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Pre-laboratory technique-based simulations: Exploring student perceptions of their impact on in-class ability, preparedness and emotional state

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ABSTRACT

Teaching laboratories are a highly complex environment that require students to master: technical skills; application of theory; safe working and teamwork. Often, students have had very little prior experience to prepare them to this alien and pressured environment. Pre-laboratory tasks are typically considered key to mitigating this issue, with simulations being developed to help students prepare for class and also to help improve their technical abilities. Building on a prior initial study, this contribution evaluates student perceptions toward dynamic laboratory simulations as part of their freshman chemistry course. Our data shows that the majority of students found the simulations to have a positive impact on their learning experience, especially during the enforced online learning experiences that resulted from COVID-19. Students were generally found to be less anxious and more excited to attend the laboratories, and frequently utilized their experiences with the simulations during the in-laboratory class time.

GRAPHICAL ABSTRACT

KEYWORDS

First-Year Undergraduate / General

Laboratory Instruction

Computer-Based Learning

Chemical Education Research

Multimedia-based Learning

Include *JCE*-specific keywords: these must exactly match the keyword terms selected in ACS Paragon Plus during electronic submission. Choose at least one term from each category: Audience, Domain, Pedagogy, and Topic. The keyword term “Chemical Education Research” is reserved for manuscripts that have been written and reviewed using the specific criteria described online. Keywords aid in finding appropriate reviewers and in readers discovering the work online.

BACKGROUND

Laboratory classes form the backbone of most chemistry degree programs.[1] This is a result of the practical nature of our discipline coupled with the expectations of key stakeholder groups including accrediting bodies, employers of chemistry graduates, applicants to chemistry courses and the students themselves[2–4] Running laboratory classes that support the development of high levels of laboratory skills and experience also serves faculty by training the next generation of graduate students. This fundamental importance of laboratory classes in chemistry degree programs coupled with the advent of digital learning technologies in recent years provides faculty with opportunities to enhance the laboratory learning experience by using appropriate digital approaches, for example in assessment,[5] as a means of running remote experiments,[6,7] and as pre-laboratory preparation resources.[8–10]

A number of recent studies have demonstrated the important role that digital technologies play in preparing students for learning in a laboratory environment. Examples of digital approaches that have been used to enhance student preparation for laboratory classes include the use of multimedia resources for use before or during laboratory sessions (e.g. recordings of demonstrations of laboratory techniques,[11] interactive video resources,[12] interactive quizzes (including quizzes that can provide immediate feedback to the student),[13] animated simulations of experiments (or techniques) that provide students with feedback on their attempts[10] and virtual 360° tours.[14]

LABORATORY SIMULATIONS

Laboratory Simulation software packages are computer programs that are designed to mimic some aspect of the laboratory experience. This might be a full experiment, a specific technique used as part of a larger experiment or general laboratory procedures and behaviors. These software packages are designed to be interactive so the user can interact with the experience in a way that mirrors the actual laboratory experience (e.g. by opening and closing the tap on a virtual burette in a titration). Laboratory Simulation software usually provide students with feedback on their performance that can be used to help them better prepare for the laboratory class. Some (but not all) Laboratory Simulation software packages, for example Labster,[15] can act as substitutes for physically doing an experiment by also providing the student with data from the simulated experiment that can be used as the basis of a report the student can be assessed on.

Laboratory simulation software has been available for some time. As early as 1995, a study by Mariana Blackburn reported using pre-laboratory computer simulations to improve student's use of scientific instrumentation.[16] Amongst the praise for this emergent technology was the fact that simulations promoted "logical thinking, active learning and the formulation testing of hypotheses". Bellido et al. reported the use of the Virtual Chemistry Laboratory (VCL) software package with a group of first year engineering students at the Polytechnic School of Córdoba in 2003.[17] Supasorn et al. investigated the impact of a pre-laboratory organic extraction simulation on student comprehension and attitudes in 2008.[17] It was found that students believed the simulation had greatest effectiveness when they were supported by text-based captions rather than narration (this may be as a consequence of the different cognitive loads experienced when engaging with a simulation with caption based versus narrated explanations). A key advantage to using preparatory simulations is their provision of a safe, and flexible, platform in which a student can have multiple attempts, whilst also receiving rapid feedback (either in text or though simulated consequences).[18] This utility for practical classes, and the best practice of embedding simulations in laboratory courses, was highlighted by the University of Leicester's work in 2019 (vide infra).[10]

The adoption of laboratory simulations had been gaining momentum in recent years but this process has been accelerated by the Emergency Remote Instruction (ERI) introduced during the COVID-19 pandemic.[19,20] The pandemic resulted in university courses in many nations transferring to remote or blended delivery modes.[21] For chemistry degree courses there was a clear need to provide students with a means to engage with laboratory learning at times when access to laboratory learning spaces was either limited or non-existent.[22] One way of achieving this was to provide laboratory simulation software that could either better prepare students for the more limited than normal access to the laboratory environment they were given during the pandemic (i.e. to make sure they made most efficient and effective use of their time in the laboratory) or to complement remote experimental work when laboratories were unavailable for use. Alternatively, simulations have the potential to be used as a replacement, but perhaps only in an extremis, and a study by the team at Oxford University highlights the possibilities, utility and benefits of simulations for this means.[23]

AIMS OF THIS STUDY

This study focuses on the impact of digital simulations of laboratory experiments on the laboratory experience of a Freshman General Chemistry cohort at the University of Sydney (Sydney, Australia) in 2020. The simulations studied in this project were procured through by Learning Sciences Ltd. and take the form of a series of self-contained interactive animations that allow students to practice techniques that they will be using in upcoming laboratory sessions. The simulations provide detailed feedback to learners and allow multiple attempts at each simulation. A previous single-cohort study at the University of Leicester has shown that using the same suite of simulations resulted in a non-statistically significant increase in student confidence when setting experiments up in the laboratory.[10] This was supported by student feedback that indicated they were more confident in the laboratory and they felt they were making more efficient use of laboratory time as a consequence of engaging with the simulations. The aim of this study is to build on these initial findings by conducting a systematic study of a larger cohort of students, which to the best knowledge of the authors, is a novel area of research heretofore not studied on this scale or with this methodology.

The research question for this study was:

- What is the effect, if any, of the learning science platform on the perceptions of the students with regards to confidence, independence, and technical ability in the undergraduate chemistry teaching laboratories?

METHODS

Context of the study

Our first-year chemistry cohort routinely includes approximately 2000-2500 students in semester one and 1000-1500 in semester two. The University has historically attracted academically strong domestic students from many schools (both urban and rural), with some students enrolling into chemistry subjects without having completed science courses for their final secondary studies. Additionally, the university attracts many international students with up to 25-30% of the students in some core courses enrolled as international students.

The students in first year chemistry are a mix of chemistry majors, science majors (e.g. physics and biology) and non-science majors. Typically, the majority of first-year chemistry students are *not* intending to continue with higher year chemistry, with a retention rate of about 20% from semester two first year courses to semester one second year courses. In this first year, semester one focuses on quantum chemistry, periodic trends, molecular shapes, thermodynamics, equilibrium, acids/bases and introductory organic chemistry (stereoisomers and functional group identification). Meanwhile, semester two focuses on structural elucidation, kinetics, organic reaction mechanisms, electrochemistry, solid states and metal complexes.

In a traditional year (like 2019), students would complete at least eight 3-hour laboratory sessions per teaching semester. The laboratory program is taught separately from the lecture and tutorial content, which means that the two rarely align. However, where possible, some laboratory activities are aligned within a given semester (e.g. the kinetics and electrochemistry laboratories are run in semester two, not one).

During 2020, and the start of the COVID-19 pandemic, most laboratory sessions were run online. In semester one, students interacted with the online laboratory simulations, attended support Zoom sessions and then completed online quizzes to ascertain their level of understanding. These experiences were then followed by virtual experiments in which students were provided videos of demonstrators completing activities (with a voice over description) and then were asked to analyse the resulting data. In semester two, this structure was repeated for remote students, whereas anyone who was able to attend on-campus sessions instead tasked (in the place of the online ‘experiments’) with two 3-hour ‘technique-focused’ sessions in which all awarded marks were based on observation of technical proficiency.

Questionnaire creation, data transcription and validation

To enable us to collect data from the large cohort of students, a questionnaire was selected as our research instrument. This is available to view in the supplementary material. The questionnaire, distributed upon a student’s completion of the class, featured one open ended question to enable us to capture, in their own words, what effects they believed the simulations were having. The majority of the questions however were consisted of one demographic question (gender identity), as well as 24 closed Likert questions using a five-point scale featuring neutral which would allow us to gain a quantifiable measure and various analysis pathways of intrinsically qualitative data. These 24 questions were chosen to probe: students’ confidence towards the class; confidence toward set techniques/instruments; their competence/attainment; how they sought support; and how they interacted/utilised the simulations. This part of the questionnaire had already been piloted with students at the University of Leicester, with further validation sought at the

University of Sydney through video-interview of nine participants. The interviews asked the participants to read the question aloud and then explain what they understood the question to be asking and how they would answer it. The responses were transcribed and upon review the research team confirmed that most of the questions were being interpreted correctly by the participants and that the instrument was therefore appropriate for analysis. The interviews were then jointly coded using NVivo for analysis.

The closed questions from the questionnaires completed by the undergraduate students were transcribed directly into Excel after recoding (e.g. Strongly Disagree = 1, Disagree = 2, Neutral = 3, Agree = 4 and Strongly Agree = 5). To ensure the questions within the survey held a reasonable amount of internal consistency, a Cronbach's alpha was calculated by SPSS software for all student responses and found to be 0.67. This value is slightly under the literature threshold of 0.7 (Nunnally and Bernstein, 1994), but as this was likely underestimated, as per the use of Cronbach's alpha on ordinal data (Gadermann et al., 2012), the internal consistency of the survey was considered reasonable.

Furthermore, using a factor analysis protocol, 5 factors were found roughly aligning with:

1. the cognitive load experienced by the students (Q 1, 8/9 and 12-17, Cronbach’s alpha = 0.832),
2. the confidence of the students (Q 2-5 and 10, Cronbach’s alpha = 0.814),
3. the students’ perceptions of the simulations (Q 18-24, Cronbach’s alpha = 0.730),
4. the overall experience of the pre-laboratory activities (Q 6-7, Cronbach’s alpha = 0.611) and,
5. the students’ general enjoyment (Q 11, Cronbach’s alpha = N/A).

The factor analysis results show that additional questions relating to the general experience of the pre-laboratory activities and the interest/enjoyment of the laboratory would be required to explore those considerations. Regardless, factors one, two and three align well with the aims of this study and all exhibit alpha values above 0.7, implying sufficient reliability.

To further investigate the validity and reliability of the questions used, online Zoom interviews were also undertaken in late 2020 with nine student volunteers who were awarded a gift card for their participation. Student volunteers were sought via a course-wide announcement asking for students to participate in the interview process. The students were asked to read aloud each question, comment on their interpretation of the question, state how they would reply (e.g. agree) and then *why* they would reply in this way. The result of these interviews is discussed later in the results and discussion section.

Data Collection

The questionnaire was disseminated in a paper-based format during the last 2019/2020 on-campus laboratories in semester two. In 2019, food was provided to students who chose to complete either the questionnaire for this study or a different project running simultaneously. As such, the total number of students were split between the two investigations with 598 questionnaires distributed for this study ($N = 598$). To randomise this process as much as possible, teaching staff handed out the questionnaires in an alternate manner as each student approached the questionnaires and food. In 2020, while only one study was running, not all students attended on-campus laboratories which again limited the total number of participants ($N = 712$ on-campus students). Additionally, in 2020, food was not provided due to the COVID-19 pandemic and the surveys distributed at the commencement of a laboratory lesson. In 2019, 519 responses were collected (87% of the potential respondents) with 419 collected in 2020 (59% of the potential respondents).

Data analysis

Comparison of group responses (i.e. students in 2019 as compared to students in 2020) to each of the individual closed questions was achieved through a Pearson's chi-squared test to check that differences held to Bonferroni corrected confidence interval (i.e. $p \leq 0.05$ became $p \leq 0.002$). Cramér's V was also calculated in order to measure the effect size of any differences (Sheskin, 2003). The cut-offs for the 'size' of the effects were determined through the work of Hattie (2008), which was later extended (Fritz et al., 2012; Lenhard and Lenhard, 2016) to r values. The ranges were defined by:

1. $0 \leq V \leq 0.1$. 'Student effect size'. This refers to the natural variation in any group of students. For example, a more motivated student may respond more positively than a less motivated student.
2. $0.1 < V \leq 0.2$. 'Teacher effect size'. This refers to the effect of a particularly motivated teacher over the course of a single year (i.e. this effect size could be achieved given time/motivation).
3. $V > 0.2$. 'Zone of desired effect'. This refers to interventions that have an immediate impact and are where educators should typically focus their efforts.

Analysis of the aforementioned factors was also considered by first combining student responses to all questions within a given factor. These combined results were then subjected to a Pearson's chi-squared test of the 2019 responses as compared to 2020, using the same effect size calculation and cut-offs as per the individual item analysis.

The interview transcripts were treated to a thematic analysis approach. A single interview was coded by all researchers in a joint meeting resulting in a preliminary set of emergent themes or sub-themes. The research team then coded a second interview separately and a subsequent meeting was used to raise any difficult responses or any inaccurate themes, before the coding of each researcher was combined. Following this, the researchers coded two transcripts each with no additional coders utilised, with one reviewer reanalysing a previous transcript due to a change in themes noted. Once all the data had been coded, the number of times each theme was raised in all interviews was extracted from NVivo.

The responses to the open question in the questionnaire were also treated to a thematic analysis approach. The student responses were transcribed verbatim and a subsection (100-150 responses) of each data set was coded by all researchers in a joint meeting resulting in a preliminary set of emergent themes or sub-themes. The research team then coded a portion of the remainder of the responses separately and before combining. A subsequent meeting was used to raise any difficult responses or any inaccurate themes, and larger parent themes were generated from similar themes coded by the researchers. Once all the data had been coded, the number of times each theme was raised was extracted from NVivo.

RESULTS AND DISCUSSION

Before the responses to the questionnaire could be considered, it was deemed necessary to first consider whether the students were responding to the questionnaire in the manner which was intended. As such, the interview data was used to critically evaluate each item in the questionnaire as well as to provide insight into *why* the cohort responded in the way that they did. As stated in the methodology, the four authors first analysed a single interview together and held multiple meetings to reach consensus. After this point, the authors analysed two interviews each before again meeting to compare and contrast their findings.

Student perceptions – interviews

Of the nine students interviewed, eight were not chemistry majors (but rather science/medicine students), only one had no secondary chemistry experience, seven identified as female and seven had middling to low confidence in their technical abilities after their secondary experiences. As such, the interviews were slightly biased towards:

1) female identifying students,
2) with secondary chemistry experience,
3) who were not likely to major in chemistry,
4) and had low confidence in the technical skills upon entering university.

Out of the 24 closed items in the questionnaire, most students (i.e. at least 7 out of 9) held 'correct' interpretations of 19 (79%) of them. Question six (I prefer my pre-laboratory activity to allow input) was found to be particularly confusing, with seven out of nine of the students holding different interpretations of what 'input' meant. As such, this question was discarded in any further analyses.

An additional four questions also saw many of the students seeking clarification during the interviews:

- Q3 - *I am confident I can operate the analytical instruments (e.g. IR) unaided.* Some students were not sure what other equipment this referred to.
- Q4 - *I am confident I can operate the bench equipment (e.g. balance/rotary evaporator) unaided.* As above, the students were unsure of the identity of the equipment.
- Q13 - *I feel overwhelmed by information during class time.* In this case, we found that students simply did not seem to grasp the overall meaning of the question and often provided responses that did not match the query.

- Q14 - *I sometimes can't understand what to do next as there is too much going on.* Once again, the students simply did not understand the question and struggled to give coherent responses.

While it is difficult to generalise this to the larger student cohort, this high degree of confusion would indicate that caution needs to be undertaken when analysing the cohort's response. This issue will be very discussed later in the article.

Lastly, the students responded to an interpreted open question (What effect(s) do you believe (if any) that the Learning Sciences simulations (that you completed in your previous online technique Zoom sessions and quizzes) had on your laboratory experience?). Again, clarification was required by many students (5/9) as they struggled to understand the difference between the online Zoom support sessions held in place of some on-campus laboratories and the Learning Science simulations (which were shown and embedded within in these sessions and in separate quizzes). Again, this issue would alter how the cohort responses would be considered, with a particular focus on whether the students are clearly referring to the simulations required. The issue of confusion aside, once clarification was provided, eight of the nine participants stated the simulations were helpful in increasing their technical abilities in the laboratory. This positivity is exemplified by the quote below:

'I would say, yes, I think it had a good effect on the lab experience because I remember there was like one simulation where it was about…I think it was like a heating thing. We had to test the melting point and it looked exactly the same as the one in real life, so I found that pretty helpful.'

Overall, the interviews provided confidence in the questionnaire items and provided guidance on issues that needed to be considered when analysing the cohort's responses to the questions that may be flawed. Additional quotes and themes from these interviews will be raised throughout the following sections.

Student perceptions – closed questions (item analysis)

Of the responses collected, approximately 70% of the students identified as female. University records show that our second semester units tend to have an almost two-third split in favour of female identifying students. As such, the data would appear to be homogeneous and representative of the cohort, at least through the lens of gender identity.

As noted earlier, the Likert responses from 2019 and 2020 were compared using a Pearson's Chi Squared test alongside a calculation of Cramer's V to determine effect size. Only two questions were noted to be both significantly different and have an effect size within the 'Zone of Desired Effect', question 3 (I am confident I can operate the analytical instruments (e.g. IR) unaided, $p<0.000$, $V=0.260$) and 11 (I enjoy undertaking practical work, $p<0.000$, $V=0.206$). The responses of the student cohort to these questions are shown in Figures 1 and 2.

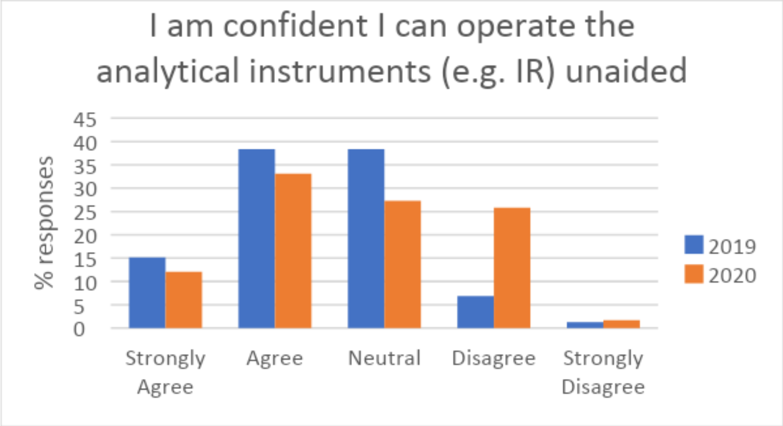

Figure 1. Percentage of students in late 2019 and late 2020 responding to the question 'I am confident I can operate the analytical instruments (e.g. IR) unaided'.

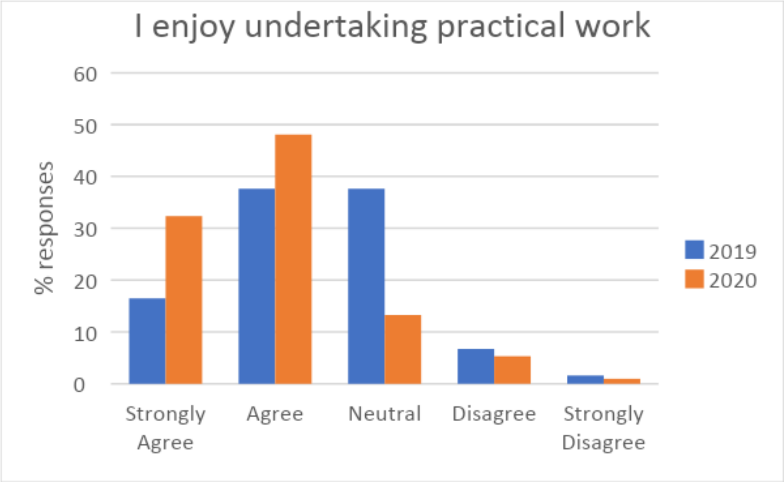

Figure 2. Percentage of students in late 2019 and late 2020 responding to the question ‘I enjoy undertaking practical work’.

It is important to recall that Question 3 was raised earlier as a potentially misleading question, but there is no reason to believe that the 2020 cohort would have been more confused than the 2019 cohort. If true, it would seem that students were somewhat less confident in 2020, a point that will be raised again in comparison to the other closed questions. Alongside this, question 11 was not known to be a potentially compromised item and indicated that students *were* indeed more likely to enjoy their laboratory experience. This increase in enjoyment in the 2020 cohort is considered to likely the result of the reduced laboratory time in 2020 when the COVID-19 pandemic forced many classes online.

Another five questions were noted to be significantly different, but with smaller effect sizes calculated. The questions that showed clear trends towards agree/strongly agree responses in 2020, with no bimodal data, were question 1 (I feel intimidated by the laboratory environment, p<0.000, V=0.192)) and 8 (I often feel anxious or worried during class time, p<0.000, V=0.169). Question 12 (The techniques that I have used in these classes have been difficult to master, p<0.000, V=0.154) resulted in more neutral responses in 2020 with less agree *and* disagree options. Two other questions, 2 (I am confident I can correctly set up experiments in the teaching laboratory, p<0.000, V=0.185) and 4 (I am confident I can operate the bench equipment (e.g. balance/rotatory evaporator) unaided), showed increased bimodal agree/disagree responses in 2020, indicating a split response from the cohort. Graphs of this data are shown in the appendix.

Overall, the responses to the closed questions point to students in 2020 (in comparison to 2019) potentially feeling more intimidated/anxious, more *and* less confident (as the data was more bimodal in nature in 2020) but also being less sure of the difficulty of the tasks completed. The students' increased confidence was noted in the interviews and is exemplified by the quote:

'*So, I think I agree … because the simulation videos before the laboratory and the lab readings really help me to know how to set up an equipment properly and know the structure of it.*'

Student feelings of intimidation or increased anxiety were noted to likely be caused by a range of issues, such as:

- Fear of judgement or loss of marks - '*I'm very scared if I couldn't pass the experiment or I'll make a very silly mistake and then the demo knows that I'm making a silly mistake and they would be like, oh, you're not doing it properly and they will take marks off me.*'
- The physical space itself - '*Because I did feel intimidated like when I went in everything so big. It had all these different sections, like A, B, C, D and I didn't really know what section I was going on*'
- Fear of breaking glassware or instruments - '*there's always that slight stress of you don't want to do anything wrong or break anything.*'

It is of interest to consider why this may have been heightened in 2020 and it is believed that this was due to the decreased laboratory time, which would have limited these issues as the students became familiar with the teaching space.

Lastly, the perception from some of the students that the 2020 laboratory sessions were less difficult to master is likely due to their simplified nature resulting from the technical skills focus utilised in 2020. Indeed, one interviewed student noted that:

‘*The face-to-face classes I actually found really good. They were pitched at a good skill level and so I strongly disagree – so they weren’t difficult to master but they also weren’t too easy*’

The final seven closed questions to consider were only asked of the 2020 cohort as they referred specifically to the Learning Sciences simulations (which were not utilised in 2019). The students’ responses to these questions can be split into three main categories – majority agreement (agree and strongly agree responses > ~60% of the cohort), split/neutral response (neutral responses >30% of student responses with split responses either side) and majority disagreement (disagree and strongly disagree responses > ~60% of the cohort). The breakdown, alongside representative quotes from the interviews, can found in Table 1.

Table 1. The simulation focused questions receiving mostly positive responses, negative responses, or neutral responses alongside aligned interview quotes. The percentage of students giving these responses are also shown.

Question (% positive responses)	Representative interview quote(s)
Majority agreement (% sum of Strongly Agree/Agree responses)	
I engage with the simulations as many times as I need to get the "correct" answer (70)	*'You can do it multiple times and nothing happens – you can just keep doing it and keep doing it and it's all good.'*
When attempting the experiment in class, I utilize the feedback from the simulations (63%)	*'I could sort of try to remember back to the simulations and remember what I was meant to do in them and then use them in the lab.'*
I am motivated to use the simulations as the feedback provided told me where I made mistakes (71%)	*'You can do all the stupid things that you shouldn't do in a lab*
I am motivated to use the simulations as the feedback provided told me where I was correct (68%)	*'I think that positive feedback is just as useful as the constructive feedback.'*
Split/neutral response (% Neutral responses)	
I engage with the simulations multiple times since I know I am not being assessed (29%)	*'if it is marked then you won't intentionally choose a wrong answer, right? So, instead if it is marked, you'd be more cautious in what you're answering.'*
	'it didn't matter either way whether I was being assessed or not'
I prefer simulations to the equivalent video instruction (31%)	*'I go for like neutral on that one because I think they both are important to be honest.'*
	'The videos were helpful but I think the action of like actually having to set it up in a simulation myself'
Majority disagreement (% sum of Strongly Disagree/Disagree responses)	
I prefer to get feedback from the simulations rather than a demonstrator (60%)	*'I think the simulation is very fixed and it's not flexible as a real experiment'*

Overall, these results show positive results for the simulations, with students tending to state that they engaged with the simulations multiple times and recalled the information during class time. Interestingly, the split responses show that:

a. the use of assessment would need to avoid marking individual interactions and should potentially focus on holistic marking (e.g. completing the overall simulation)

b. the simulations pair well with video instructions, creating a multi-modal teaching environment.

Lastly, the students were very clear (in both the questionnaire and the interviews) that the simulations could not be used as a replacement for the demonstrating staff. This need for human interaction is a positive outcome as the student-demonstrator relationship is a key component of a successful teaching laboratory.

It is interesting that students tend to repeat these simulations to support their learning. This aligns with the findings of Blackburn et al. when using the same simulations at the University of Leicester and the findings of Nicholls' investigation of student use of pre-laboratory quizzes.[10,24] It is worth noting that Makransky et al. reported a much lower level (only 20%) of repetition of a different set of pre-laboratory simulations by University of Glasgow Microbiology students.[25] This difference may be due to the fact that the protocol of the Microbiology simulations included an element of intrinsic repetition (i.e. students had to repeat the same general approach in a number of different contexts in order to successfully complete the simulation).

Student perceptions – closed questions (factor analysis)

Of the five factors raised in the methodology, only factor one (student cognitive load) and two (student confidence) can be considered for comparison between 2019 and 2020. This is due to factor three (use of simulations) only being raised to the 2020 cohort, and factors four (perceptions of pre-laboratory tasks) and five (enjoyment) having too few questions/low reliabilities.

A comparison of factors one and two (using a Pearson's chi-squared analysis) showed significant differences in both factors between 2019 and 2020 (p =0.008 and p<0.000 respectively). However, only factor two showed an effect size above the small/student range (0.137). Figure 3 below shows the decrease in student confidence noted through comparing factor two between 2019 and 2020 – which matches with the discussion raised earlier.

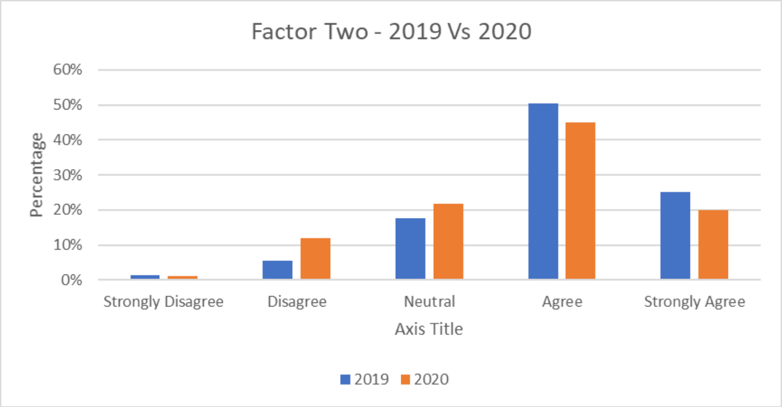

Figure 3. Percentage of students in late 2019 and late 2020 responding to a group of ‘confidence’ related questions (i.e. factor two).

Student perceptions – open questions

The final data set to be considered was the student responses to the open question ‘What effect(s) do you believe (if any) that the Learning Sciences simulations had on your laboratory experience?’. Of the 373 student responses in 2020, 237 (64%) of the students stated positive effects, 36 (10%) felt that the simulations had no impact, 33 (9%) had mixed perceptions and, lastly, 67 (18%) provided responses that did not align with the use of the simulations and could not be coded (similar to the confusion noted during the interviews). With regards to the confusion, future studies would be well placed to provide an image of a given simulation in order to clarify the question. The reasons behind *why* students felt there was (or wasn’t) an effect are shown below in Table 2.

Table 2. The themes raised by students when asked ‘What effect(s) do you believe (if any) that the Learning Sciences simulations had on your laboratory experience?’

Theme / *N*	Quotes
Generally positive impact *(237)*	
‘Good’ functionality (132)	*‘very helpful in showing a more visual simulation of practicals without being in a lab’*
	‘they prepared me for the experiments well by showing what would and would not work, ability to make mistakes & learn from them’

	'A good demonstration of the laboratory techniques. Very useful and convenient.'
Eased in-laboratory experience (82)	*'helped be more prepared in my lab sessions.'*
	'it enabled me to complete the lab activities more efficiently and with more ease'
Reduced anxiety or increased confidence (27)	*'It makes it easier, it prepares me for what is to come during the practical and made me less nervous when I was conducting my practical.'*
with a caveat (13)	*'Ultimately could not replicate an in person lab experience'*
No impact (36)	
No clear value noted (24)	*'They were quite forgettable (personally). The F2F pracs were much better to actually pick up on the nuances of experiments with demos.'*
Disconnect between virtual and reality (14)	*'Not much as there is a difference between watching & actually performing the skills'*
Mixed experience (33)	
Flawed, but at least provided *some* practice (33)	*'Provided some familarity with procedure and equpment but gave no practical experience or skills - in person labs taught those skills much quicker and easier + more engaging.'*

The data in Table 2 shows that students who were positive about the impact of the simulations tended to feel that the simulations ran well / provided a good visualisation of the techniques, made their in-lab experience a little easier and/or less anxiety producing. This last theme, that of an eased in-lab experience, may imply a reduced cognitive load during class time due to the simulations. Additionally, it is important to note that a handful of students were quite clear that despite their overall positivity, an in-person laboratory class was still required to master the techniques.

Of the students who noted no perceived impact, this was typically due to a feeling of disconnection between the virtual simulations with real-life experiments and/or simply finding the interaction with the simulations to be unappealing/forgettable. While this was a minority of the cohort, efforts could be made to clarify this link by utilising the simulations again *during* class time, especially when we return to on-campus laboratories.

Lastly, students with mixed perceptions tended to raise themes from both the positive and no impact theme lists while overall stating that the simulations were either ‘better than nothing’ or particularly subpar when compared to an on-campus experience. The perceptions of these students is again worth taking into account, and would likely shift to a more positive stance if the simulations were more clearly shown to be intended to *enhance* the on-campus experience rather than to replace it (which was more the case during the height(s) of the COVID-19 pandemic).

Overall, the responses noted to the open question are in good alignment with the interview data previously collected. The simulations are generally perceived to be impactful, especially when acknowledged as a preparatory tool only. Further research into their impact is still needed from the perspective of the laboratory teaching staff, alongside actual data on the behaviour of students and the questions asked (likely through video or audio captured data). However, this study shows that the student cohort is typically in favour of the simulations and their use in laboratory teaching and learning.

The above outcomes suggest that the simulations may help support complex learning in the laboratory environment through scaffolding. Agustian and Seery have noted that using pre-laboratory simulations can support the development of mental models and allow students to become familiar with the whole-task procedure in the simplified context of the simulation before attempting the experiment in the laboratory environment.[13]

Limitations

The three main limitations of this study are:

1. The COVID-19 pandemic. Undeniably, the lack of on-campus activities and the stress of the pandemic itself likely impacted the experiences of the students. However, this is exceedingly difficult to quantify and as such, remains an unknown limitation to the data collected.

2. The low number of interviews undertaken. Nine students out of a potential 516 is clearly a small number, and it is highly likely that the perceptions of many students were not represented in these interviews. However, the interviews were mostly used to extend the highly representative number of closed and open question responses, thereby partially negating the impact of this limitation.

3. The issues noted with the questionnaire. As the interview data clearly showed (alongside the factor analysis results), additional work would be required before the questionnaire correctly measured each artefact of interest. However, as this study was relatively exploratory and the aim was not necessarily to create a questionnaire for wider distribution, this limitation is not considered to undermine the study completed.

CONCLUSION

The impact of the use of a range of technique-based simulations (from the Learning Sciences Inc.) was considered through the use of a paper-based questionnaire distributed to students in 2019 and 2020 at the University of Sydney. The questionnaire was devised to interrogate the students' experience of the laboratory through consideration of the affective domain to their learning, the cognitive load induced by the learning environment and the level of their interaction with the simulations both outside of and during the on-campus classes. 519 responses were collected in 2019 (before the simulations were utilised) and 419 collected in 2020 (after the simulations were utilised during the COVID-19 pandemic). Additionally, nine student interviews were conducted in 2020 to both validate the questionnaire and to provide depth to the analysis of the student responses to the questionnaire.

Comparison of the closed questions between the 2019 and 2020 cohorts indicated only a small number of questions that were answered significantly differently. However, as this data represents one of the first studies into the impact of simulations of the student laboratory experience, the authors believe this data to be an important contribution to the growing research field. In general, students in 2020 had more mixed responses to confidence related items, were more likely to be excited to come into the labs but also more anxious/intimidated, and, lastly, were less able to identify the 'difficulty' of the techniques encountered. The interview data generally aligned with these findings, with students indicating the overwhelming nature of the laboratory was likely exacerbated by their limited experience in 2020.

Even with the overall shift in perception in 2020, students were very positive towards the simulations. It was noted through the simulation-focused closed questions that students were highly likely to repeat the simulation experiences until they got the correct answers and that they tended to recall the positive *and* negative feedback provided by the simulations during class time. Analysis of the open-question, 'What effect(s) do you believe (if any) that the Learning Sciences simulations had on your laboratory experience?', backed this finding with the majority of the students raising positive impacts on their laboratory experience as a result of having completed the simulations prior to class. This positive outcome was, through a thematic analysis of student responses, attributed to the ease of utilizing the simulations, their relatively 'correct' visualisation of real-world equipment/techniques and the lowering of in-class anxiety (or an inverse increase in student confidence). Once again, many of the interviewed students reported similar findings.

Implications

Overall, this research has shown that the technique simulations are having a positive impact on the student experience when they enter a given undergraduate laboratory. However, it is unclear if students are actually technically more able, or are just experiencing an increased confidence akin to the Dunning-Kruger effect (i.e. they don't know what they don't know).[26] As such, future research is needed to track the actual behaviour and competencies of students in the laboratories as a result of completing the simulations.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX.

Appendix (DOCX), containing raw data and the questionnaire

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NOTES

The methods used to evaluate the student perceptions and performance data was carried out in accordance with the University of Leicester's Code of Practice for Research Ethics and with approval from the University of Sydney Human Research Ethic Committee.

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