# Perceptions of a program approach to virtual laboratory provision for analytical and bioanalytical sciences

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# Perceptions of a program approach to virtual laboratory provision for analytical and bioanalytical sciences

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**Abstract:** When teaching chemistry and biosciences courses to undergraduate and postgraduate students, laboratory experience is a crucial requirement for skills development. Due to COVID-19 related closure of laboratories it became critical to replace that experience with virtual delivery. Through carefully designed learning experiences it is possible for students to gain skills such as experimental design, problem solving, record keeping and data analysis.

Here we present a coordinated approach to the design of laboratory classes for a cross discipline postgraduate program. Virtual laboratory classes, using freely available web-based simulators, were run in a synchronous manner with pre lab briefing and post lab data analysis sessions. The laboratory scripts were developed using a command prompt design: [Do][Explore][Act] framework, which is intended to provide students with a guided approach to using the simulator while in a remote setting. The intended outcome was to develop student's record keeping and understanding of the scientific principles of the instrumentation through practical experimentation.

Student experience of the virtual laboratory provision was surveyed via a mix method approach, with an 81% response rate. Satisfaction with the virtual labs was high (68%), with students agreeing the laboratories contained the appropriate balance of challenge and support. The command prompts were thought to be a very useful way to structure a lab script (77% agreement) and many suggested this approach should be kept for future laboratory use. Students self-identified the main skills learnt as being laboratory bookkeeping, analyzing data, problem solving and use of equipment.

**Keywords: virtual laboratory, dry lab, laboratory instruction, postgraduate education, active learning**

## Introduction

When restrictions came into force due to the COVID-19 pandemic, many Universities were unable to deliver physical laboratory experience due to social distancing restraints and had to undergo a rapid transition in order to teach all their subjects remotely (1,2). For those teaching science-based subjects, this provided a particular challenge; how do we deliver an authentic practical experience in an online environment? Many professional bodies both require a set number of laboratory hours to be covered to gain accreditation (e.g. RSC (3), CSoFS (4) and ACS (5)) and they are an important aspect to science-based teaching (6). To address the challenge of maintaining the experience and learning outcomes the physical laboratories programs were moved onto an online setting, a consistent approach to delivering online labs was developed (7,8). In this study, a series of course specific simulated practicals were prepared based on core methods relevant to each of the degrees. The purpose of these activities was to gain familiarity with the types of parameters and concepts that influence the efficiency of a given experimental procedure, for example a chromatographic separation or PCR optimization (9). To achieve this a set of practicals using pre-existing open access online simulations were developed (**TABLE 1**) within a novel delivery framework.

Through exploration and practical experimentation, we want the students to develop record keeping skills and create their own understanding of scientific principles, essentially following the Kolb learning cycle (10). By following a set protocol the answers will often already be known and although this approach allows the student to experience what should happen and see the practical application of their knowledge, it lacks higher level thinking as the outcome is set. Through the use of inquiry-based learning focusing on iteration within the practical environment, students can be encouraged to "play" with a given scenario, exploring a range of different parameters, thinking deeply about the actions and outcomes (11). Simulations also allow students to experience a given methodology prior to performing it within a physical laboratory and this approach has been demonstrated to enhance the student learning (12,13). Exploration in this setting involves trying out new experiences and ideas in a "safe" way. Permission is given to explore parameters and it is the act of exploration that is important, not the outcomes. Assessment is then of the process, by documenting the exploration and reflecting on and rationally thinking about the outcomes through the creation of laboratory notebooks. Ownership and control of the experience is passed to the student and lets them take the task in their own direction. Through iterative simulations the student is acting in an authentic manner experiencing what it is like to become a researcher and problem solve for themselves.

**Framework Design**

The challenge we faced was to facilitate and support the students through the laboratory practical at a distance. Lab scripts were structured by use of a sociocultural approach to teaching which recognizes the role of mediation (e.g., peer to peer communication) and the role of a more knowledgeable other (the academic) to facilitate knowledge construction (14). To achieve this series of command prompts were used to structure the lab script and allow students to act in an autonomous manner.

In developing the framework for effective mediation of online instrumentation simulations, we sought to provide a mix of directed and exploratory tasks to promote engagement with the simulation and minimize the feelings of confusion often expressed by students working on these types of activities in relative isolation. Further, we wished to provide transparency in assessment such that students understood what tasks were assigned to develop an understanding of the content and what tasks were evaluated for grading.

[Do][Explore][Act] is derived from the Predict-Observe-Explain approach to presenting scientific demonstrations. The premise of Predict-Observe-Explain is to foster engaged learning skills in what is for many students a passive activity – watching a demonstration. (15). Through providing a set of questions and tasks to perform before, during and after the demonstration, students are provided with a framework for identifying key concepts that are being explored and developed.

[Do][Explore][Act] attempts to provide an analogous structure for on-line simulations and faces two challenges not common in Predict-Observe-Explain. First, the instructor/mediator is remote – both spatially and temporally – from the student's learning experience. Any mediation or facilitation must occur pre-emptively in the form of properly guided inquiry. Second, students tend to struggle with a level of exploration that is appropriate for learning from an online simulation.

The [Do][Explore][Act] framework consists of three levels of tasks/commands. In developing the script for an activity, it is useful to align the tasks with the various levels of Bloom's Taxonomy for knowledge-based learning and Dave's taxonomy for skills-based tasks (16,17). [Do] tasks are appropriate for situations where students are copying or following instructions (Dave's Imitation level) or reproducing a scenario (Bloom's Remembering level). These tasks are typically related to instructions for proper operation of the simulation (e.g., navigating to a particular website, loading a preconfigured set of parameters) that are necessary to complete the activity but otherwise have minimal pedagogical impact. Tasks assigned the [Explore] tag expect the student to develop an Understanding of some content (Bloom) or Manipulate (Dave) the simulation in order to perform an action. [Explore] tasks encourage students to understand the operation of the simulation and might include observing the effect of a parameter slider on the visuals presented in the simulation. The [Act] tags address higher order cognitive tasks such as creating a procedure to perform on the simulation that models real-world experiences and is a generic tag for tasks that are meant to be assessed. The actual activity will have [Act] tags replaced by actions that are specific to the simulation or activity. For example, the three [Act] tags used in these activities are [Report], [Write] and [Plot]. The first two tags require short and long written responses, respectively, while the [Plot] tag is used to indicate that a figure needs to be generated. One could envision other tasks such as [Calculate] depending on the desired learning outcomes of the activity.

Given the open-ended nature of many of the practical situations, assessment was based around the ability to keep accurate records of the process rather than reaching a definitive conclusion. Here the experience was captured as a summative electronic laboratory notebook held within Microsoft OneNote as it is both cloud based and cross platform (18,19). Electronic lab books have been used as an assessment tool in other situations and have been demonstrated to be preferred to paper based notebooks and enhance good documentation practices and data integrity (20–22). Such scientific data recording and reporting systems are central for endorsing reproducibility and transparency practices among the scientific community (20,21). Here WHO guidelines on record keeping (25) were adapted into an assessment grid with students assessed on their ability to keep records in line with good laboratory practices and analysis of observations. Within the framework the commands [REPORT], [PLOT] and [WRITE] were used to specifically identify to the students' areas where notation was expected.

Here we report on a cross program virtual laboratory delivery strategy. A framework for effective mediation of online instrumentation simulations was developed to allow semi-autonomous completion of the virtual laboratory tasks. The effectiveness of this delivery from the point of view of the student cohort was assessed through Likert questionnaires and open text responses. Students report that the command structure framework was helpful when navigating the virtual simulations and assisted in the creation of electronic laboratory notebooks. The learning experience was seen to be of value to the student cohort and key skills associated with practical learning (problem solving, data analysis) was noted.

## Methods

### *Delivery*

The virtual labs were designed to replace a set of problem-solving optimization scenarios in which the students undertake multiple iterations of the same experiment. Simulations were used to replicate the physical problem-solving laboratory environment that the students would have undertaken. Similar approaches have been reported before (7). For example, the PCR and HPLC simulators took the place of traditional optimization practicals for the respective techniques. Single or multiple simulations used within the virtual labs are listed in **TABLE 1**. Where available pre-lab activities from the digital tools provider Learning Science (UK) were used to build prior knowledge or built on background knowledge covered in taught sessions. The learning objective was to analyze using appropriate statistics and critically evaluate the outcomes of practical experimental results. We aimed to create an environment in which students could interact with each other and the academic lead in real time. To do this the virtual laboratories were held in real time via video conferencing software (Zoom). Small group pre-lab tutorials were held in which the academic explained the experimental theory behind the technique in question and performed a briefing on the simulations to be used. Areas of importance in the script were highlighted for extra consideration or topics noted for revision prior to the lab (e.g. highlighting relevant equations). On the day of the practical students were admitted to the virtual lab room and welcomed. They were then split into groups in breakout rooms along long course lines. Sessions were delivered with an academic member of staff on hand throughout the day. The same academic delivered all the virtual labs to a given cohort of students. Interaction was encouraged by use of the chat boxes and screen sharing facilities. The aim of the breakout sessions was to allow peer to peer and tutor interactions within small groups. This process was repeated four times over four weeks for each course. An on-line post lab tutorial was then held at the end of the suite of labs to debrief and support data analysis sessions. Students were encouraged to submit data prior to the post lab to facilitate results discussions.

**TABLE 1** *Open access simulations as used in the postgraduate bioscience virtual lab program*

| Objective | Simulator | Unique data generated? |
|---|---|---|
| PCR optimisation of product yield and purity. | Electrophoresis (agarose gel) https://sites.google.com/view/dry-labs-site-special-edition/home?authuser=0 Returns a random set of seven DNA bands relative to standards. | YES |
| | Spectroscopy (DNA) https://sites.google.com/view/dry-labs-site-special-edition/home?authuser=0 Simulator generates A260 and A280 with ratio between 1.6 to 2.0 | YES |
| | PCR [9] http://virtual-pcr.ico2s.org/ Fully interactive PCR simulator allows the exploration of buffer and experimental conditions. | YES |
| GC-MS Analysis | GC-MS Pesticide Analysis https://learn5.open.ac.uk/course/format/sciencelab/section.php?name=pest01 Environmental analysis, qualitative and quantitative data. | YES |
| HPLC: Day 1 Familiarisation | HPLC Simulator 1 http://kabyn.com/hplc5/index.html Qualitative and quantitative analysis of standards and urine samples to detect illicit use of testosterone | NO |
| HPLC: Day 2 Method development | HPLC Simulator 2 http://www.multidlc.org/hplcsim_3_3_0/hplcsim.html Fully interactive HPLC simulator | YES |
| Purification of target proteins from simulated cellular lysate. | ABooth Protein Purification http://www.agbooth.com/pp_java/ Fully interactive protein purification simulator. Exploration of FLPC chromatography methods. | YES |
| Experience methods used to identify a specific protein from biological materials. | Spectroscopy (Bradford Assay) https://sites.google.com/view/dry-labs-site-special-edition/home?authuser=0 Simulator generates unique standard curves and unknown protein concentrations | YES |
| | Electrophoresis (SDS-PAGE / Western Blotting) https://www.labxchange.org Walk through lab simulation covering major experimental steps, in a click and drag manner | NO |

*Evaluation*

Ethics (ER31260026) for this study was acquired through the College of Health, Wellbeing and Life Sciences ethics committee following the Sheffield Hallam University Research Ethics Policy. Ethical approval was given as no identifiable, confidential, or controversial information would be collected. No gender, age, other educational experience, or other demographic factors were requested or considered within the analysis, primarily to ensure the questionnaire was concise and the length not a barrier to completion. Participation in the study was opt in. Out of 58 students enrolled in the module 47 opted into the study, a response rate of 81%.

*Participants*

Student participants in the study were enrolled in a one-year MSc program. Data was collected during the second semester of study with students enrolled on MSc Analytical Chemistry, Pharmaceutical Analysis, Microbiology, Cancer Biology, Biomedical Laboratory Science and Pharmacology & Biotechnology.

*Collection of Student Perceptions*

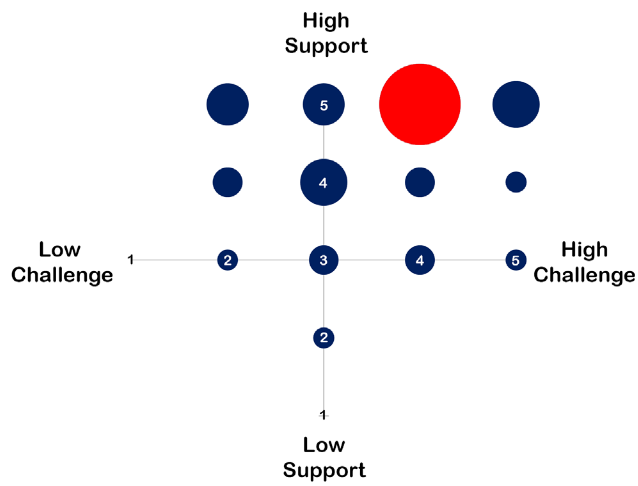
Data was collected during the second semester of study with students enrolled on a core research and laboratory practice module. An electronic survey was administered to assess students' experiences of the virtual laboratory provision. The survey consisted of statements on a Likert scale and open-ended questions. Questions were aimed at determining the students' overall experience of the delivery style, the use of simulations in virtual laboratories, the command prompt structure for lab scripts, perceptions of skills gained and the use of the electronic notebook. The survey was conducted during weeks four and five of the practical experience.

## Results

*Challenge vs Support*

The virtual lab experience was designed to be both academically challenging and appropriately supported. Prior learning through previous module content was taken into account when preparing the new challenge being undertaken. Sanford's challenge/support theory is centered around the idea "that for growth and development to occur, a student needs to have the correct balance of challenge and support for their level of readiness (Sanford 1962)". This idea is often expressed as a grid with challenges and support increasing on each of the axes and a list of descriptors or emotions in each quadrant. This matrix has also appeared as the Daloz's mentoring model and as a means of measuring job satisfaction alongside hygiene factors (Herzberg model). The theory states that when the level of challenge is balanced by appropriate support, (academic) growth can occur. Students were asked to rate on a five-point scale the level of support and challenge they experienced during the virtual labs (**FIGURE 1).** A mode score of 4 for challenge and 5 for support with means of 3.5 and 4.4 respectively were recorded. The responses indicate that the level of challenge and the support was appropriate for the current state of readiness and that the students gained in terms of real learning and growth. This outcome is supported in open text responses.

**FIGURE 1** *Students were asked to rate the level of challenge and support on a five-point scale from 1 - low challenge/support to 5 high - challenge/support. Data is presented as a bubble plot where the blue dot size represents the number of responses. The Mode value is shown in red and corresponds to 14 responses.*

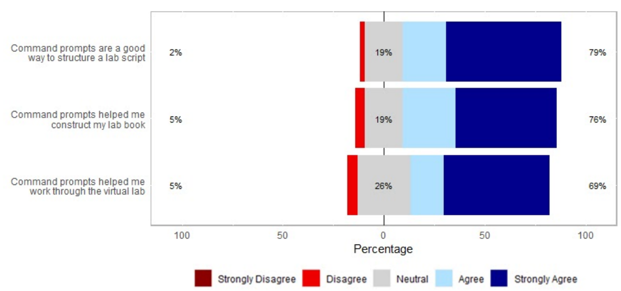



*Command Structure*

To evaluate perceptions of the command prompts as a means of navigating the virtual laboratory and lab book assessment, students were asked a series of questions relating to structure, assessment and navigation. Responses were rated as on a Likert scale between 1 (strongly disagree) and 5 (strongly agree). For the three questions asked, the students predominantly agreed with the statements; "Command prompts are a good way to structure a lab script" **77%**, "Command prompts helped me construct my lab book" **73%,** and "Command prompts helped me work through the virtual lab" **63%**. No responses were recorded as "strongly disagree" for any of the three questions, as shown in **FIGURE 2**. Open text responses to the question "What aspects of the virtual lab experience would you like to see kept for future labs?" recorded that students wished for the system to be incorporated into future laboratory experiences:

"Command prompts could be used in other labs in the future."

**FIGURE 2** Likert scale data responses to student perception of command prompts as a means of navigating the virtual laboratory and lab book assessment. Dark red = strongly disagree, red = disagree, grey = neutral, blue = agree, dark blue = strongly agree.




*Experience*

To gain a broad understanding of student perceptions of delivery, the students were asked to give a three-word response to the question "Describe your virtual lab experience?" The data was cleansed before analysis to remove misspellings and consolidate words of a similar meaning e.g. interested and interesting. A 'word cloud' was then generated as a visual representation of word frequency (23) with more common words appearing in a larger font (**FIGURE 3**). Responses were positive in nature with words such as "interesting", "good" and "informative" used to describe the experiences. "Challenging" was also highlighted as a key word and echoes the responses to the challenge support matrix:

"Generally it was a first, and excellent experience"

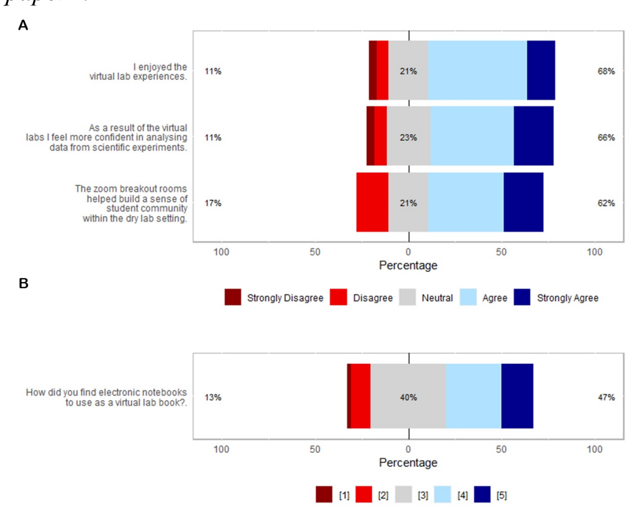
The word "frustrating" was mentioned by a number of students. On deeper investigation of the individual comments this response could be linked to a single effect that occurred during the lab delivery. Due to the number of students accessing the PCR simulator, the website crashed under the demand, preventing student access to the simulation during the allotted time:

"The PCR simulator is frustrating it kept crashing"
"I was not able to complete the lab on a given day - website would not allow me on, frustrating."

**FIGURE 3** *Students were asked to give three words that best describe the virtual lab experience, their responses were used to generate the word cloud shown. The larger the word, the more often it appeared as a response.*


To better understand their perceptions of learning in a virtual classroom, students were asked a series of questions relating to their overall experience and the use of Zoom rooms (**FIGURE 4**). Responses were rated as on a Likert scale between 1 (strongly disagree) and 5 (strongly agree). The overall enjoyment of the virtual lab experience was rated at 68% as either agree or strongly agree, with only 9% of students stating they disagreed with the statement. The use of breakout rooms as a means of building a student community was rated at 59% agree or strongly agree, with 18% of students stating they disagreed with the statement.

**FIGURE 4** *Likert scale responses to (A) Perceived enjoyment of the virtual lab experience, perception of the breakout rooms and data analysis skills development. Text for each question is shown. Dark red = strongly disagree, red = disagree, grey = neutral, blue = agree, dark blue = strongly agree. (B) Student experience of using electronic lab books, ranked on a five-point scale from "Difficult to work with, prefer paper" to "Easy to use, better than paper".*



Open text responses around the use of breakout rooms as a means of support was very positive in reply to the question "In this virtual lab, we worked in a live online environment using break out rooms. Do you have any comments about this style of delivery?" The open text responses were in the majority positive (27 out of the 29), with two being neutral. The comments highlighted the ease of interaction with the academic who was present, and the small groups of peers making it feel easier and more comfortable to ask questions.

> "The breakout rooms are very useful because it splits larger groups down and also having additional general rooms to talk to your supervisor in private is a good idea"
> "Allows for assistance when needed and not distracted by help for other groups"
> "It was really good because the lecturer was always available and ready to answer any concerns"
> "very good because it allowed close contact with our tutor and allowed for asking questions without fear of embarrassment"

Although the use of breakout rooms was not strongly seen as a means of building a sense of course identity, it was seen to be an effective means of support and delivery.

*Skills*

Development of employability skills are a key component of the laboratory experience. Alongside the psychomotor skills associated with handling lab equipment students develop skills around experimental planning, problem solving, data analysis, communication and collaborative work. To address the perceived skill acquisition by the student group each respondent was asked the open-ended question "What skills do you think you have developed as a result of the dry labs?" Each of the 38 responses to the question were thematically grouped based on the textual content. When a given response covered more than one theme the data was counted against each theme (**TABLE 2**).

Prior to the virtual lab 96% of students had never used an electronic lab book. Of the 38 responses, 17 stated in the open text question that they had gained experience in note taking. Given the nature of the assessment and the strong link to the creation of a detailed lab book the number of comments around improvements in this trait is not surprising. When asked about their preference for written notation over electronic notation 47% stated that they were "Easy to use, better than paper" with 40% giving a neutral response. No negative comments were reported regarding the lab books assessment or creation; however, some did ask for further guidance on structuring.

> "I just wanted more info on how to structure them but the command system did help with this a lot ".

With respect to data analysis skills, 39% stated that the virtual lab had increased their abilities. This observation is echoed in the Likert data shown in **FIGURE 4** with 66% of students agreeing or strongly agreeing that the virtual lab increased these skills. Problem solving and critical thinking were also highlighted by the cohort as skills that have been developed. This presumably comes from the iterative nature of the simulations and the open-ended design of the practical day. The virtual labs from the point of view of the students met the key learning objectives of developing critical thinking and record keeping skills. Electronic notebooks were generally accepted by the students.

**TABLE 2** *Thematic analysis of open text comments in response to the question "What skills do you think you have developed as a result of the dry labs?"*

| Theme | Count | Example Quote |
|---|---|---|
| Lab bookkeeping | 17 | "Improved my lab bookkeeping skills" |
| Data analysis | 15 | "The labs also helped develop my data analysis skills as certain aspects forced me to confront my dislike of using excel." |
| Problem Solving /Critical Thinking | 11 | "Critical evaluation of data" |
| Use of equipment | 3 | "The fact that you can play around without fear of breaking a machine is very good as it helps in the understanding of concepts" |

*Student reflections on the virtual lab experience*

Respondents were given the opportunity to comment in general on the virtual lab delivery and experience and what they would like to see retained for future practicals. Of the 34 from 47 who took the opportunity to respond, two reported a negative experience such as "I didn't like them at all". The remaining respondents were positive or offered constructive feedback on the experience. A number of comments reflected on the length of time it took to complete the more in-depth practicals "way too much on the script to fit into the one day" and "first HPLC session very easy but the second one was way too long to fit into one day". Those undertaking further developments in the delivery of virtual laboratories and the use of the simulations need to be mindful of the increased amount of time it takes a student with developing experience to complete tasks as compared to an experienced academic. Overall, a clear theme did emerge from these open text responses. Although the students enjoyed and valued the experience of the virtual lab (**FIGURE 4A**) comments indicated that the student perception was that the virtual laboratory experience was not a complete replacement for the physical lab experience. Rather virtual labs and simulations make excellent learning experiences helping prepare the student to tackle a physical laboratory.

> "They can't replace labs but they might help students make better use of lab time."
> "Would have been better to do physical labs but understandable in the current situation."
> "Exciting new experience but as we all know real time analysis has its own significance."
> "I think it was good but cannot substitute the real lab"
> "They should always come before real life experiments."

*Staff reflections on the virtual lab experience*

Staff running the virtual labs saw many parallels with the experiences in a physical laboratory class. The well organized and prepared students were able to work through the lab scripts with minimum additional support and got results quickly and efficiently. The students who had not come to the lab prepared took longer to complete the labs, requiring much more interaction and support from the academic and their peers whilst also finding the labs harder. The general themes from academic staff and take homes for supporting future classes:

- Better prepared students do better. Some had not done enough pre-lab, for instance research equations required for HPLC analysis. The stronger students had them to hand whilst other students spent considerable time during the lab looking them up.
- Some students require constant reassurance they are on the right track, others are happy to work independently. This does not always correlate to the academic level of the student.

**Discussion and Conclusion**

We have presented here a framework for effective mediation of online biosciences instrumentation simulations. These were developed as a necessity for replacing traditional wet labs during the COVID-19 pandemic, allowing students to develop their laboratory skills remotely. The structure we developed was designed to replicate our traditional laboratory module, with a pre-lab tutorial, lab and post lab tutorial structure, all of which were facilitated synchronously through Zoom. Synchronous delivery with collaborative learning has also been successfully reported elsewhere (7,24).

Students appreciated and enjoyed the experience of using these virtual labs in place of physical laboratories with 68% agreeing that they enjoyed experience. They reported the challenge and support of the simulators was correct for their level of study.

The use of the [Do][Explore][Act] command prompts in lab scripts has been evaluated here for the first time, and they were positively received. When surveyed, 79% of students agreed that they were a useful way to structure scripts. Some students suggested this approach should be kept for future wet laboratory use. Almost all students were new to electronic lab books, as were most staff. The general feeling was that they were better than paper with few negative responses although staff and students did note issues with inserting tables and data into the lab books. The template used for recording results will need refinement for future iterations to avoid such issues. We will also look at whether other available platforms may be more user friendly (18).

Virtual lab simulations can link the scientific theory and laboratory practice in the same way physical labs do, in some cases more so because you can perform more iterations in one day than in a physical lab. The skills that students reported they developed: data analysis, problem solving, understanding how a piece of equipment works and record keeping align closely with the learning objectives for our lab module.

We have some recommendations to academics wishing to (or requiring) to run virtual labs in future. Much of this is achieved through good staff guidance:

- Ensure a pre-lab briefing is used, so students come prepared to the lab.
- Do not underestimate the time it could take a student. What takes an academic two hours could be a full day for some students.
- Not all students appreciated that a simulation or experiment can give open responses, they have been schooled in the idea of a correct answer to their experiments.
- Using the command prompts tells students what and when they are expected to perform an action or record observations into their lab record.

- Have a separate tutorial before the lab sessions to get students used to the electronic lab book platform.

For the future, when laboratories are completely open and we can run our program as originally designed we will keep virtual labs at all levels. They may be interspersed with the wet labs and used prior to key labs as a learning experience. The use of command prompts has also started to be incorporated into lower level labs and it is anticipated that they will be used more as we review the undergraduate program.

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