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Acquisition of experimental chemistry skills with the use of virtual laboratory simulations

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Abstract

The acquisition of laboratory skills is an essential aspect of any Biological Science degree. Access to the physical laboratory has been limited in recent years and as such alternative provision was necessary to ensure students learn these essential skills. This study focusses on the provision of virtual materials in the teaching and learning of the specific technique of acid-base titration on a Life Sciences foundation year chemistry module. To assess the efficacy of this alternative provision is in maintaining the acquisition of students' experimental skills, worksheet outcomes were compared when students performed a titration themselves in the laboratory or virtually, using a Labster laboratory simulation. Student opinions of the virtual resources were generally positive, although perception of the utility of these virtual resources in student confidence to perform the experiment for real was lower for online only students. This study demonstrates that the use of virtual materials successfully supported student understanding of the technique of acid-base titration, with comparable worksheet scores between online and in person cohorts. However, the reduction in confidence levels in online students should be noted, highlighting the importance of providing a range of materials to support student learning; including performing physical experiments to acquire essential scientific laboratory skills and increasing confidence.

Keywords: Higher Education, foundation year, virtual laboratory, titration.

1. Introduction

Traditional teaching of experimental laboratory skills has been via the laboratory practical, where students follow a prescribed method and so become familiar with the use of specialised equipment in a controlled environment (Johnstone & Al-Shuaili, 2001; Reid & Shah, 2007). Engagement in such physical laboratory experimentation is not always possible, due to issues such as cost, laboratory time, space limitations, student circumstances and most recently the COVID-19 pandemic. This has driven a need for the provision of the learning of practical skills using alternative resources. One possible alternative is the use of laboratory simulations to allow students to experiment virtually and so continue to participate in the active, inquiry-based learning of experimental laboratory skills.

The positive impact on student learning from active inquiry-based learning are well established (Adams, 2009; Allchin, 2013; Attard et al., 2021; Cairns & Areepattamannil, 2019; European-Commission & Rocard, 2007;

Hofstein & Lunetta, 2004; Minner et al., 2010; Oliver et al., 2021) encouraging engagement with STEM subjects. This can be provided either through the traditional practical laboratory or via virtual laboratory computer simulations (Chernikova et al., 2020; De Jong, 2006; De Jong et al., 2013), which follow the guided discovery principle of multimedia learning (Mayer, 2014). Experimental computer simulations such as those provided by Labster (Labster) or Physics Education Technology (PhET) (PhET) can still support all stages of the scientific inquiry-based learning cycle: Orientation, Conceptualization, Investigation, Conclusion, and Discussion, in electronic learning environments, reviewed in (Pedaste et al., 2015). Research demonstrates that these active discovery simulations can successfully support student learning, engagement and motivation (reviewed in (Smetana & Bell, 2012) (Osborne & Dillon, 2008)).

Comparative studies support the idea that virtual laboratory simulations can result in student learning outcomes similar or even greater than physical experimentation (e.g. (Coleman & Smith, 2019; Finkelstein et al., 2005; Makransky et al., 2016; Pyatt & Sims, 2012; Scalise et al., 2011; Thisgaard & Makransky, 2017; Toth et al., 2014; Zacharia & Olympiou, 2011). However, it should be noted that the greatest positive impact of using virtual laboratory simulations is achieved when these materials are used in conjunction with, rather than a replacement for, more traditional methods (Bonde et al., 2014; Polly et al., 2014; Smetana & Bell, 2012).

The Labster virtual laboratory simulations utilised in this case study provide an authentic laboratory experience containing all 5 aspects of the design principles for interactive multimedia activities (Moreno & Mayer, 2007): Dialoguing, Controlling, Manipulating, Searching and Navigating. (Labster; Plass & Schwartz, 2014).

Dialoguing: students answer questions and receive immediate feedback within the simulation or interact with the theory sections which are always available (figure 1).

Controlling; Students have the ability to work at their own pace, return back to checkpoints, pausing the simulation or even restarting from the beginning.

Manipulating; students are required to move particular instruments or materials within the simulation correctly to perform the virtual experiments or interact with animations of the sub microscopic levels of molecular concepts and reactions (Johnstone, 1991) (figure 1).

Searching; students can choose which reactions to perform and can search within the theory sections.

Navigating; choosing menu options which control the movement of the student through the simulation, access to instructions (written and verbal from Dr One, the in-simulation guiding instructor) and the theory section (see figure 1).

This very broad range of interactivity for the students allows for the effective construction of knowledge (Bada & Olusegun, 2015; Mayer, 2014).

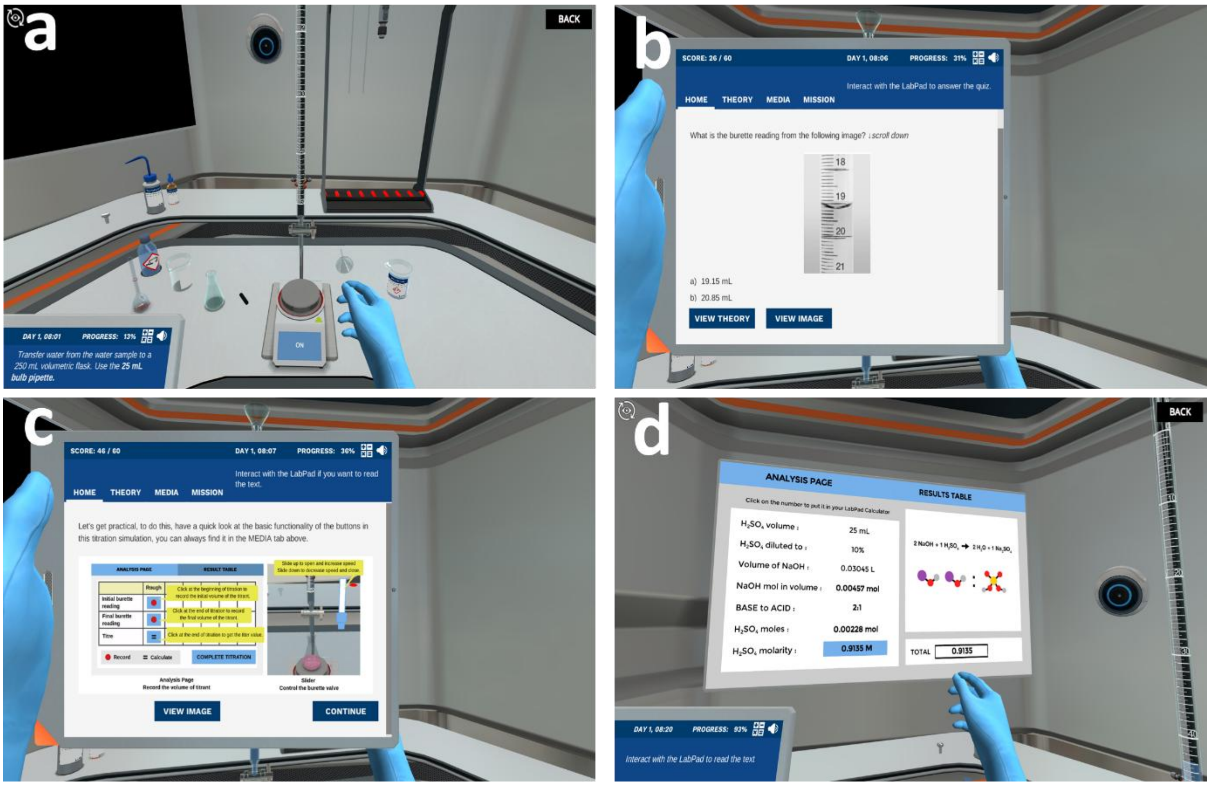

Figure 1. Still images from the Labster titration simulation.

a) Titration experiment. Students are guided to manipulate the titration equipment and perform the experiment. Dr One, the guiding instructor can be seen to the top left of the burette, as a black sphere indicating the moving drone.

b) Practise at reading a burette with multiple choice answers and instant feedback.

c) Detailed instruction on how to carry out titration and record experimental data.

d) Example of detailed stepwise calculation of titration results, including symbolic representation of molecules.

Any inquiry-based learning must be explicitly guided to be effective (Alfieri et al., 2011, de Jong and Lazonder, 2014, Zacharia and De Jong, 2014, Zacharia et al., 2015, Kapici et al., 2022). The addition of human like characters providing instruction with verbal and visual social cues, provides a learning environment which encourages the learners to feel their interaction with the computer is a social one (Moreno and Mayer, 2004, Atkinson et al., 2005), encouraging engagement, as students feel this relationship is cooperative, meaning more effort is made to make sense of the information (Grice, 1975, Mayer et al., 2003, Mayer, 2014)). Within Labster this is provided by Dr One, the in-simulation guide (figure 1a), helping to provide collaborative interactions traditionally made with other students and staff.

One of the significant advantages of using virtual laboratory simulations is the possibility to connect theoretical background information directly within experimental practice. (Makransky et al., 2016a, De Vries and May, 2019). Labster provides a theory tab which is always accessible, explaining the theory behind the experiment and including molecular animations to support student understanding of the theoretical concept (Johnstone, 1991). This immediately accessible embedding of theory within the experimental simulation has a positive impact, reducing the level of student misconception significantly (Admoko et al., 2019), which must be overcome to learn effectively (Nakhleh, 1992, Tümay, 2016).

The skills obtained from laboratory experimentation can be divided into three categories: Conceptual, Motivational and Technical (Zhang et al., 2021) all of which can be supported by Labster virtual laboratory simulations.

Conceptual – the laboratory reinforces or enhances the understanding of concepts, through the experiment and access to theory pages, molecular animations and symbolic representations (Johnstone, 1991) see figure 1d. The construction of conceptual knowledge is well supported by engagement with virtual laboratories (Bonde et al., 2014, Smith and Coleman, 2017, Coleman and Smith, 2019) and is arguably more effective as there is the ability to visualise sub microscopic and symbolic representations in ‘real time’ within the experiment (Johnstone, 1991, Gilbert and Treagust, 2009).

Motivational – the laboratory motivates students to engage with scientific processes such as experimental design and exploration. It also encourages students to engage in actively learning from their mistakes, through allowing incorrect actions within the simulation and unlimited repetitions of the simulation. All of which increases student motivation, engagement and confidence (Smith & Coleman, 2017). This is further enhanced by the use of a real-world narrative to contextualise the experiment. In the titration simulation used for this study, the context is given is a train accident which has resulted in the contamination of a lake with acid. The task being to work out the amount of alkali needed to neutralise the acidified lake water.

Technical skills development – enhances students’ technical skills by physically using equipment as well as research skills when analysing and interpreting their own data (figure 1). This is particularly significant when simulations are utilised as preparation for a real experiment, where cognitive load can be reduced by prior exposure to techniques and the underlying concepts (Coleman & Smith, 2019; Makransky et al., 2016; Polly et al., 2014; Winberg & Berg, 2007), enhancing the ability to develop physical skills in the laboratory.

The advantages of using virtual laboratory simulations are numerous, including: There is a reduced cost as there is no longer the need for specialist equipment and the associated staff to look after equipment. Virtual laboratories require much less physical space and students can complete the simulation at their own convenience, which allows for asynchronous learning and increasing student numbers. Students can work at their own pace, repeating steps or whole experiments as necessary, with the advantage of instant feedback to in simulation questions. Virtual laboratory simulations also provide a safer environment where the use of human or animal subjects can be mitigated, and students can make mistakes and learn from them in a risk-free environment. Whilst virtually practising techniques and so being better prepared for performing the experiment in real life, using physical laboratory time more productively with a reduced cognitive load. Simulations are also able to provide immersive real-world scenarios which would not be possible in the setting of a teaching laboratory. However, there are advantages to the engagement with physical laboratory experimentation; The essential development of physical technical skills, including the incorporation of appropriate health and safety into the experimentation. Time management is an essential aspect of any experiment and this needs to be developed. Without the possibility of pausing the real-life experimentation and coming back to it later, students need to develop the skill of planning their time accordingly. In-person laboratory experiments also allow for social interactions and collaborative learning which is not as easy to replicate in virtual simulations. Again, an essential skill that students need to develop. Reviewed in (Chan et al., 2021; Sypsas & Kalles, 2018)

To provide an alternative virtual resource, video demonstrations were also provided for the online cohort of students, so that they could directly watch a similar experiment taking place in real life under realistic timescales. Such demonstrations have been shown to increase student knowledge on topics such as chemical laboratory safety (Pekdağ, 2020), providing familiarity with equipment and procedures and hence reducing cognitive load when performing the experiment 'for real' (Jolley et al., 2016). However, video presentations provide little opportunity for the interactivity which promotes learning.

This study focusses on the use of virtual resources within the foundation year Chemistry for Biology module, a core module for all students, comparing student worksheet outcomes where virtual materials were supporting or replacing physical laboratory experimentation. The aim of this study was to investigate whether replacement of the real labs with virtual materials had any effect on the worksheet outcomes of students in an online only cohort, as well as inquiring into the students' perception of the utility of virtual practical materials.

2. Methods

2.1. Participants

Student cohorts on the Chemistry for Biology module, in the Life Sciences Foundation Pathway (University of Essex, UK) cohort 1 in person, face to face teaching (n = 63) and 2 online only (n = 47).

2.2. Teaching provision

The teaching provision for the two cohorts, face-to-face for cohort 1 and online only for cohort 2 is summarised in table 1.

Table 1. Learning material provision for topic of Acids, bases and buffers, relating to the titration practical and associated worksheet.

Cohort 1	Cohort 2
Lecture – Acids, bases and buffers	Lecture – Acids, bases and buffers[1]
Lecture support activities	Lecture support activities
Tutorial - titrations	Tutorial - titrations

[1] Cohort 1 Lecture was face to face with embedded lecture support activities. Cohort 2 Lecture was pre-recorded and followed up with lecture support hour revision and supporting activities.

Experimental protocol	Experimental protocol
Wet lab practical including pre-lab quiz	Pre-lab quiz[2]
Collected data	Provided with data
Labster – Titration	Labster – Titration
	Video demonstration[3]
	Laboratory support class[4]
Physical experience	Potential previous experience

2.3. Acid base titration coursework worksheet

Having completed the acid base titration, either in-person (cohort 1) or virtually using the Labster titration simulation (cohort 2), students were asked to complete a topic worksheet to assess understanding. The worksheet included data analysis, of either their personally collected data, cohort 1, or sample data from previous student experiments provided, cohort 2, as well as similar background theory questions. Details available on request.

2.4. In simulation survey

Within each Labster simulation there are embedded Likert scale questions which students are asked to answer when they have completed 100% of the simulation. Data is recorded for each student within their record for each simulation. This was extracted, anonymised and imported into Excel and SPSS for analysis of their experience of the titration simulation.

2.5. Virtual laboratory experience surveys.

Surveys were constructed and distributed via Qualtrics and responses anonymised.
Statistical analysis was performed using IBM SPSS version 27.
Data was tested for normality using the Shapiro Wilks test and as all data sets were not normally distributed or sample numbers were low (<30) non-parametric Mann-Whitney U tests were used to compare data distributions between academic cohorts.

3. Results

3.1 Comparison of coursework outcomes between cohorts.

To investigate the potential impact of online learning of laboratory skills a comparison of worksheet outcomes between the two cohorts was undertaken.
The total worksheet scores of the two cohorts were compared. There was no statistically significant difference between the distributions of the total worksheet outcomes (figure 2), suggesting that the online learning

[2] Pre-lab quiz was in the form of multiple-choice questions for cohort 1 in the physical laboratory using 'clicker' handsets and for cohort 2 a self-marking document via Moodle.
[3] Video demonstration of titration technique provided by Royal Society of Chemistry.
[4] 2 hour support class provided for students to clarify understanding and discuss the experiment.

provision had been as effective as the face-to-face learning in terms of understanding and importantly there was no detrimental effect on coursework outcomes for this task. The mean score for cohort 2, however, is slightly higher than that for cohort 1, which may be a result of being provided with acceptable data, which was not the case for all students who performed the experiment themselves and so had individual data sets.

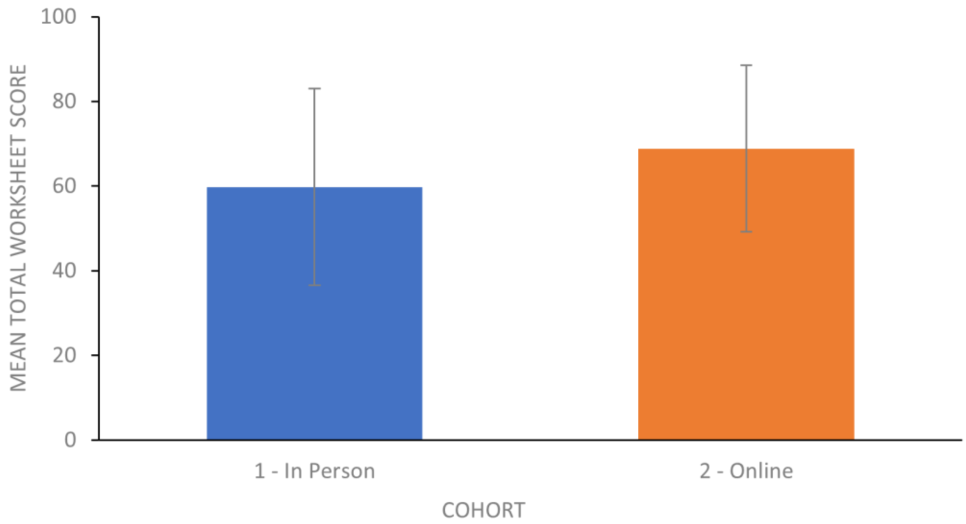

Figure 2. **Total Acids and bases titration worksheet mean scores** for cohorts 1, in person (blue, n = 56) and 2, online (orange, n = 35). Mann Whitney U test p value 0.81. Error bars represent the standard deviation from the mean.

As the worksheet questions include analysis of experimental data and application of theoretical knowledge, to assess students' experimental understanding, a comparison of the scores from the data analysis question from both cohorts is shown in figure 3.

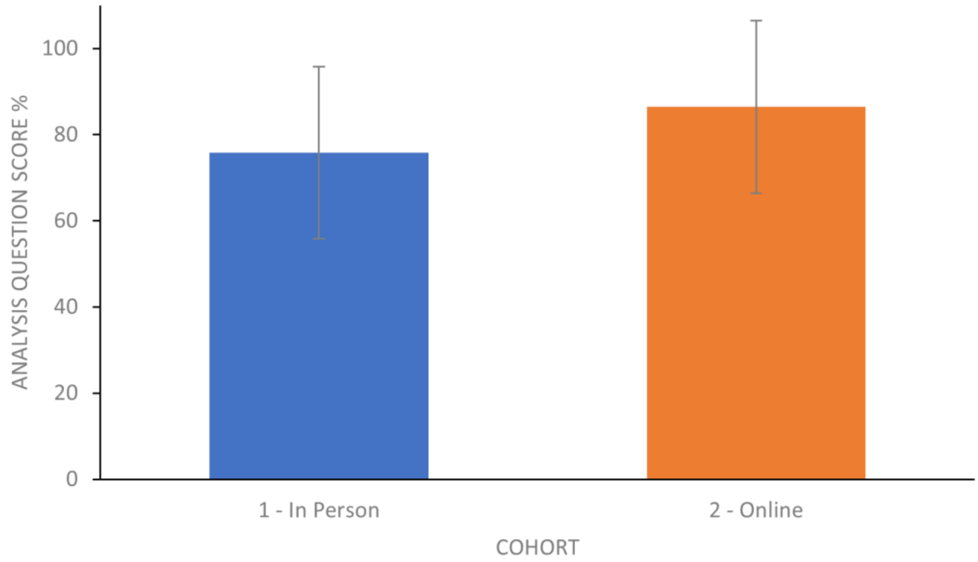

Figure 3. **Acids and bases titration worksheet data analysis question mean scores** for cohorts 1, in person (blue, n = 56) and 2, online (orange, n = 35). Mann Whitney U test p value 0.120. Error bars represent the standard deviation from the mean.

Statistical analysis showed no significant difference in the total worksheet scores or data analysis question scores between cohorts.

As it was possible that students studying online may have had previous physical experience of a titration experiment and so could have been drawing on that experience rather than the virtual materials provided to support their understanding, students were asked if they had previous experience. Responses were matched with their coursework mark to investigate if this previous experience gave them an advantage over their peers, either in terms of the final worksheet score or the data analysis question (figure 4). Note that not all students chose to provide this information.

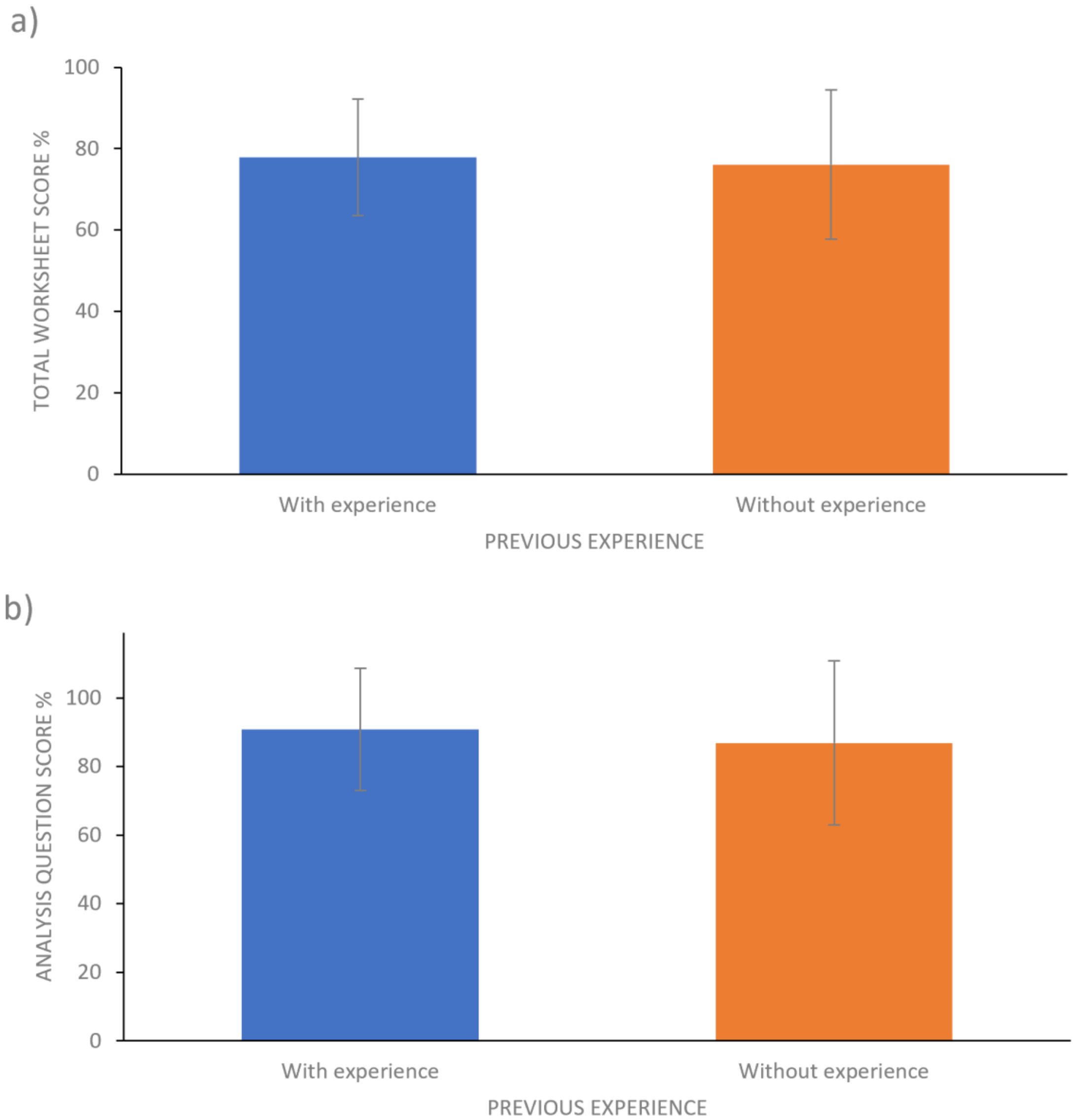

Figure 4.

a) **Comparison of cohort 2, online, mean total worksheet outcomes by experience level.** Acids and bases worksheet outcomes for cohort 2 were separated by previous experience of a titration experiment, blue = without previous experience (n=7), orange = with previous experience (n=10). Mann Whitney U test p= 0.844. Error bars represent the standard deviation from the mean.

b) **Comparison of cohort 2, online, mean data analysis question scores by experience level.** Neutralising acids worksheet data analysis question outcomes for cohort 2 were separated by previous experience of a titration experiment, blue = without previous experience (n=7), orange = with previous experience (n=10). Mann Whitney U test p= 0.378. Error bars represent the standard deviation from the mean.

The lack of significant difference between outcomes suggests that the virtual laboratory resources, and other module materials, provided sufficient learning opportunities for students without previous experience of the experimental technique of titration to perform as well as their more experienced peers in the coursework task. Whilst it was a very positive outcome for students as assessment outcomes were not detrimentally affected by the need for remote study, it was important to assess their opinions on the resources provided.

1.1. Student feedback on virtual resources

At the end of each Labster simulation there is a short feedback survey. A comparison of the in-simulation survey from the Titration simulation were analysed from both cohorts to investigate the opinions of the students of the specific simulation (figure 5). Note that not all eligible students completed the survey.

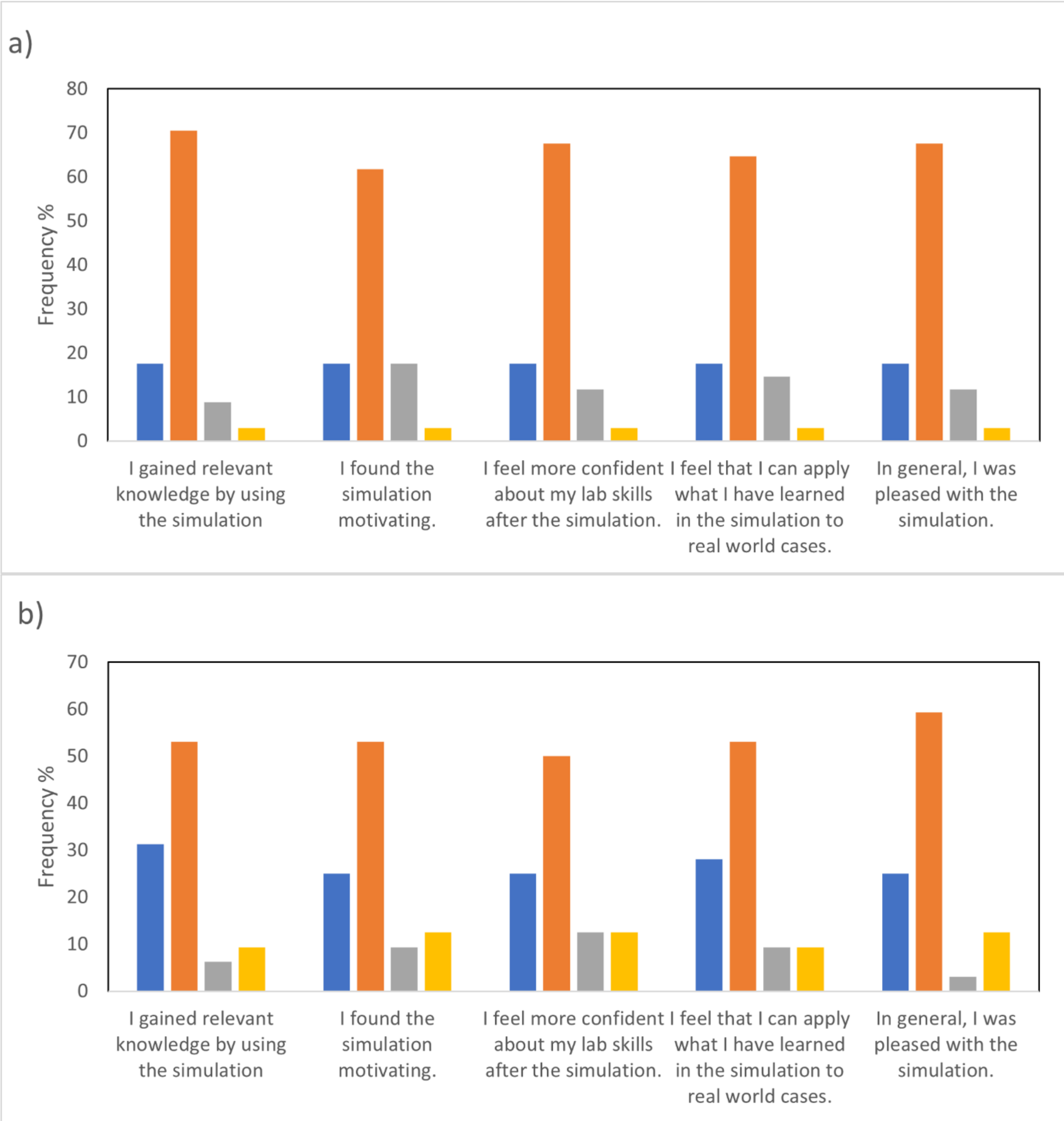

Figure 5. Labster in-simulation survey data from Titration simulation Frequency of responses from a) Cohort 1, in person (N = 34) and b) Cohort 2, online (N = 32). Titration simulation feedback survey on Likert items: Completely agree (blue), Agree (orange), Disagree (grey) and Completely disagree (yellow).

No statistically significant differences in the distribution of responses between two cohorts in the Labster Titration in-simulation survey were observed (table 2). A majority of students reported gaining relevant knowledge and feeling more confident about their lab skills having completed the simulation.

Table 2. Mann Whitney U tests comparison of distribution of responses in-simulation Labster survey from Titration simulation between cohorts 1 (n =34) and 2 (n=32). Significance level 0.05.

Question	U	Total N	P	Decision
I gained relevant knowledge by using the simulation	499.5	66	0.508	Retain null hypothesis
I found the simulation motivating	528.0	66	0.824	Retain null hypothesis
I feel more confident about my lab skills after the simulation	562.0	66	0.794	Retain null hypothesis
I feel that I can apply what I have learned in the simulation to real world cases	508.0	66	0.601	Retain null hypothesis
In general, I was pleased with the simulation	521.5	66	0.736	Retain null hypothesis

It is of note that despite a lack of statistically significant difference, there is a higher frequency of extreme responses from cohort 2 which could reflect the higher stakes of these simulations, as a replacement for physical experimentation, in preparing the students for their assessment.

To further investigate the perceived usefulness of online materials as preparation for the coursework task students in cohort 2 were surveyed and asked ‘Completion of the Labster titration or handout and online demonstration video helped me to prepare for the assignment’, again, there was a range of responses (figure 6). Whilst most students agree that both resources were helpful, the handout and video demonstration is reported as being more helpful than completion of the Labster, and a significant number disagree that the resources helped them.

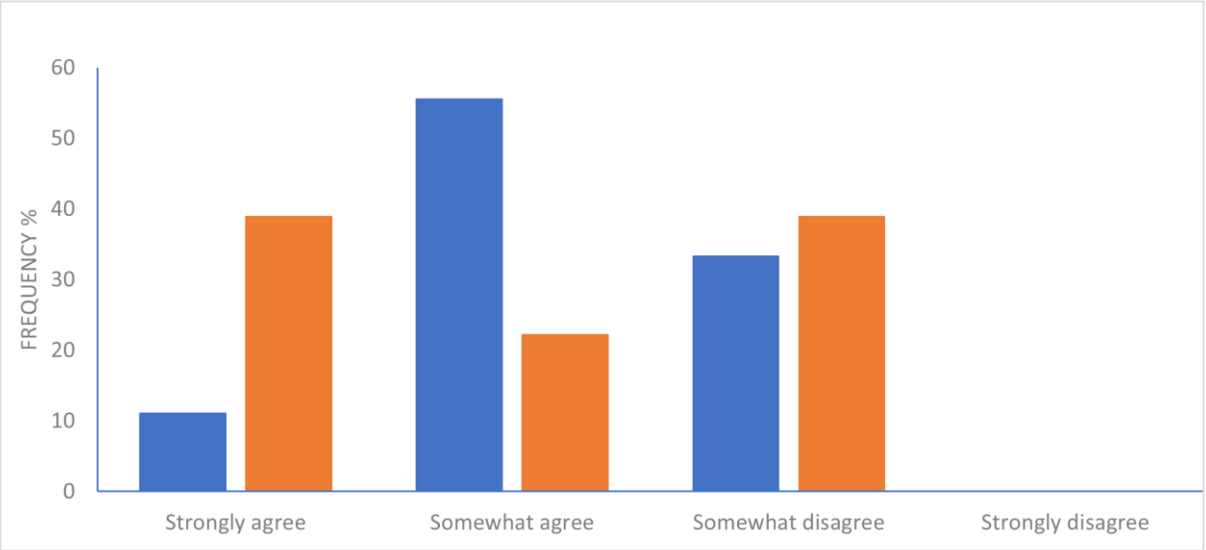

Figure 6. Which resources were most helpful in preparation for the coursework assignment? Frequency of responses from cohort 2, online, on a Likert scale to the question 'Completion of the Labster titration or handout and online demonstration video helped me to prepare for the assignment.' N = 18. Blue – Labster, orange – handout and video demonstration.

Whilst the online resources appear to be an effective learning tool, it is essential that these resources prepare students for physical experimentation. As students on the foundation year programme have varying levels of experience and confidence in the laboratory it was important to assess how much confidence they have gained in their ability to perform the experiment for themselves in real life through performing a virtual experiment in Labster or watching a video demonstration. The question asked was 'Completion of the Labster titration or handout and online demonstration video has given me more confidence in my ability to perform the experiment for real.' The majority of students agreed that the handout and video demonstration were useful (figure 7), but a significant number of students disagreed that the Labster gave them confidence in their physical ability to perform the experiment.

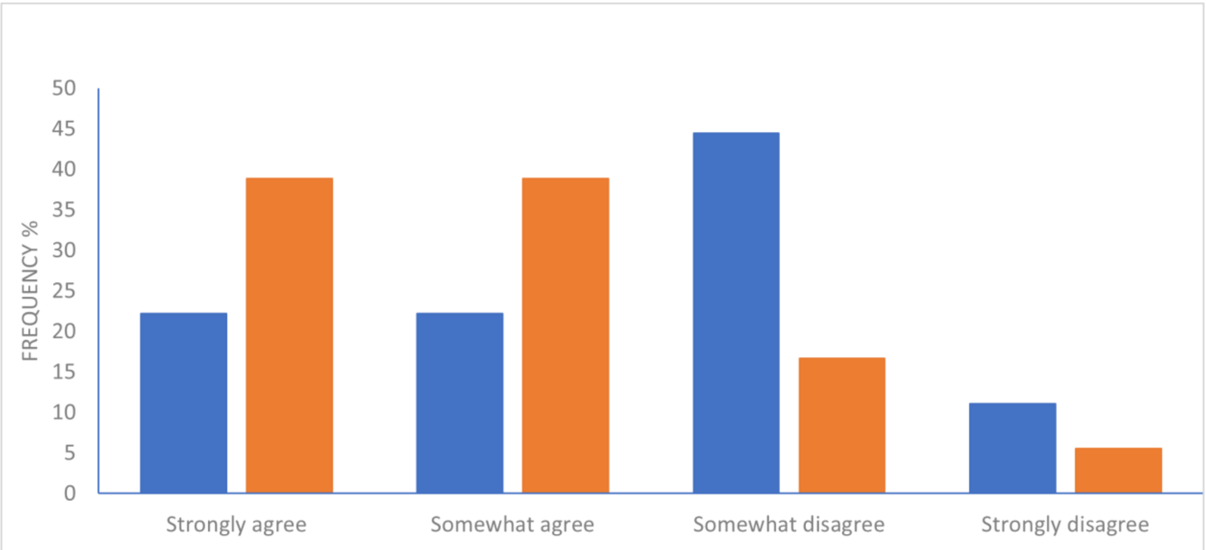

Figure 7. Which resources gave more confidence in performing the experiment for real. Frequency of responses from cohort 2, online, on a Likert scale to the question 'Completion of the Labster titration or handout and online demonstration video has given me more confidence in my ability to perform the experiment for real.' N = 18. Blue – Labster, orange – handout and video demonstration.

Interestingly, whilst Labster provided virtual experience of performing an acid base titration students report finding this less effective, in terms of increasing their laboratory confidence (44% agree), than watching a passive demonstration video of the technique and reading a lab handout, with a comprehensive lab protocol and associated background information (78% agree). This was surprising, since the simulation is interactive, the expectation was that this would be more effective at increasing their confidence. This result contrasts with the in-simulation survey (figure 5b) where the majority of students (75%) agreed that 'I feel more confident about my lab skills after the simulation.'

4. Discussion

Ensuring the continuous high-quality provision of learning materials and environments for our students is essential for them to gain the necessary practical skills. The recent development of advanced laboratory simulations as learning tools has given us a potential alternative to traditional teaching of practical scientific skills.

The purpose of this study was to assess the ability of virtual materials to teach students the experimental chemistry technique of acid-base titration and prepare students for a specific coursework task. Student opinions were also collated on the learning support provided through online materials and the impact on their confidence with laboratory skills.

It was encouraging to find that when coursework outcomes were compared, there was no statistically significant difference between outcomes for those students who performed face-to-face physical experiments or the online cohort with access to virtual materials. No additional advantage was obtained by members of the online cohort with previous experience of the technique in either data analysis or application of theoretical concepts, therefore the remote study teaching materials provided have supported successful acquisition of knowledge of this technique for all students. This result is in line with other studies where learning outcomes were maintained with the use of virtual laboratory simulations (Bonde et al., 2014; Coleman & Smith, 2019; Makransky et al., 2016; Polly et al., 2014; Pyatt & Sims, 2012; Thisgaard & Makransky, 2017; Toth et al., 2014), reinforcing the utility of laboratory simulations as a tool for levelling the playing field for students who may not have as much laboratory experience and giving students confidence in their ability to perform experiments in-person.

Contrasting results from the in-simulation survey and in-house post-assessment surveys regarding students' confidence in their lab skills may reflect the passing of time between the completion of the simulation and assessment. Could it be that immediately after completion of a virtual laboratory simulation there is a peak in confidence in students' laboratory abilities whilst the materials are fresh in their minds, and this reduces over time? Alternatively, this could be a consequence of all students being required to respond to the in-simulation feedback to obtain completion of the virtual experiment, and therefore representing the opinions of the whole cohort, whereas my surveys, although sent to everyone, rely on students choosing to respond, with no consequence to failing to participate. This is a challenging limitation of the study and requires further investigation.

The majority of students report positive experiences with the Labster virtual laboratory simulations. When the simulations were used as replacements for in-person experimentation for cohort 2 this meant that it became a more 'high stakes' activity than when it was an additional learning activity for the first cohort. This, along with the generalised challenges of online learning and potential digital inequality may have detrimentally affected the student experience as a whole and more extreme responses in feedback surveys could reflect this frustration rather than the quality of materials.

Whilst coursework assessment outcomes were available for the whole cohort, the response numbers to surveys were quite low and, by their very nature, self-selecting therefore may not be reflective of the views of the entire group.

As educators we need to consider the wider experience of our students and how their lives impact their ability to study. Never has this been more important than during the recent pandemic. Whilst advances in technology enhanced learning tools provide possible solutions, it cannot be assumed that all students are digital natives, with access to sufficient equipment to be able to fully utilise these resources (Kirschner & De Bruyckere, 2017; Wolstencroft & Zhou, 2020).

This case study has demonstrated that the remote provision of online laboratory materials has maintained student outcomes between the in person and online cohorts, however, the experiences of students varied and, for some, was not a positive experience. This highlights the need to provide a variety of physical and virtual resources to support the diverse learning needs and encourage engagement of all students.

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