiment, and the resources (time, financial, space, staffing) of the institution. Therefore, unfortunately the teaching environment is frequently determined by logistical and resource limitations instead of educational requirements.

Remote lab experience has shown that students have the option to select a working mode that best suits their learning style, be that working alone or in small groups in a computer room^[17]. This flexibility has been seen as advantageous in supporting the needs of increasingly diverse cohorts of students where peer group dynamics can impinge on individual learning.

"I worked with my housemate who was on the same course, that was really helpful"

"It really helps to bounce ideas off each other"

The opposite case is also possible: the working mode can be enforced if that is suitable: Read & Sarmiento^[19] presented a technique to develop modern communication skills by requiring that groups of students only conducted their meetings online, in a professional manner.

Focused Learning Outcomes

Prior to running a hands-on lab, it is necessary to ensure that the starting conditions for the equipment are always returned to a consistent state, as far as possible. Depending on the laboratory in question, many experimental setups will have their own peculiarities and teachers might be familiar with explaining that "Where the lab instruction sheet says 'connect the blue wire' instead you should connect the red wire". These realities, while being a non-trivial, valuable part of the student's overall experience, should not be allowed to interfere with the designed learning outcomes. Students offered mixed opinions on their hands-on labs experiences:

"In real life things go wrong and you don't get to learn that experience if you just use [the remote lab]"

"...having to set it up and then being frustrated that it didn't work"

"As an engineer do we need to operate all the kit in a workshop?"

"All the setting up wasn't assessed ... I thought it was a waste of time"

Magin & Kanapathipillai^[3] report of a degree course which has completely separated the teaching of practical lab skills into a year-long module "engineering experimentation" to ensure that students have hands-on experience. This option may not be suitable for other courses though, where lab experiments are perhaps more fundamental to the understanding of theories.

Learning Psychology: Motivation

The situations in hands-on labs described above can be stressing, de-motivating and counterproductive for learning.

"...you go into the lab with the focus being on the assessment and because of that you are not really thinking about the engineering side of it, you are just thinking 'I need to get written down what I need for my lab report'"

"Trying to cram everything into two hours is too much concentration and stress"

Elton^[18] recommended that to enhance the intrinsic motivation of students they should be:

- Treated as individuals;
- Expected to show individuality, originality, creativity;
- Allowed choices and preferences in their learning;
- Allowed to negotiate the means by which they are assessed."

These recommendations were made before remote-labs became available, however each point is certainly attainable using remote access. The ability to individualise experiments has been reported^[11], as has the provision of choice in their learning method^[17].

Any experiment can promote motivation of students through these routes, if it is thoughtfully designed in the first instance and then kept up-to-date.

"Lecturers that use practical up to date examples are the most popular"

Maintenance of a lab is facilitated through remote-access:

- Updating apparatus and instructions documents only needs to be performed once (as opposed to many duplicated sets of apparatus)
- The 24/7 accessibility offers increased opportunity for a teacher to test and update the protocol.

Learning Psychology: Student Independence

The degree of control provided to a student will influence their motivation, and it will fundamentally affect their

learning^[18]. With a tightly-prescribed laboratory protocol, students may simply follow instructions robotically and gain very little deep understanding.

“following the lab procedure... you are almost doing it without thinking what is happening until afterwards”

Conversely, open-ended structures allow more-interested students to investigate to a deeper level, and to learn about effective experimental design.

In some ways remote labs are more prescribed – for example students cannot accidentally connect up the apparatus incorrectly. Also, the lack of the immediate presence of an instructor (in some cases) could mean that written instructions have to be more specific. However, in other ways remote access provides much greater freedom to explore, to make mistakes without embarrassment, to repeat experiments and to proceed at their chosen pace. An interesting result from the focus groups was that students did not always see hands-on labs as providing valuable practical experience:

“[the hands-on labs] are not teaching us the engineering as we do not get the opportunity to play with the equipment and take it to extremes”

While remote-access can offer a greater degree of student liberation, this must be supported by a teacher to avoid independence turning to isolation. Two alternate views:

“..when you get it right it is just awesome, I get really geeked out when I get things right without any help”

“[to] have the instructors there in the lab that can answer your questions, that helps a lot”

Learning Psychology: Reflective Cycles

The traditional method of providing feedback on students' performance in a laboratory has been the submission of reports which are then graded and returned. Apart from the time required to grade these reports, there exists a necessary further delay in that no reports can be returned until the whole class has completed the laboratory (some schedules can run over months). This severely limits laboratories as a tool for providing formative feedback within a course, impinging on student learning and motivation.

Laboratories are often used to demonstrate theoretical concepts in practice. To link theory and practice, the student should have access to theoretical material while carrying out the experiment; here “access” means physical access to books and notes, and also cognitive access – that the relevant concepts are “fresh in the mind”. Due to scheduling restrictions of hands-on labs, it is often not possible to coincide the teaching of a particular concept with the relevant laboratory. This can lead to the laboratory work being seen as conceptually separate from the theory.

The more flexible access options afforded by remote-labs mean that students can learn in reflection cycles: referring to the theory, performing an experiment, comparing and then repeating this cycle as required. They can even return to the experiment while writing a report, for example to check a particular detail or verify an unusual/unexpected result.

“[the online lab] helps you to understand things better as ... you can think about what is going on in the system while you are doing it and how that relates to what you have learnt [in lectures]”

We suggest that this learning method could promote deeper, better-linked understanding, making more effective use of the laboratory experiment.

4. Recommendations for Best Practice

We have proposed that remote labs are fundamentally different from hands-on labs and should therefore not be directly substituted for hands-on laboratory work. Instead, we have illustrated several specific affordances provided by the remote laboratory format:

- Personalised experiments
- Collaborative work
 - Ability to learn from peers' results
 - Anonymous if desired
- Flexible access (often 24/7)
- Immediate feedback, which can be either
 - purely formative
 - assessed
- Flexibility of learning environments:
 - physical environment
 - social environment

These can be exploited to promote:

- Deeper learning for interested students
- Greater student control and ownership of their learning
- More inclusive and accessible teaching environments
- Better linking of practical and theoretical work

Since each educational discipline and course will have its own learning objectives, with different priorities, the incorporation of the technology will have to be tailored to each specific laboratory. The “best practice” is to recognise that there is no universally-suitable approach to the use of remote labs. The means to ensure the labs are applied appropriately in every situation is “reflective practice”^[20]: the practice of continually evaluating and reflecting on features of the course which are successful, and those which need addressing. Learning and research are linked by the common theme of “enquiry”^[21], and teachers should continually evaluate and refine their teaching methods.

5. Conclusions

The only *necessary* difference between hands-on and remote-labs is the physical separation of student and apparatus. Other differences and similarities between the modalities are controllable factors, to greater or lesser extents. Remote labs have potential to offer some valuable educational advantages if, like any other teaching technique, they are used appropriately within the curriculum and not advocated purely on a cost-saving basis.

Now is the time to debate and to reach conclusions on the use of remote labs in education. Researchers have made remarkable achievements in demonstrating the efficacy of technologies, and if predictions are correct, the technology will begin to be marketed on a wide scale in the coming years. It is important that, as consumers of this technology, we are well-informed.

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