Article:

Hyde, J. orcid.org/0000-0001-8819-2411 (2025) A new perspective on chemistry foundation level students laboratory skill development using reciprocal peer-teaching, laboratory simulations, and Practical Skills Portfolio (PSP) during COVID-19 and post-pandemic in 2024. Journal of Chemical Education, 102 (3). pp. 984-1003. ISSN 0021-9584

https://doi.org/10.1021/acs.jchemed.4c01124

JOURNAL OF
CHEMICAL EDUCATION

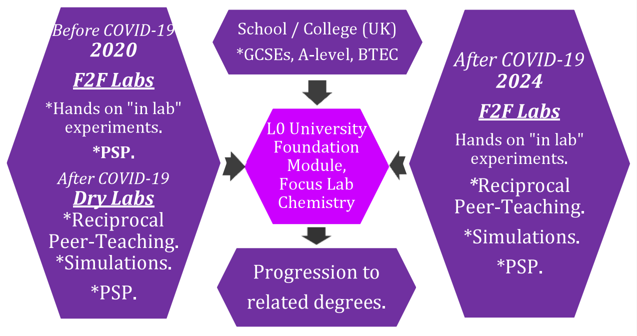
A New Perspective on Chemistry Foundation Level Students Laboratory Skill Development using Reciprocal Peer-Teaching, Laboratory Simulations, and Practical Skills Portfolio (PSP) during COVID-19 and Post-Pandemic in 2024

Julie Hyde*

Cite This: *J. Chem. Educ.* 2025, 102, 984−1003

Read Online

ACCESS | Metrics & More | Article Recommendations



ABSTRACT: Foundation (L0) programs as an entry to degree courses are offered in many UK universities. With chemistry, it is important to develop practical skills as students progress from school to university (*in this manuscript, the term school is used to mean either school or college in the UK*). Investigating the development and confidence of students' laboratory practical skills during COVID-19, 2020 (cohort A) as compared to the 2024 (cohort B) is the subject of interest, in particular finding out what laboratory skills students gained from school and how they improved through the course using different laboratory teaching styles. The teaching styles used were reciprocal peer-teaching, laboratory simulations, and Practical Skills Portfolio (PSP). During COVID-19, dry-labs replaced the Face-to-Face (F2F) laboratory sessions. This study used questionnaires through a mixed methods approach with both quantitative and qualitative questions followed by SPSS and thematic analysis. It was found that due to students entering the course with such a mix of entry chemistry qualifications, they favored differentiated teaching where students would prefer to be taught in two separate groups at their appropriate entry level. Reciprocal peer-teaching was found to be valuable for practical preparation and developing employability skills. The Practical Skills Portfolio was useful to compile a collection of documented skills that could be reflected on for future practical work. Simulations were useful during dry-labs for the preparation of a laboratory session and being able to see actual practical details, although students did not develop hands-on practical skills, and it was discovered that students preferred actual F2F laboratory classes. F2F laboratory teaching led to higher confidence levels for cohort B in comparison to cohort A. Evidence from this research confirmed that students from cohort A (2020) agreed that nothing could replace a hands-on laboratory.

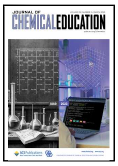
KEYWORDS: *Chemical Education Research/First Year Undergrad/Chem, High School/Introductory Chem, Laboratory Instruction/Curriculum, Hands on Learning, Laboratory Equipment/Apparatus*

■ INTRODUCTION

What is a Foundation Year at University?

Foundation courses are pre-degree courses typically delivered at university[1] that allow progression onto the first year of a related degree program. The University of Sheffield (UoS) offers foundation year courses for students who need to gain qualifications for progression directly onto undergraduate degree programs across a spectrum of different subjects. A science foundation year may be suitable for students who have not studied sciences previously or had an educational break as it consists of a mixture of subjects (chemistry, biology, mathematics, physics, and engineering subjects) together with related laboratories taught during one complete academic year (September to July). The academic content is approximately equivalent to courses delivered at school over two years before university where students gain three "A" levels,[2] where they choose three individual academic subjects to study, such as chemistry, biology, and math (or alternative combinations), leading to 3 specific grades upon completion. Alternatively, a science Business and Technical Education Course (BTEC),[3] can be studied which is a broad vocational science course that includes modules of math, physics, chemistry, biology, and IT, together with work experience. For the BTEC, delivery is

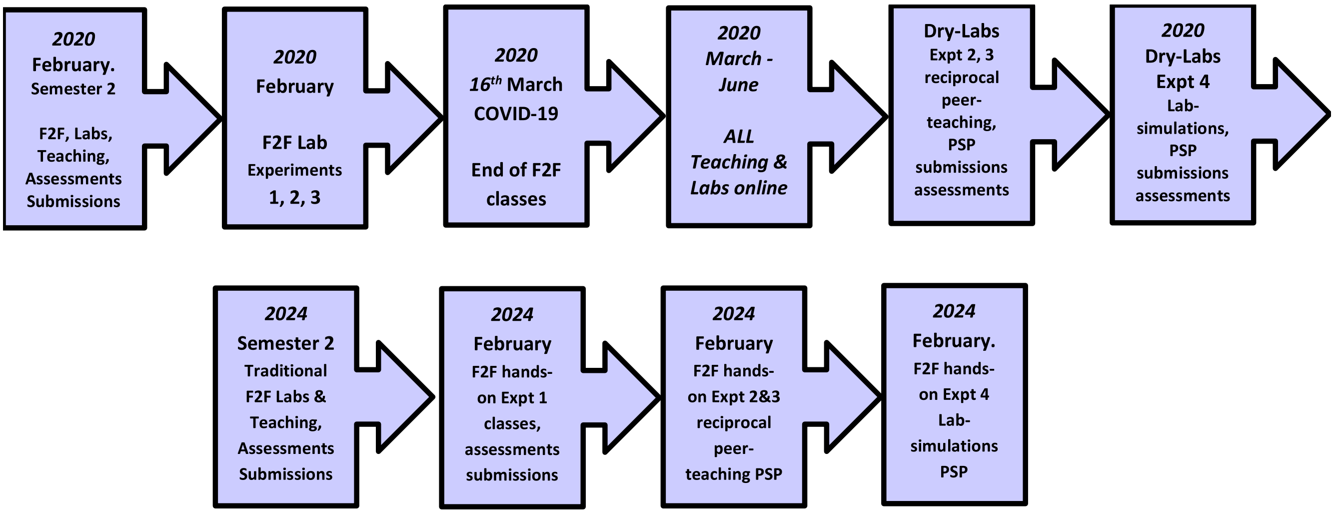
Received: September 10, 2024
Revised: January 16, 2025
Accepted: January 17, 2025
Published: February 13, 2025



https://doi.org/10.1021/acs.jchemed.4c01124

Table 1. Teaching Strategies for Laboratory Work and Theory before and after COVID-19 in 2020 (Cohort A) and 2024 (Cohort B)

	Laboratory Teaching and Theory before COVID-19, Cohort A. Later for the Laboratory Teaching, Cohort B.	Changes to Laboratory Teaching and Theory after COVID-19, Cohort A
Methodology for Practical Laboratory Experiments	**Experiment 1*: Determination of the percentage of copper in a copper salt	**Experiment 1* before COVID-19
	**Experiment 2*: Extraction of limonene from oranges or lemons using steam-distillation	**Experiments 2 and 3* before COVID-19 and **Dry Lab** after COVID-19. For students who did not carry out one of these experiments before COVID-19 the methodology used was **reciprocal peer-teaching**. After students were given a new set of results, writing up experiment 2/3 as if they carried it out themselves.
	**Experiment 3*: Determination of the RMM of an organic acid using a potentiometric titration	
	***Reciprocal peer-teaching** for the second week of experiments 2 and 3	
	**Experiment 4*: Synthesis of aspirin and its analysis by spectroscopic techniques including online laboratory simulations	**Experiment 4*: **Dry Lab**, synthesis of aspirin and analysis by spectroscopic techniques adapted to include online laboratory simulations
Laboratory Work, Assessment and Submissions	*Prelab submitted before the lab	*Prelab submitted online before the lab
	*In-lab assessment	*No in-lab assessment
	*Results sheet is a written report submitted to the tutor 1 week after the laboratory session	*Results sheet is a written report submitted online 1 week after the laboratory session.
	*Practical Skills Portfolio (PSP) submitted to the tutor 1 week after the lab session	*Practical Skills Portfolio (PSP) submitted online 1 week after the lab session.
	*All marked work returned with individual feedback.	*All marked work returned with individual feedback online through blackboard
	NOTE after COVID-19 and in **2024** submissions and marked work online through blackboard	
Methodology Delivering Theory	*Three class face-to-face weekly sessions	*Blackboard online class delivery including Q&A session, synchronous
	*Flipping	*Flipping
	*Online videos	*Online videos
	*Textbook reading	*Textbook reading
	*Classroom discussions and peer-discussions	*Revision questions
	*Questions in class	*E-mail support with Q&A
	*Extension homework questions	
Theory Assessment	*Each three-week block (organic, inorganic, physical), a mini test “in class”	*Each three-week block (organic, inorganic, physical), a mini test “online”
	*Once a month a workshop in class	*Once a month, exam style timed workshop online
	*End of module exam	*No end of module exam
Final Module Grade	*Theory and lab assessment combined to give an overall coursework mark together with the **final exam mark**	*Theory and lab assessment combined to give an overall coursework mark, **no exam**



more vocational (hands-on) and related to the world of work, where each module is graded, leading to one overall grade at the end of the course; this can then be used as entry to a degree at a university. Many UK universities offer a foundation year that has fast-moving and challenging courses.[4,5]

Summary of Teaching Strategies Used for Laboratory Delivery and Theory

The focus of this study is the laboratory delivery and practical skills gained using reciprocal peer-teaching,[6] laboratory simulations,[7−9] and Practical Skills Portfolio (PSP).[10,11] All practical methodologies were used before and after COVID-19 for cohorts A (2020) and B (2024). Various teaching

Table 2. Practical Skills Portfolio (PSP) Illustrated for *Experiment 1*: *Copper Determination*[a]

Practical Skill[b]	Requirements[c]
Observation:	**Observation Requirements:**
*Students document the information and photographs on a proforma.	(i) Take a photograph of the color of the solution when the potassium iodide is added
*Students are required to observe and record the color changes during an iodometric titration.	(ii) photograph the titrated solution when pale yellow/straw
*As well as the color, students are asked how easy it was to observe at different points in the titration, and what is seen at the end point.	(iii) photograph the solution when starch is added (iv) photograph the color of the solution at the end point
Technique:	**Technique Requirements:**
*Students are required to record a photograph of weighing the solid unknown copper solid.	(i) photograph weighing of the unknown copper solid using an accurate balance
*Students are asked about the difficulty of the technique, how to document the weight, and improvements to their performance next time.	(ii) document the exact weight (iii) performance improvement next time
Safety:	**Safety Requirements:**
*Students need to take a photograph of a hazard label of one reducing agent.	(i) photograph the hazard label of a reducing agent
*Students are required to document the hazard for a reducing agent.	(ii) write the chemical name and formula for this reducing agent
*Students are asked how that reducing agent will be disposed of.	(iii) what is the main hazard of the reducing agent you selected (iv) how will you dispose of this chemical?

[a] PSPs for other experiments follow a similar pattern. [b] Typical skill requirements for each section of a PSP. [c] That students need to carry out during the experiment and submit.

strategies were used for delivering laboratory chemistry and theory for the module before and during the pandemic year 2020 (Table 1) some of which are briefly introduced below. This manuscript describes the value of using reciprocal peer-teaching, laboratory simulations, and Practical Skills Portfolio in the situation of dry-labs, and Face-to-Face delivery in the laboratory for students studying a chemistry module on a Science Foundation Year at the start of the international COVID-19 pandemic in 2020 (cohort A) and again with a different cohort four years later in 2024 (cohort B). The motivation for this study is to investigate practical skills progression for these two cohorts of students whose laboratory experiences are similar yet different. Cohort A studied this module before and during the pandemic, whereas cohort B studied the module after the pandemic, and the aim is to look at differences or similarities in students' chemistry laboratory skills. Semester 1 is a bridge for students with General Certificate of Secondary Education (GCSE)[12] (pre-"A" level) courses, who changed their subject interest, or were unsuccessful at their "A" levels or mature students who are returning to study after a break from education. Semester 1, although introductory, is taught in the university style preparing students for semester 2. This 20 credit chemistry module delivered during semester 2 is academically challenging, but successful completion of the foundation course allows progression onto a chemistry degree. Cohort numbers were 26 in 2019/2020 (cohort A) and 37 in 2023/2024 (cohort B), and all students followed either the chemistry or biology route.

Partial Flipping/Blended Learning

Used to overcome high course content,[4,5,13−18] this methodology has been used in science and nonscience courses and is well documented.[19,20] Read and Lancaster brought flipping to the attention of the chemistry community, particularly its use in foundation programs.[4,21] After flipping, tutors check understanding with electronic quiz questions using response devices such as clickers, turning point, Socrative, audience programs, or similar.[4,5,21] The "just in time" teaching methodology can also be used to check understanding.[22−24] Participation in learning this way, by an active learning approach, means flipping frees up class time from traditional lecture delivery, which can be used constructively for other activities.[25] Flipping should not replace course time but is used to enhance the learning experience helping to improve students' preparation, knowledge, and engagement during sessions.[13,26] Laboratory flipping or blended learning[4] was used through pre-lab activities to prepare students for laboratory classes, meaning the actual laboratory time focuses on hands-on activities.

Videos

The value in using videos for teaching chemistry is widely documented, as students can review and keep reviewing videos when the theory is new or the topic challenging.[18,26−29] Students like to see or hear their tutor in the video, as a "personal approach" is popular with students.[14,30] Videos were a major asset for teaching during the pandemic and have been retained for use in many courses complementing Face-to-Face (F2F) teaching.[31−34]

Peer-Discussions or Teaching and Reciprocal Peer-Teaching

This methodology has gained popularity through tutors incorporating it into their usual classes.[35] Subject material is introduced, and students work through more challenging questions or activities by discussions with partners or in small groups. Finally, tutors pull the work together as a group before the end of the class to aid the students' understanding. Peer-discussions are a valuable active learning approach helping to improve students' knowledge and understanding.[20,36] An approach known as reciprocal peer-teaching was used during the laboratory work in 2020 for cohort A and again in 2024 for cohort B.[6] In this methodology, students previously carried out a practical activity; then, in pairs, students who had already done two different experiments joined together, forming a group. In this group, each pair of students explains details and give hints and tips to their peers who have not done the laboratory activity before. The two pairs of students in the group teach each other, and they learn from their peers about a new experiment before carrying it out. This methodology where they are both "teachers" and "learners" was reported in 2023.[6]

Practical Skills Portfolio (PSP)

PSP is a methodology used for laboratory experiments that requires students to complete a short proforma about practical skills carried out and then write brief reflections, Table 2. PSP was developed between two UK Universities, Southampton and Sheffield.[10,11] In Southampton, PSP was used for their Foundation year, and UoS used PSP on the joint BSc (3 + 1) TransNational Education (TNE) degree that was delivered in China, then more recently on the Foundation degree.[37−40] PSP has been found to help students remember practical skills as they carry out laboratory experiments. Writing short reflections about laboratory techniques and chemicals used helps to improve language skills, particularly in the case of international students.[40] Each PSP has several or all of the following categories; apparatus, techniques, observations, and safety. During the experiment, students take photographs, answer questions, write short reflections, and indicate their skill confidence gained on a scale 1 (low) to 5 (high), where each PSP has different requirements. Asking students to report on their confidence about different skills encourages them to consider their performance and honestly state how competent they feel about their proficiency with the skills.

Students are required to prepare a PSP for each laboratory experiment so they generate a document of practical chemistry skills carried out during the module; this can be referred to when they progress onto future courses. These skill notes are similar to how students would document notes during a theory lecture for future reference and revision. Other valuable methodologies that can be used to reinforce and help practical skills development in the laboratory are digital badges and peer-review activities.[41−43]

Challenges Before and After COVID-19

The need to update teaching due to the COVID-19 pandemic was unprecedented, which led to a sudden change in the delivery of practical chemistry and theory in March 2020. Universities and schools were not prepared, and with no time for development it was an overnight change. After 5 weeks of delivery in 2020, Face-to-Face (F2F) teaching abruptly stopped, although fortunately these foundation students knew each other from the initial laboratory sessions and classes, which proved to be a valuable support mechanism.[30] Teaching continued following the original delivery plan as far as possible, ensuring coverage of content and learning objectives (LO). Support and guidance were given to the students about how sessions would be "synchronous" and maintain continuity, with recordings available if students could not attend due to various new and extra commitments.[7,17,26] Experienced educationalists around the world are coping with similar challenges, all working hard to give their students the best experience possible under extremely difficult circumstances. For this UoS module, laboratory sessions and lectures remained mainly synchronous, keeping to original class times, although some were asynchronous, and this style was similar to that found in other university courses.[17,26,36,44−47]

It was important to keep the routine as similar as possible to F2F teaching for the laboratory after COVID-19. Chemists nationally and internationally were challenged on how to deliver practical chemistry.[47] In the absence of the laboratory, many educationalists turned to "Dry Labs", which were adopted for cohort A and are discussed further in the Results and Discussion.[8,48,49] Since the pandemic, educationalists have been incorporating some of the new technologies developed during lockdown into current-day teaching, particularly from the digital platform, where online teaching has changed dramatically. These include the use of videos,[32,33] online conferences,[33] and virtual experiments that were created.[34,50] Students were keen to keep virtual chemistry laboratories after the pandemic to complement F2F laboratories to promote deeper learning.[31,33] It was reported that students are better at self-learning and more organized.[32,33,50] Students reported missing hands-on experiments, particularly trying to imagine procedures online. They are familiar with techniques, but students are still unsure returning to an actual lab, and many reported being nervous about handling apparatus.[32,33] In 2024 at UoS, the same "Dry Lab" methodologies were used in F2F laboratories, reciprocal peer-teaching, and laboratory simulations for cohort B foundation students, allowing comparison of the laboratory skill development of two different cohorts before and after the pandemic.

■ RESEARCH QUESTIONS

The international pandemic has given a rare opportunity to compare student laboratory skills development for a chemistry laboratory program before and after lockdown, leading to the following research questions:

> **RQ1**. How did the students' laboratory skills develop for both cohorts using the methodology of reciprocal peer-teaching and laboratory simulations during Dry-Labs and Face-to-Face (F2F) teaching?
>
> **RQ2**. How were the students' laboratory skills improved using the Practical Skills Portfolio (PSP) as a tool for reflection and consolidation of laboratory skills for both cohorts?
>
> **RQ3**. How did the self-efficacy of both cohorts of students in practical laboratory skills change from what they had after leaving school having completed the laboratory course at university?

■ METHODOLOGY

This research investigated how students progressed with their practical chemistry during and after the international COVID-19 pandemic in 2020, which was a unique situation. In 2024, an opportunity to repeat the same laboratory classes and compare data from both academic years was possible. Teaching styles used for laboratory and theory sessions with changes from F2F to online are summarized in Table 1.

The laboratory for chemists in which students learn and interact with experiments is unique. Students develop hands-on practical skills and understanding through results, interpretation, findings, and communication during laboratory work. Practical investigations for this course fall into this category, and they align with the framework of a complex learning environment.[51] This research used a mixed-methods[52] approach with both quantitative and qualitative questions to investigate development and confidence of practical skills from school to university. This investigation looked at different approaches to deliver practical chemistry before and after COVID-19. Instruments were designed specifically for this research, as the area of investigation was new. The first survey probed students' entry qualifications, previous practical experiences about different practical approaches experienced in the laboratory, and developments during their chemistry course at University. Survey one was inductively developed, as it did not depend on a previous survey. Following analysis of the results from cohort A, four years later a second survey was deductively developed, and it was based on the first survey and used to investigate similarities or changes for another group of foundation students, cohort B, because their formative studies were during the pandemic.[53]

Both surveys used a combination of yes and no questions, Table 3. Likert questions on a five-point scale from 5 (strongly agree) to 1 (strongly disagree), where analysis of responses using SPSS showed a normal distribution, and parametric tests were used according to research in the field as proposed by Creswell,[52] Sullivan and Artino,[54] Lalla,[55] Norman,[56] and Jamieson[57] (Table 4). Open-ended questions were included because it was valuable to get students to discuss their own experiences. These questions were analyzed using thematic analysis by looking at the raw data using a combination of inductive and deductive analysis, which allowed coding of themes and subthemes to be developed, giving a better understanding about laboratory development for both cohorts before, during, and after the pandemic according to methodologies of Thomas,[53] Braun and Clarke,[58,59] and Saldana[60] (Table 5). Students were asked to complete a laboratory skills table about previous skills gained from school and their confidence in these skills after the course (Table 6). These questions were used to gather information to help in understanding students' laboratory progress.

A word question was included to gauge mood and feelings about students' course experiences. Students could select none, one, or more words from four lists of 6 educational words. These results give a general opinion about students' feelings of the course (Figure 13).

Participants, Data Collection, and Analysis

Two different cohorts of foundation students were given an opportunity to take part in a survey about their practical chemistry studies before university and laboratory delivery before and after COVID-19. Ethical approval was gained from the University of Sheffield, Professional Services, Ethics Department (reference numbers 036167 (2020, cohort A) and 059573 (2024, cohort B)). Students were not given any incentives to take part in the survey; it was their own personal choice to participate or not, and they voluntarily took part in the anonymous survey. The survey was administered online, and students needed to consent before taking part. In cohort A there were 26 students with a survey response rate of 46%, and cohort B had 37 students with a response rate of 32%.

Yes/no questions asked about how prepared students felt about the course (Table 3, Figure 1) and about previous laboratory skills (Table 6, Figures 6, 8, and 10). Responses were calculated as % values, enabling analysis about students' preparedness and their previous laboratory skills.

Quantitative questions were analyzed by statistical analysis using SPSS[61,62] and Excel, with both packages used to cross reference data and confirm accuracy of the calculations. Means, standard deviations, and % values were calculated (Table 4, Figures 2−5, 7, 9, 11, and 12). Responses showed normal distribution by considering data as reported by Sullivan and Artino,[54] Lalla,[55] Norman,[56] and Jamieson.[57] To determine the internal consistency of the Likert questions, Chronbach's alpha (α) was calculated to gain an indication about the overall reliability. Survey one for cohort A found $\alpha = 0.88$, survey two for cohort B found $\alpha = 0.85$, and these values are in the "highly reliable" range.[61−65] Independent *t*-tests carried out using SPSS on Likert questions for both cohorts showed there were no significant results for the general questions (Table 4) or about students' confidence in practical laboratory skills after the module (Table 6). These results were confirmed as not being statistically significant because the critical values (CVs) were all lower than standard reference value [CV = 2.074 for df = 22][61,62] and the significance levels of the *p*-values were <0.05 for a 2 tailed test with α at the 0.05 level. A third confirmation is the "95% confidence interval of the difference", which found that all values crossed zero [(+) to (−)]. If values do not cross zero [(+) to (+)] or [(−) to (−)], this indicates the results would be significant. Size effects were not significant according to Cohens-*d*[61,62] as they were found to be small or medium. However, in response to how confident cohort A students were about their practical skills after the dry laboratories (*Q20*) in comparison to cohort B who did hands on laboratories (*Q21*) (Table 6) the results gave a higher CV value than the standard reference of [CV = 3.223 for df = 22], a *p*-value below 0.05 where $p = 0.004$ (2 tailed test), and zero was not crossed [(−) to (−)] ("95% confidence interval of the difference"), meaning these results were significant ($t = 3.223$, df-22, $p = 0.004$). The size effect was large at 1.316 (according to Cohens-*d*).[61,62]

Qualitative questions were analyzed using thematic analysis according to methodologies published in the literature by Thomas,[53] Braun and Clarke,[58,59] and Saldana.[60] To ensure inter-rater reliability, two independent researchers conducted thematic analysis by reading the text a number of times, coding the data, and identifying main themes, whereby the strongest subthemes emerged and the data were reviewed again. The two researchers jointly agreed on the final themes to ensure validity (Table 5). Selected quotes from this data are included throughout the Results and Discussions in italics.

Word analysis questions were calculated as % discussed and presented graphically (Figure 13).

Table 3. Student Preparedness for Foundation Chemistry at the University, Cohorts A (2020) and B (2024)[a]

Q Number	Yes/No Questions[b]	Yes % 2020	Yes % 2024
Q1	I have studied Chemistry before attending University.	92	83
Q2	I have "A" level qualifications in nonscience (or non-Chemistry) subjects.	83	83
Q3	I have GCSE Chemistry (or equivalent).	100	100
Q4	I have "A" level Chemistry (or equivalent).	50	50
Q5	Would it be useful to have revision work in the summer before starting the course?	100	50

[a] Yes/No questions ($n = 12$/year). [b] Q numbers used in text (% value quoted).

RESULTS AND DISCUSSION

Cohorts A and B Starting the Foundation Chemistry Module

Students are from a variety of backgrounds with different educational experiences. Findings from yes/no questions about pre-course experiences were not unexpected and were

Table 4. Laboratory Chemistry: Peer-Teaching, Simulations, PSP, and Confidence, Cohorts A (2020) and B (2024)[a]

Q Number	Quantitative Likert Questions[b]	Mean 2020	SD 2020	Mean 2024	SD 2024
	Preparation for Foundation Chemistry, Survey 1 and 2, Cohorts A and B				
Q6	My previous Chemistry studies prepared me for semester 1 at University.	3.25	1.357	3.5	1.168
	Laboratory Chemistry, Survey 1 and 2, Cohorts A and B				
Q8	The laboratory video clips for semester 2 were clear and helpful to extend theory for the laboratories.	4.25	1.138	4.08	0.9
Q9	The "peer teaching" for the Limonene and Relative Molecular Mass (RMM) worked well ("peer teaching" was when you taught/supported each other for a practical that you carried out the previous week/did not actually carry out in the laboratory).	3	1.128	3.33	0.788
Q11	I found the introductory lecture for the Aspirin laboratory practical useful.	4.17	0.718	3.83	0.718
Q12	I found the Aspirin "Learning Science Interactive" helpful in developing my laboratory skills.	4.17	0.835	3.42	1.311
Q13	I found the Aspirin, Royal Society of Chemistry (RSC) laboratory link helpful in developing my laboratory skills.	4	0.853	4.08	0.793
	Laboratory Chemistry, Survey 1, Cohort A				
Q15	I found the Practical Skills Portfolio (PSP) for practical 1 (copper titration), practical 2 (limonene) and practical 3 (RMM) a helpful aid to reflect on my practical knowledge.	3.83	0.577	n/a	n/a
Q16	I found the Practical Skills Portfolio (PSP) for practical 4 (aspirin), a helpful aid to reflect on my practical knowledge.	3.42	0.793	n/a	n/a
Q20	I feel that I have gained enough confidence in my practical skills as a result of the "dry labs" for me to carry out "hands on practical work" in the laboratory.	3.25	0.965	n/a	n/a
	Laboratory Chemistry, Survey 2, Cohort B				
Q17	I found the Practical Skills Portfolio (PSP) for practical 1 (copper titration), practical 2 (limonene) and practical 3 (RMM) and practical 4 a helpful aid to reflect on my practical knowledge.	n/a	n/a	3.08	0.669
Q18	I found the safety questions in the PSP helpful for developing my safety knowledge	n/a	n/a	3.67	0.651
Q21	I feel that I have gained enough confidence in my practical skills as a result of the L0 Foundation Laboratory Chemistry course for me to carry out future work in the laboratory.	n/a	n/a	4.33	0.651
Q23	Do you feel that studying chemistry during COVID-19 has limited your practical skills	n/a	n/a	3.64	1.502

[a] Quantitative Likert questions, 5 (strongly agree) to 1 (strongly disagree) (*n* = 12/year). [b] Q numbers used in text (5 = strongly agree, 3 = neutral, 1 = strongly disagree).

generally consistent for both cohorts (Table 3, Figure 1). Both student cohorts had studied chemistry before university (*Q1*), and 100% of them gained GCSE[12] in chemistry as single or double sciences or an equivalent BTEC[3] qualification (*Q3*). For both cohorts, before the course 50% had studied "A"-level chemistry[2,66−69] (*Q4*), and 83% had non-science "A" levels (*Q2*). Some students had a chemistry "A"-level, whereas others had only GCSE, meaning there were big differences in previous chemistry knowledge and making it challenging to ensure delivery was academically appropriate for both levels. Educationally it is better to have two separate classes where the students are grouped according to their entry qualifications, resulting in ***differentiated teaching***. This methodology was published in 1930[70] and revisited by the original author in 1979.[71] Differentiated teaching is traditionally used in schools, although not as frequently in higher education. Offering two classes was popular with students, ***course structure*** (*Q7*) "*. . .split the students with "A" level chemistry and those without. Those without "A" chemistry would be able to learn the same content but at a more slower pace*" [cohort A].

There was a mix of opinions from both student cohorts about feeling academically prepared to join the course after school in semester 1. 50−59% of the students in both cohorts thought their previous chemistry studies had prepared them for university. More students disagreed in cohort A (41%) as compared to cohort B (25%) (*Q6*), suggesting this outcome was not pandemic-related (Table 4, Figure 2). These results were not found to be statistically significant after carrying out an independent *t*-test. Foundation groups are a mix of students with varied backgrounds and students who did not feel prepared had possibly not studied chemistry after GCSE.[4,5,20] Even with different academic backgrounds, 100% of cohort A wanted chemistry pre-module revision enabling them to start the course with a basic knowledge; however, this figure was lower for cohort B (50%) (*Q5*), who clearly felt more prepared for university in spite of the pandemic (Table 3, Figure 1).

Qualitative analysis (*Q7*) about what pre-support or guidance would be valuable to the students found three themes (Table 5): ***Course structure*** (discussed above), ***Pre-course resources***, and ***Preparing students***. ***Pre-course resources*** suggests students wanted high quality online resources to be available the summer before starting the course: "*providing reading material ahead of the course start date*", "*possibly sharing some resources on the fundamentals/basics during the summer before semester one could scaffold further learning*" [cohort A]; "*recommended reading for chemistry at university before arrival*" [cohort B].

Comments about ***Preparing students*** suggested students had gaps in previous knowledge or they had not studied chemistry for several years: "*Work set beforehand to ensure that I understood the basics needed to understand the more complicated chemistry*", "*I had not studied "A" level chemistry and it had been 3 years since GCSE...an extremely big jump!*" [cohort A]; "*I think I would have benefitted from sitting "A" level chemistry before coming to University*" [cohort B].

Both cohorts wanted extra guidance in addition to resources such as a scheme of work, including laboratory and theory assessment information. Differentiated teaching offering two groups for these students would enhance their learning and academic experience.[70,71]

Laboratory Delivery during 2020 (Cohort A) and 2024 (Cohort B)

Laboratories need to be challenging to ensure that students develop the skills necessary for progression onto a chemistry degree. For both cohorts, 50% had previously studied "A"-level chemistry, but 50% had not (*Q4*), so good practical

Table 5. Laboratory Chemistry: Peer-Teaching, PSP, Dry Labs, and Confidence, Cohorts A (2020) and B (2024)[a]

Overarching Theme: Differentiated Teaching		
Q Number[b]	Themes[c]	Sub-Themes (ST)[60−62,51,57−59][d]
Preparation for Foundation Chemistry, Survey 1 and 2, Cohorts A and B		
Q7 *Briefly comment on what support or guidance that would help with your preparation for Chemistry at University?*	***Course structure***	*Split group to entry qualifications
		*Teach each at own pace
	Precourse resources	*Valuable online resources: Videos, You-tube clips
		*High-quality information: Questions, reading materials, text references
	Preparing students	*Scheme of work
		*Guidance laboratory assessment
		*Information on topics
Laboratory Chemistry, Survey 1 and 2, Cohorts A and B		
Q10 *Briefly comment about the “peer teaching” for the Limonene and Relative Molecular Mass (RMM) practical, did it help you understand and develop your laboratory skills, was the experience valuable?*	***Good for facts***	*Understanding from peers easier
		*Simplified language
		*Improved understanding of science behind practical
		*Useful tips for good results
		*Consolidate knowledge
		*Efficiency and better acquisition of results
	Team pairing	*Talk and meeting new people
		*Interesting to see how others worked
		*Depends on who was in pair
		*Lack of enthusiasm
		*Not learnt anything
	Laboratory skills development	*Helped development of lab skills
		*Understanding basics of equipment set up
		*Able to develop my lab skills
		*No lab skills were developed
Q19 *The Practical Skills Portfolio (PSP) is a new idea to allow you to reflect on your practical work. Do you feel that it has been useful to help you enhance your practical skills? Briefly add any comments below.*	***Reinforce practical skills***	*Creative idea to record experiments
		*Highlight skills and key points of a lab
		*Think about equipment
		*Keep as a record
	Reflection	*Value of reflection
		*Remembering lab skills
		*Helps understanding and recall
	Disruptive	*Distraction during experiment
		*Phone adds another level of complexity
Laboratory Chemistry, Survey 1, Cohort A		
Q14 After COVID-19. *Briefly comment on “dry labs” and “hands on practical work” in the laboratory.*	***Best alternative***	*Dry-labs useful
		*Good job of replacing laboratories
		*Temporary substitute in COVID-19
		*Only Choice
		*Not same as hands-on
	Being in the laboratory	*Nothing compares to being in a lab
		*Dry-labs not like hands-on
		*Practical work more beneficial
		*Hands-on practical should definitely be prioritised
	Interactives	*Focused on science behind experiment
		*Great job of showing equipment
		*Useful preparation for actual lab
		*Guidance still needed for actual lab
Laboratory Chemistry, Survey 2, Cohort B		
Q22 *Studying practical chemistry during COVID-19 was potentially challenging, however, after studying the Foundation Laboratory Chemistry, do you feel that you have gained the required practical skills for progression. Briefly add any comments below.*	***Confidence***	*Little experience due to COVID-19
		*Proper independence
		*Work alone
		*Never seen or done the practicals before
		*After foundation chemistry ready for progression

[a] Qualitative questions analysis: themes, sub-themes (ST) (n = 12/year). [b] Q numbers used in text. [c] Italics in text. [d] Selected quotes in text, in italics.

preparation was needed. Four foundation experiments were prepared to develop or extend practical skills (Table 1),[37−40] which were inquiry-based activities similar to those of working chemists in industrial laboratories. They require students to research, apply, and understand the chemistry, developing applied vocational thinking as well as future employability

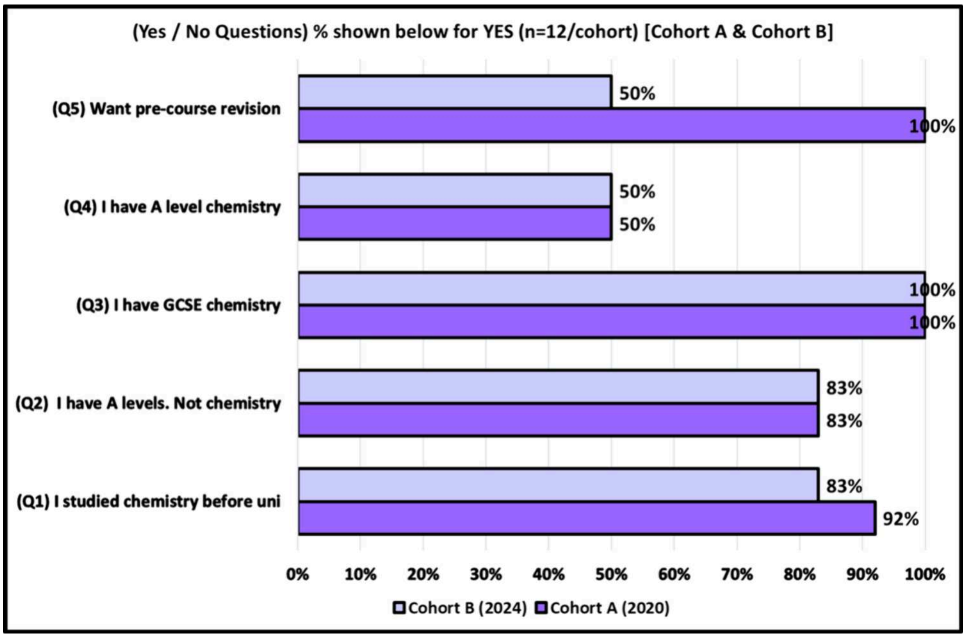


Figure 1. Student preparedness for foundation chemistry at university, cohorts A and B. *Yes/no questions (n = 12/year).*

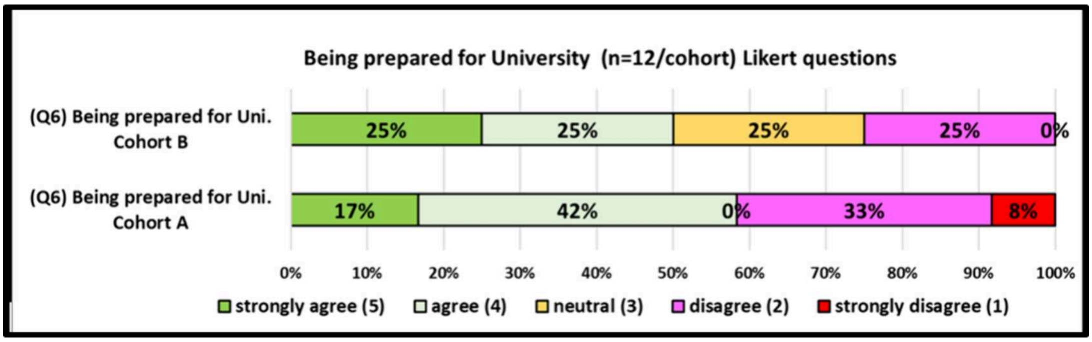


Figure 2. Student preparedness for foundation chemistry at university, cohorts A and B. *Likert questions, 5 (strongly agree) to 1 (strongly disagree) (n = 12/year).*

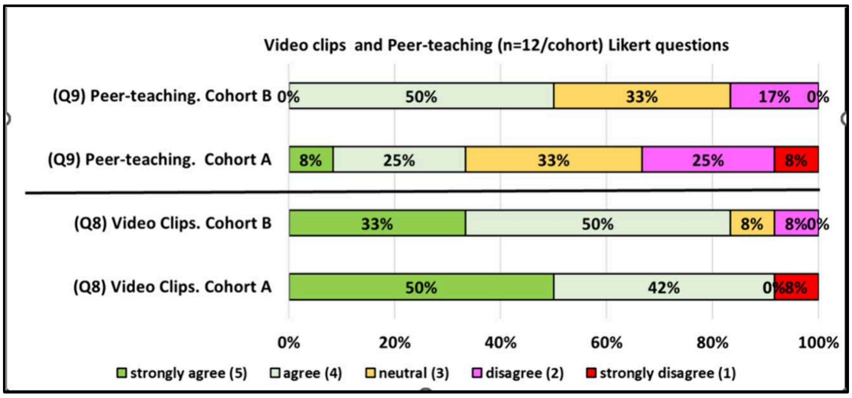


Figure 3. Video clips (Q8), Peer-teaching (Q9), Cohort A and B. *Likert questions, 5 (strongly agree) to 1 (strongly disagree) (n = 12/year).*

skills.[72−74] Experiments 1, 3, and 4 are carried out individually, with students working in pairs for experiment 2 over a 2-week rotation due to the lack of available instrumentation. Half of the group carried out experiment 2 while the other half carried out experiment 3. Students submit pre-lab activities for experiments, which must be passed and returned with feedback.[72] The pre-lab is an example of "laboratory flipping" as it is carried out before the laboratory and content is not repeated during the lab session, meaning laboratory time can be used more productively for actual hands-on activities.[4] Preparatory work before the laboratory reduces cognitive load, so students do not have to worry about too many new things at once.[75] "In-lab" assessment is carried out by Graduate Teaching Assistants (GTAs).[76]

Students submit experimental results using a proforma aimed to develop scientific writing and communication and also complete the PSP in which they record and reflect on their practical skills. Both are marked and returned to students a week later. Overall laboratory grades are a combination of the four parts of the laboratory activities, Table 1.

Peer-Teaching (Limonene and RMM) and Laboratory Simulations (Aspirin)

Educationalists found laboratories challenging to deliver during COVID-19.[48,77] Students could not actually carry out laboratory experiments, although learning objectives (LO) still needed to cover skills, techniques, observations, and safety. Practical experimental videos were not available at UoS, although some universities were able to record experiments during the pandemic.[8,46,78,79] Supportive videos for laboratory calculations were available for both cohorts, and over 80% of the students agreed they were valuable (*Q8*) (Figure 3). Skill development improved after COVID-19, although cohort B still had challenges as they had gaps in prior knowledge, particularly synthetic laboratory skills.

Reciprocal peer-teaching[6] was used during Dry Labs for cohort A and again during F2F teaching for cohort B for experiments 2 (limonene) and 3 (RMM of an organic acid). Reciprocal peer-teaching was used for the experiment the students carried out themselves hands-on in the laboratory the previous week. The methodology of reciprocal peer-teaching was introduced to the students verbally from the tutor, allowing opportunity for discussions and questions from the cohorts to ensure they knew what to do, along with an accompanying guidance sheet. Students who carried out one of the experiments the previous week were paired randomly with students who had not done that experiment before. Each student "taught" their partners from their personal experiences, explaining full details about the experiment they had previously carried out and discussing methodologies, laboratory procedures, result collection, tips, and tricks they used in the laboratory, and their partners "learnt" about the experiment. Then the "teachers" and "learners" swapped duties, repeating the process and resulting in all members of the group knowing about each other's experiment; however, this process had to be carried out online for cohort A.[6] The outcome for cohort A during COVID-19 meant that each student was able to confidently write up their "new experiment" with different results supplied from the tutor. Students in Cohort B carried out experiments they had not done previously F2F in the laboratory after reciprocal peer-teaching, collecting, and writing up their own results. Cohort B felt it was more like the training that you would experience in a work environment regarding teaching or training each other. This was a new active learning style for all the students.[20] From quantitative analysis, student opinions were divided about peer-teaching, although these results were not found to be statistically significant from independent *t*-tests.[61,62] Both cohorts found peer-teaching valuable (33% cohort A, 50% cohort B), saying it worked well for facts and science. Some students did not think it was valuable (33% cohort A, 17% cohort B) (*Q9*) (Figure 3).

Qualitative analysis revealed three themes about the value of reciprocal peer-teaching (*Q10*): ***Good for Facts***, ***Team Pairing***, and ***Laboratory Skills Development*** (Table 5). ***Good for Facts*** suggested value was gained from sharing tips and tricks about laboratory experiments: "*Peer-teaching meant the practicals could be more easily understood as the language was often simplified and therefore more accessible*", "*the peer-teaching was fine for learning the facts about the practical...*" [cohort A]; "*for those who don't understand it that well, it was pretty helpful......those who did already understand it, it helped them consolidate their knowledge*" [cohort B].

The second theme, ***Team Pairing***, suggested concerns about peer-teaching because of unsuitable pairing. If students in mixed groups were not as interested as each other, the process was not valuable: "*I am not sure if it was the best if your partner wasn't as interested as you*", "*. . .depended on who were paired up with. . ..*" [cohort A]; "*Not really as other peers didn't seem too bothered*" [cohort B].

The overall experience, such as working with others and meeting new people in teams, suggested peer-teaching was helpful. Students found it useful to share what others did during the class, particularly for facts, which helped them understand the practical more easily: "*it was interesting to see how others worked through the labs we were unable to do*", "*. . . it helped to talk to new people who aren't in your friendship group*" [cohort A]; "*. . .it was helpful being able to have a variety of people to ask*" [cohort B].

Theme three, ***Laboratory Skills Development***, found peer-teaching was not very successful in developing skills during COVID-19 [cohort A], which was not unexpected as real practical work could not be carried out: "*. . .I did not learn anything about the equipment*", "*it did not develop any lab skills..*", "*I did not find this very beneficial as it did not allow me to carry out the practical myself so the practical write up was difficult*" [cohort A].

For cohort B, sharing skills and equipment knowledge during the peer-teaching was found to be helpful, particularly if the student was a novice "*It helped understand the basics for the equipment set up..*", "*..good tips for efficiency and better acquisition of results. . .*" [cohort B] or in the case where students had previously done the experiment "*. . ...can give useful tips on what they did and things that may have gone wrong*" [cohort B].

By working together in peer-teaching groups, stronger and weaker students were supported, and in this way the methodology can be aligned to that of differentiated teaching.[70,71]

Laboratory simulations were used for experiment 4 (synthesis of aspirin), which involves many practical skills (reflux, vacuum filtration, recrystallization, melting points, yield calculations, and safety) covering many LO. Teaching these skills was a challenge during COVID-19, although it was achieved using laboratory simulations as a dry-lab [cohort A] and good preparation for the F2F hands-on lab [cohort B]. Simulations for laboratory work have been found to be a valuable teaching tool as they allow students to attempt experiments online giving rapid feedback. By carrying out simulations prior to the laboratory, students work through techniques before trying to carry it out themselves, reducing cognitive load and acting as a good preparation for the actual lab.[7,8] Working with Learning Science (LS)[9] during the pandemic, a GTA[76] prepared a dedicated aspirin interactive closely aligned to the hands-on laboratory where interactive synthesis included involving equipment handling, technique and observations. Upon completion, the simulation was immediately marked electronically, where 92% [cohort A] and 67% [cohort B] of students agreed it was valuable in developing laboratory skills (*Q12*). Additionally, the RSC has

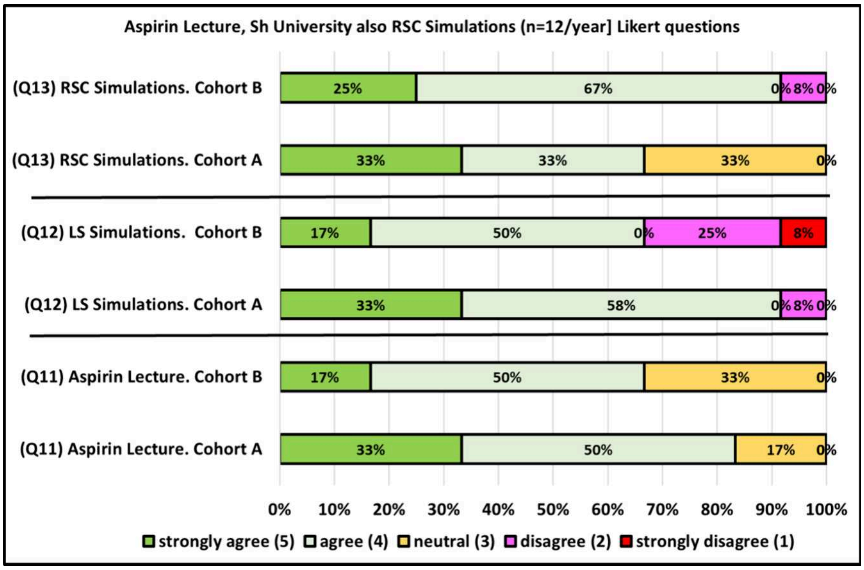


Figure 4. Aspirin lecture (*Q11*), LS simulations (*Q12*), RSC simulations (*Q13*), cohorts A and B. *Likert questions, 5 (strongly agree) to 1 (strongly disagree) (n = 12/year).*

an interactive simulation for synthesis of aspirin on their open access Web site,[80] which was also found to be a valuable experience for skill development (*Q13*). 66% [cohort A] and 92% [cohort B] of students agreed about its usefulness. Introduction to the aspirin synthesis was delivered to both cohorts as a lecture, and students agreed it was useful (83% [cohort A] and 67% [cohort B]) (*Q11*) (Table 4, Figure 4). Independent *t*-tests from Likert questions found these results were not statistically significant.[61,62] Following the simulations, students were collected together as a group so that any issues could be discussed, which proved particularly valuable for cohort A as it was important to keep group dynamics alive during COVID-19.[81,82] A short lecture was delivered giving guidance about how to write up the practical report and complete the PSP. Students were positive about simulations because they found them helpful for visualizing equipment and as useful preparation for an actual laboratory, and a similar positive report about the use of simulations has been reported by Guo and co-workers.[34] Some students who already had "A" level chemistry did not feel they learned anything new.

Three themes emerged from qualitative analysis from cohort A only (*Q14*): ***Best alternative***, ***Being in the Laboratory***, and ***Interactives*** (Table 5). Even if COVID-19 students were not happy with simulations, they agreed it was the ***best alternative*** at the time: "*the interactive online lab was useful for visualising the equipment and processes and could potentially be used as prep for an actual lab session...*" [cohort A].

Students agreed dry-labs were useful and allowed them to consider theory and support coverage of LO, although clearly hands on practical dexterity was not developed: "*I found that dry labs allowed me to be more focused on the science behind what is happening, rather than the lab skills*" [cohort A].

Dry labs were a good alternative in the situation of COVID-19, but dry-labs should only be a temporary replacement.[8,47,72,82,83] ***Being in the Laboratory*** was strongly supported by students who felt that "nothing compares to being in a laboratory", and clearly practical work is more beneficial. "*Hands on practical work should definitely be prioritised, although the dry labs were good and obviously the only choice at the time. . .*" [cohort A].

Students thought guidance would still be needed to carry out these experiments in a laboratory, and both students and tutors prefer hands-on laboratories:[84,85] "*I much preferred hands on but thought the dry labs were the best alternative*" [cohort A].

Students agreed that ***Interactives*** did a great job during the pandemic of showing the practical set up and equipment used and were a useful aid for preparation of a laboratory session. "*It is a really good way of practicing and understanding the skills needed for labs*" [cohort A].

Cohort A preferred the dry-lab for aspirin, as it was felt to be more valuable as compared to peer-teaching for Limonene/RMM. "*I much preferred the online lab we did for aspirin as this was a lot more beneficial*" (*Q10*) [cohort A] (Table 5).

Laboratory simulations allow for differentiated learning-teaching because being able to work through or repeat them in your own time supports learning abilities of both stronger and weaker students.[70,71]

Practical Skills Portfolio (PSP)

PSP aims to reinforce practical skill development as students engage with actual laboratory experience, record evidence, then reflect on their findings.[10,11,40] PSP was found to be useful for skill development before COVID-19, and 75% of students agreed it was valuable (*Q15*), although after the pandemic only 58% agreed it was valuable; however, it kept students still thinking about practical skills, therefore supporting skill development [cohort A] (*Q16*) (Table 4, Figure 5). PSP was delivered differently before and after the COVID-19. To maintain a focus on practical skills yet avoid collusion, individual PSPs were prepared online because the lab was not "hands-on". Instead, students needed to research information about a piece of apparatus or technique, include a drawing or photograph, answer a question on safety, then reflect on each section.[10,11,40] PSP was not as popular with cohort B, as only 25% agreed it was valuable, 58% had neutral opinions, and 17% disagreed it was valuable (*Q17*),; these opinions could be related to using a phone in the laboratory

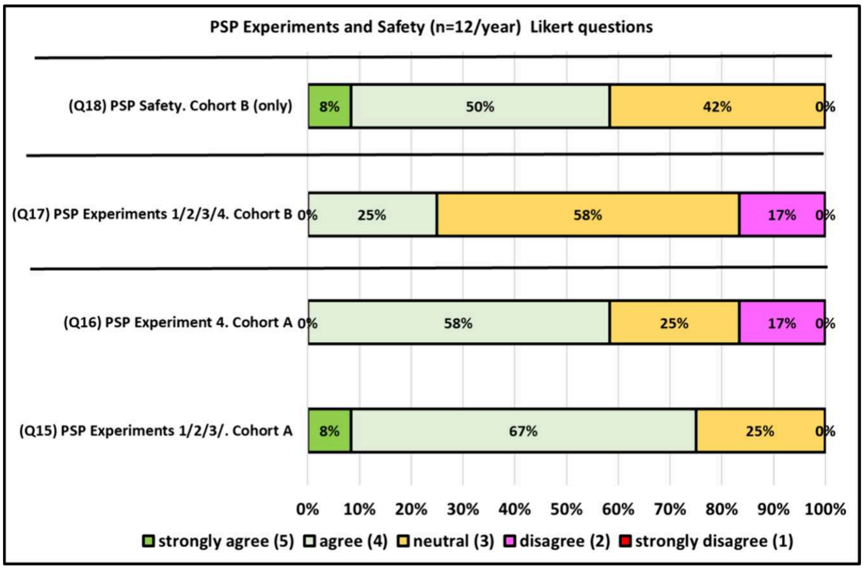


Figure 5. PSP experiments (*Q15*−*Q17*), PSP safety (*Q18*), cohorts A and B. *Likert questions, 5 (strongly agree) to 1 (strongly disagree)* (*n* = 12/year).

as supported by the qualitative analysis where using phones was found to be disruptive. Cohort B were asked about the PSP safety questions, and 58% agreed that the questions were valuable with no students disagreeing (*Q18*) (Figure 4).

Qualitative analysis revealed three themes about PSPs (*Q19*) (Table 5: ***Reinforcing practical skills***, ***reflection***, and ***disruptive***. ***Reinforcing practical skills*** suggests students felt PSP was valuable before and after COVID-19 as it reinforced practical skills and kept them engaged in lab work: "*I liked that we could take pictures to remember what we had done and to keep as a record*", "*. . .during the dry labs, I found the PSP helpful in making sure I didn't completely forget about lab skills and the importance of equipment handling*" [cohort A].

Taking pictures is a good idea for recall and understanding, a visual aid for remembering skills: "*. . .it helped guide my knowledge*", "*the addition of pictures is a creative idea that helps in remembering the lab*", "*It was good to highlight the key points of a lab, e.g. the colour changes, significant temperature changes etc.*" [cohort A]; "*I could see what practical skills I was most confident in and focus on the areas for improvement for the next practical*" [cohort B].

Reflection suggests PSP was valued for being able to reflect and look over practical work as a reminder: "*I think understanding the equipment you use is a big part of chemistry labs and I think the PSP does a great job of making you think about the equipment you use and how you should be using it properly*" [cohort A], "*. . . it was good to use as a reflection of the work and the purpose for each step*" "*. . .allows you to look over your practical setup. . .*" [cohort B]. Reminding students about experiments and keeping a visual skill record is an important feature of PSP.[10,11]

The final PSP theme was ***disruptive*** relating to using a phone in the laboratory, which is an important finding. The time the photo is taken during the experiment needs to be considered for future practical activities: "*taking pictures does add another level of complexity to the lab such as keeping the phone in a plastic wallet...*", "*. . .the PSP could distract away from carefully monitoring the practical (before COVID-19),*" [cohort A]; "*. . .. disruptive having to stop and take photos. . ..*" [cohort B]. Using a phone in the laboratory for monitoring reactions and a data source is more common at university; however, for students progressing directly from school, they are not used to using their phones in this situation.

PSP was used successfully during laboratory sessions on the UoS joint TransNational Education (TNE) BSc degree for 3 years of laboratory study in China. Students were positive about its use, particularly for skill and language development, and also being able to refer to their PSP when they studied the final year of their degree in Sheffield to remind them about laboratory techniques.[40] Being able to carry out practical skills "hands on" then reflect in their personal time is valuable for both stronger and weaker students, so in this way PSP supports differentiated teaching.[70,71]

Pre- and Post-Laboratory Skills, Experience and Confidence after the Laboratory

This laboratory course aimed to develop or enhance 18 different chemistry practical laboratory skills in four categories; analytical, synthetic, spectroscopic, and scientific writing. Skills delivered in this course are important, as students need to gain confidence in them to progress onto a chemistry degree. It is firmly believed within the sector that the laboratory is the place where students need to develop important chemistry practical skills,[84,85] which is also supported by findings of this research. Although dry-labs were acceptable, they did not allow skill development like an actual laboratory session. This investigation aimed to see if students started the course with expected practical skills from school[86] and, if so, which skills. It was also important to see if the students felt confident to carry out these skills after the laboratory course, as shown in Table 6. Independent *t*-tests were carried out on students confidence for each of the individual 18 skills after this course, and there were no statistically significant results.

Analytical Skills results before and after the pandemic confirm students were most confident with these skills, as pre-university chemistry courses in the UK include these skills.[12,86] Interestingly, for cohort B there was a higher % of students who had watched a technique by **video** before university, possibly because students were more used to watching videos as a result of a different style of studying

Table 6. 18 Practical Skills Gained Before and After the Chemistry Module (n = 12/year)

BEFORE studying on this L0 course:- Please complete the table below about your previous practical experience *(eg - at school / college / employment / other)*

BEFORE studying on this L0 course:- -------------------------- (Top nub.**Cohort A**)	Had you watched a practical chemistry **video** on line? **(%)**		Had you watched a teacher **demonstrate** this technique? **(%)**		Had **you done** this technique at school, college, club, competition? **(%)**		***AFTER studying on this L0 course:-*** I am **confident** to carry out this practical skill ***1*** = *Strongly Disagree* / ***2*** = *Disagree* / ***3*** = *Neutral* / ***4*** = *Agree* / ***5*** = *Strongly Agree* Converted to (%) for comparison				
(Bottom **Cohort B**)	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**1**	**2**	**3**	**4**	**5**
Analytical Skills											
Using a balance	33 25	67 75	50 50	50 50	92 100	8 0	0 0	0 0	0 0	17 8	83 92
Preparing a solution	25 33	75 67	42 50	58 50	92 83	8 17	0 0	0 0	0 8	33 25	67 67
Preparing a volumetric solution	17 42	83 58	33 42	67 58	75 75	25 25	0 0	0 0	0 17	42 33	58 50
Using a pipette accurately	8 42	92 58	42 42	58 58	83 92	17 8	0 0	0 0	0 0	17 17	83 83
Carrying out a titration	8 42	92 58	33 42	67 58	75 83	25 17	0 0	0 0	0 8	33 8	67 83
Simple test tube reactions	25 25	75 75	50 50	50 50	100 100	0 0	0 0	0 0	0 0	8 17	92 83
Synthetic Skills											
Synthesis of a compound	8 17	92 83	33 33	67 67	67 58	33 42	0 0	8 0	17 17	33 25	42 58
Buchner (vacuum) filtration	8 33	92 67	17 17	83 83	50 42	50 58	0 0	8 0	17 8	33 8	42 83
Recrystallization	8 42	92 58	33 33	67 67	83 67	17 33	0 0	8 0	0 8	42 17	50 75
Melting point determination	8 50	92 50	25 33	75 67	75 50	25 50	0 0	8 8	0 17	33 25	58 50
Using quickfit apparatus	8 33	92 67	8 17	92 83	33 42	67 58	0 0	0 0	0 9	50 18	50 73
Reflux	0 17	100 83	25 25	75 75	58 50	42 50	0 0	0 8	8 8	58 33	33 50
Distillation	0 25	100 75	33 25	67 75	67 58	33 42	0 0	0 8	0 8	58 33	42 50
Working in a fume cupboard	8 33	92 67	33 25	67 75	58 58	42 42	0 0	0 0	0 0	25 33	75 67
Spectroscopy											
Using spectroscopy UV/Vis / IR	25 33	75 67	17 25	83 75	25 33	75 67	0 0	17 25	25 0	33 33	25 42
Scientific Writing											
Keeping a laboratory notebook	0 17	100 83	17 33	83 67	75 67	25 33	0 0	0 0	8 8	17 8	75 83
Writing up a practical report	0 25	100 75	25 33	75 67	100 67	0 33	0 0	0 0	8 0	17 17	75 83
Scientific writing	8 33	92 67	42 33	58 67	75 67	25 33	0 0	0 0	0 8	42 17	50 75

through the pandemic. During this time, more skill videos were produced and are now accessible for students before university.[87] Practical demonstration by a teacher is a typical delivery style in the UK at the start of a practical GCSE or "A" level class.[2,12,66−69] The % of students watching their **teacher demonstrate** a specific technique before carrying it out themselves in the laboratory was similar for both cohorts, although marginally higher for cohort B. For all analytical skills 75% or more for both cohorts had carried out these skills themselves before University (Figure 6).

Asking students about their **confidence** in mastering analytical skills found it to be between 80 and 92% for both cohorts, agreeing they had mastered these skills for course progression (Figure 7). Some members of cohort B were still not confident with volumetric techniques of preparing a solution (8%), carrying out a titration (8%), or preparing a volumetric solution (17%), and this was mentioned anecdotally during the laboratory session and was possibly due to lack of opportunities for practical work during the pandemic.

Synthetic skills are generally more difficult to develop at school mainly due to the lack of expensive equipment. 50% of these students had never studied chemistry above GCSE, meaning that synthetic skills were often new. Only 8% of cohort A had watched **video** for most synthetic skills. Cohort B had watched a video for most synthetic skills, with as many as 50% for melting point determination.[87] 33% of members from both cohorts had watched a **teacher demonstrate** a specific synthetic skill.[87] Results were varied for both cohorts actually **carrying** out these techniques themselves, with more than 58% not using quickfit apparatus before university. The number of students carrying out synthetic techniques themselves was slightly higher for cohort A compared to cohort B (Figure 8). Anecdotally students from cohort B initially lacked confidence about working alone during the first synthetic laboratory session, and it was impressive to observe improvements from the first limonene extraction to the final aspirin synthesis. Well-established links with UK universities allow students to attend dedicated laboratory sessions to carry out practical work themselves; however, not all students have this opportunity,[88] and university visits would have been far less during and after the pandemic.

A number of students had not gained much experience in synthetic skills before they joined university. After the course, 75−100% from both cohorts felt confident enough with their synthetic skills for progression, Figure 9.

Spectroscopy experiences in infrared (IR), mass spectroscopy (MS), nuclear magnetic resonance (NMR), ultraviolet (UV) and visible spectroscopy were limited before university, as 75% cohort A and 67% cohort B had not done any spectroscopy (Table 6, Figure 10). This is not unusual because schools do not often have such expensive

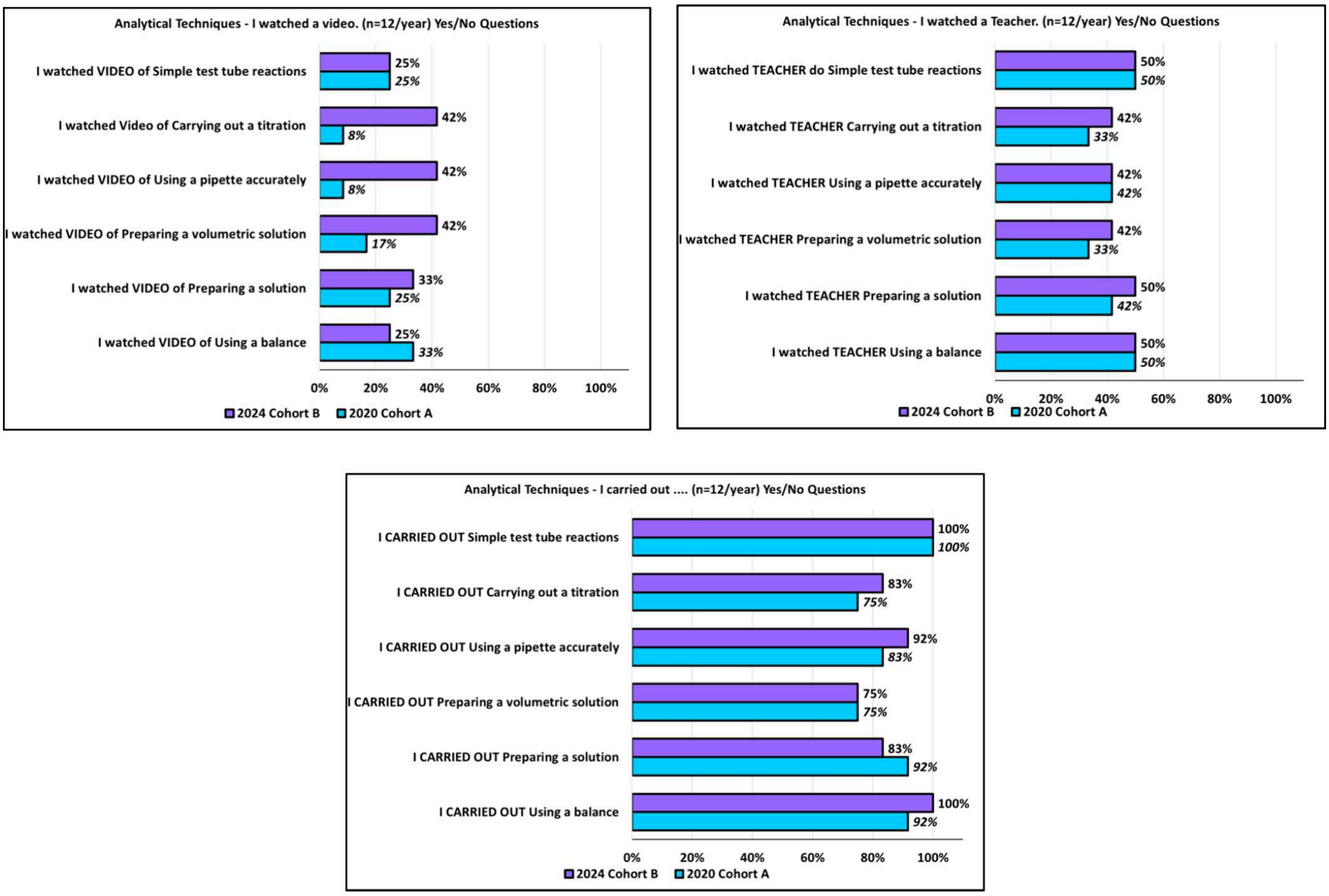


Figure 6. Analytical techniques before university, cohorts A and B. *Yes/No questions (n = 12/year).*

Figure 7. Confidence in analytical techniques after course, cohorts A and B. *Likert questions, 5 (strongly agree) to 1 (strongly disagree) (n = 12/year).*

instrumentation. To help, many UK universities offer dedicated "spectroscopy days" where schools visit for a day and students can gain hands on experience.[88] Alternatively, students can attend a Royal Society of Chemistry (RSC) "Spectroscopy in a Suitcase" (SIAS) university session or SIAS can visit the school;[89] however, during and after the pandemic visiting and taking part in such hands-on opportunities were less available. More of cohort B had watched videos, watched a teacher, or carried out spectroscopy themselves as compared to cohort A. However, both cohort B (over 60%) and cohort A (over 75%) had not actually had any spectroscopy experience.[87]

After the laboratory course, approximately a quarter of the students (17% [cohort A], 25% [cohort B]) were still not confident with spectroscopy (Figure 11).

Scientific writing was most accessible to students because the majority of UK pre-university science courses teach the basics of scientific writing and using a laboratory notebook (75% [cohort A], 67% [cohort B]).[12,86] Differences were found between cohorts in writing up practical reports. 100% of cohort A had previously written up practical reports

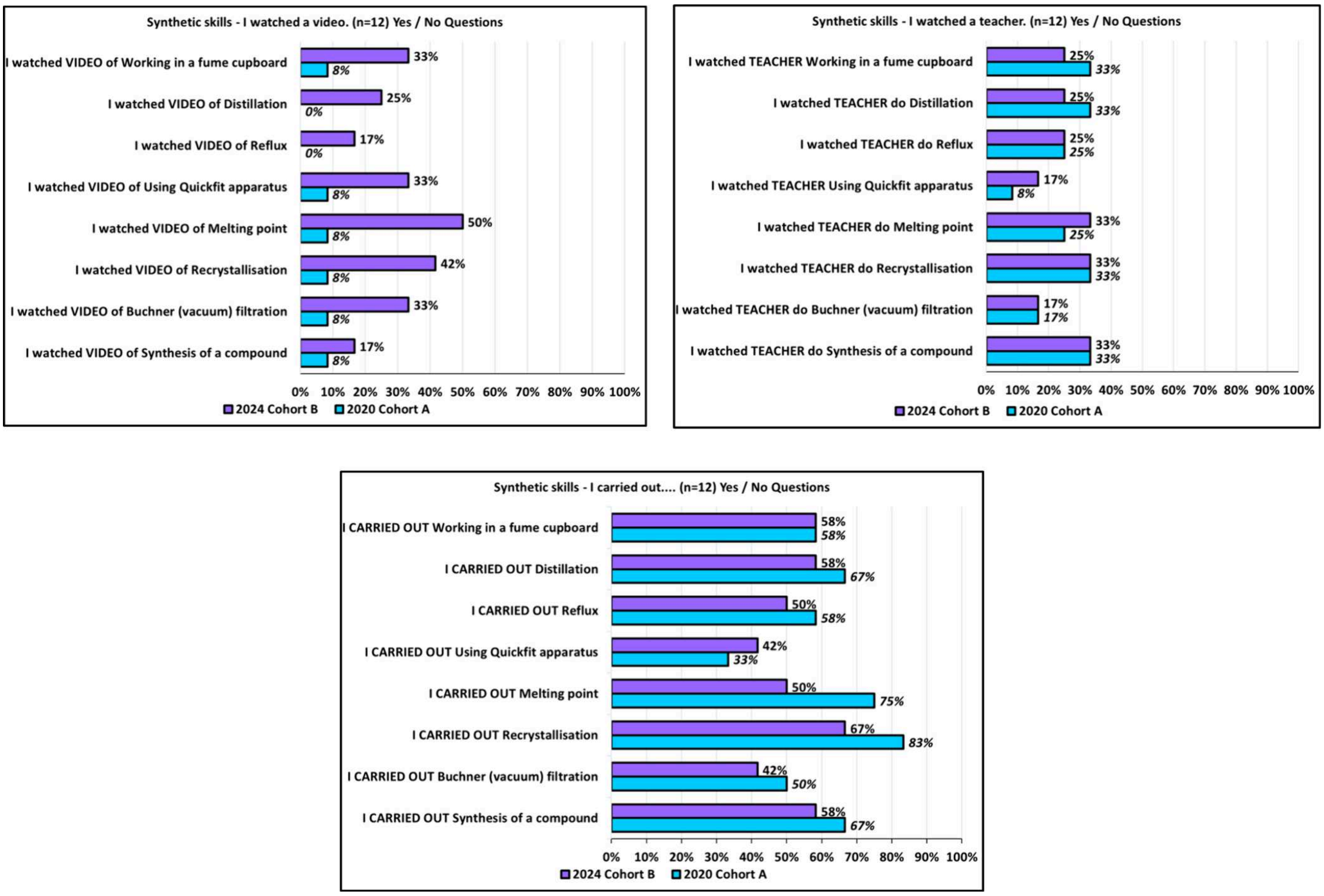


Figure 8. Synthetic skills before university, cohorts A and B. *Yes/No questions (n = 12/year).*

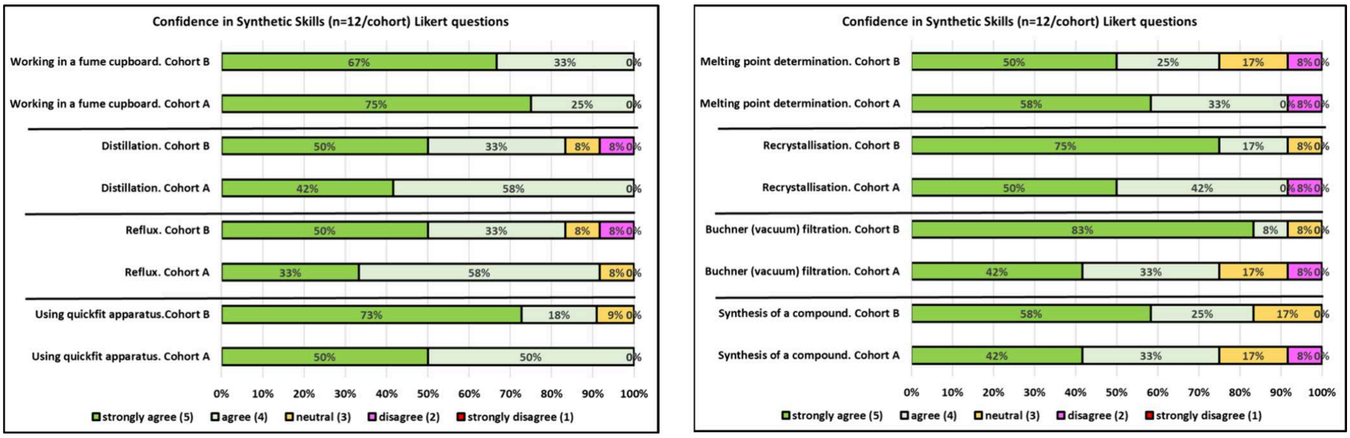


Figure 9. Confidence in synthetic skills after course, cohorts A and B. *Likert questions, 5 (strongly agree) to 1 (strongly disagree) (n = 12/year).*

compared to 67% from cohort B. As there were less opportunities for carrying out practical chemistry, writing up those experiments would have been less common due to the pandemic, affecting cohort B to a greater extent as they were still at school (Figure 10).

Students confidence after the laboratory sessions found that 92% or above for both cohorts were confident with their scientific writing, keeping a laboratory notebook, and writing a practical report (Figure 11).

Overall Confidence Levels in Students' Practical Skills after the Laboratory Course

For the individual 18 practical skills after the course, agreement in confidence levels was similar for both cohorts. Cohort A was marginally more confident with analytical and synthetic skills, whereas cohort B was marginally more confident with spectroscopy and scientific writing. Independent *t*-tests on the 18 skills for both cohorts did not show any significant differences between them, which supports the above findings.

After the laboratory course, confidence in carrying out hands on practical work in the laboratory showed 41% of

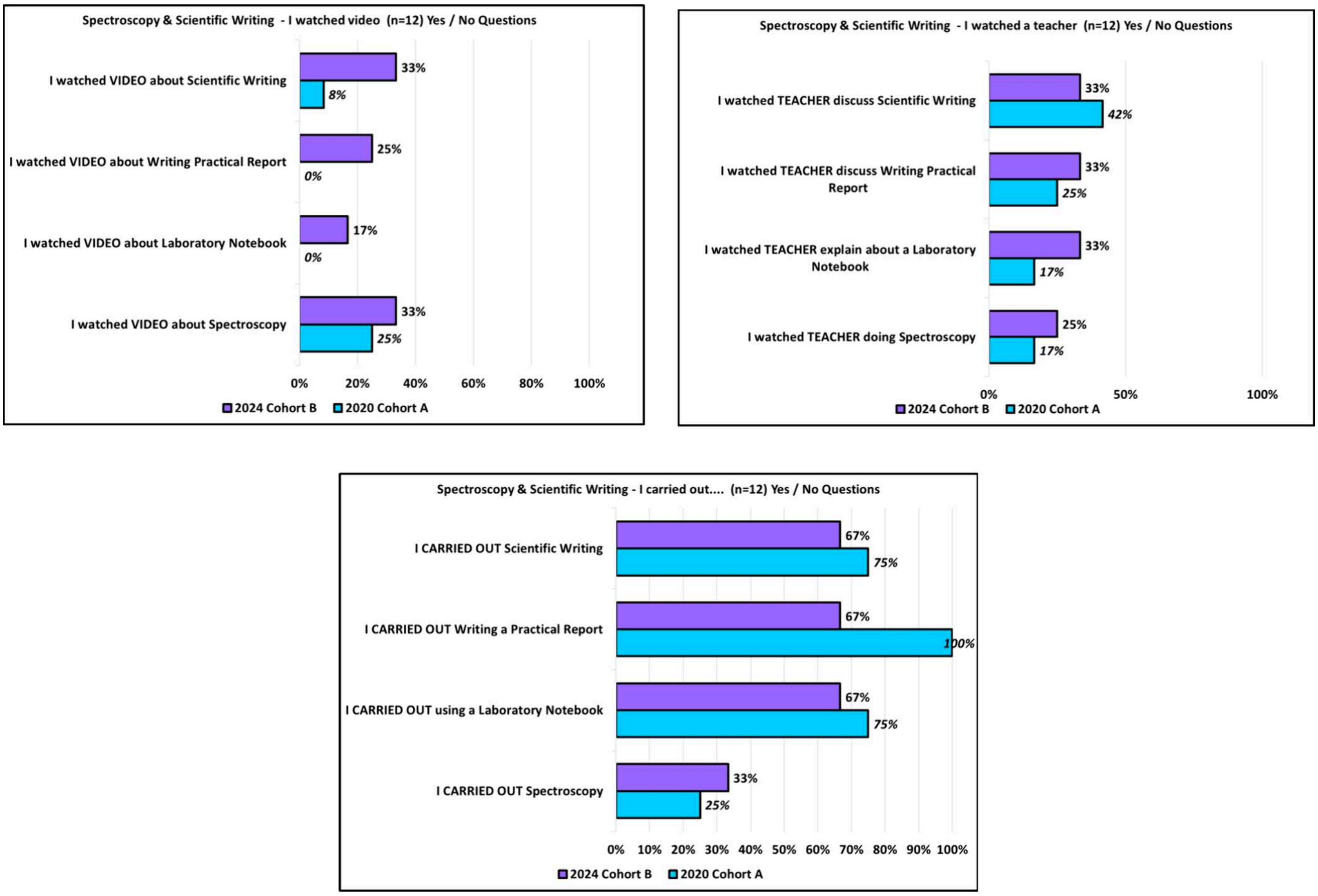


Figure 10. Spectroscopy and science writing before university, cohorts A and B. *Yes/No questions (n = 12/year).*

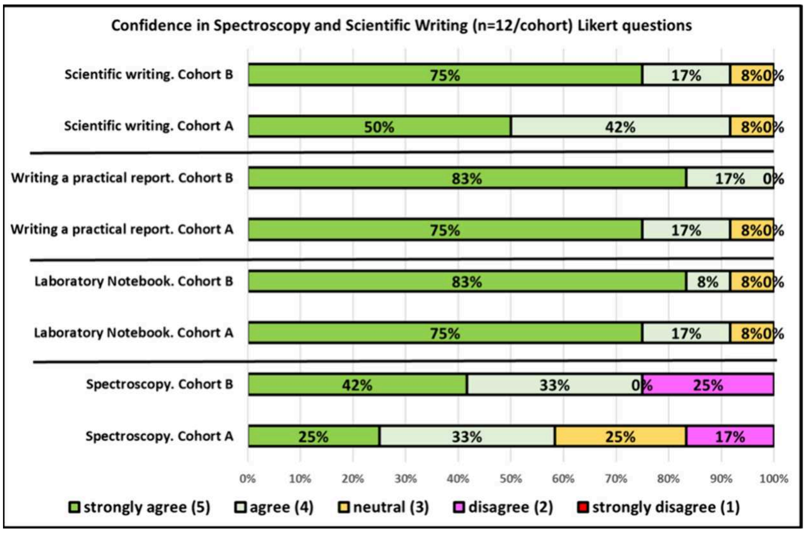


Figure 11. Confidence in spectroscopy and scientific writing after course, cohorts A and B. *Likert questions, 5 (strongly agree) to 1 (strongly disagree) (n = 12/year).*

cohort A was confident with their practical skills (*Q20*). A higher proportion of students in cohort B were confident in their practical skills (92%) (*Q21*) (Figure 12). These results were found to be statistically significant, as the *p*-value is <0.05 ($t = 3.223$, df-22, $p = 0.004$) from an independent *t*-test, suggesting that after the pandemic students gained more confidence in their practical chemistry skills by carrying out hands-on chemistry in an actual laboratory. In contrast, students in cohort A were not as confident with their skills, as half of their laboratories were dry-labs in the course.

Cohort B was asked about studying practical chemistry during COVID-19 and their practical skills after their laboratory course (*Q22*). Thematic analysis[58−60] found the theme ***confidence***, supporting the findings that these students

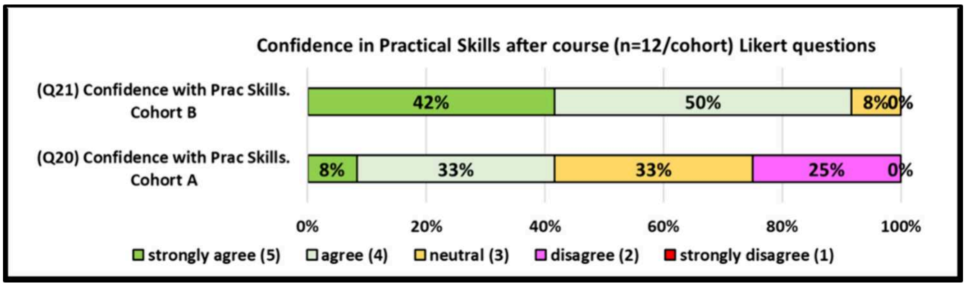


Figure 12. Confidence in practical skills (Q20 and Q21), cohorts A and B. (n = 12/year). *Likert questions, 5 (strongly agree) to 1 (strongly disagree).*

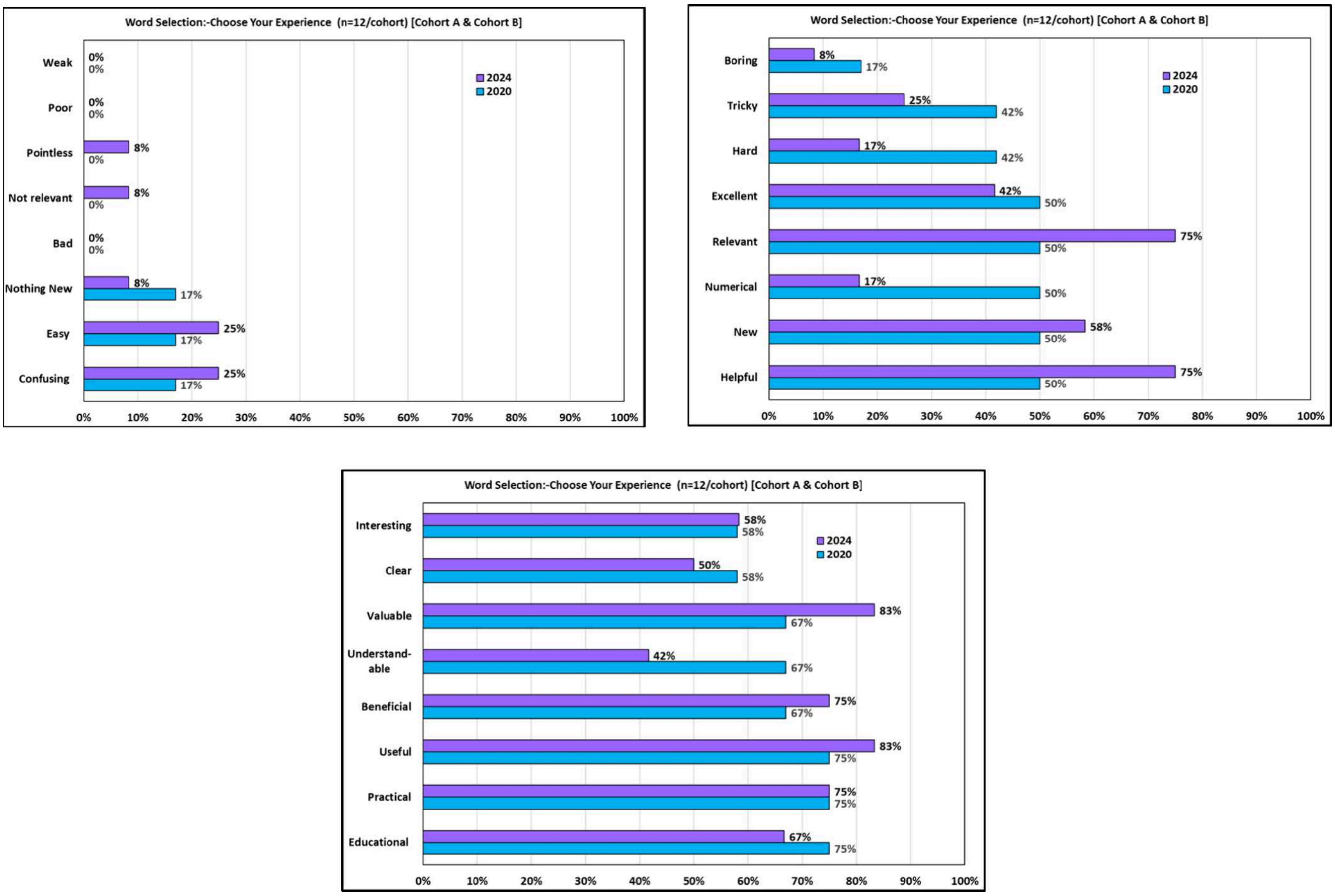


Figure 13. Cohorts A and B. Foundation students' opinions, word analysis,% values (n = 12/year).

gained self-efficacy, experience, and independence during the foundation laboratory course. Other researchers found students were nervous in a real lab situation after COVID-19 and did not know exactly what to do,[31,33] the reasons being they had never done some of the practical work before or had not had the opportunity to work alone previously: "*it felt like the first time we have been given proper independence*", "*little experience due to COVID*", "*I feel 1000% ready for my progression into first year because of the foundation laboratory chemistry*" [cohort B].

■ WORD ANALYSIS ABOUT THE CHEMISTRY MODULE

Four questions were asked to gain an alternative viewpoint about students' feelings for the course using a four-part "word" question, "*Please tick the words that you feel describe your experience of this semester 2 Chemistry course*". Students were asked which descriptive words illustrated their experience; they could select zero, one, or more words from a list to indicate what they felt about their experience of the chemistry course.

The majority of the cohorts thought the course was "*useful, educational, practical, beneficial, valuable*". These five positive descriptive words were the most selected for both cohorts, suggesting the course was appropriately designed for the students.

Many general responses were positive, suggesting the course was "*understandable, relevant, helpful*", so students were positive about the value of the course. Generally, students found the course to be "*interesting, clear, excellent, new*", suggesting an appropriate level of course for these students.

Some responses suggested that students felt challenged about some aspects of the course "*numerical, hard, tricky*", possibly from students who had not studied chemistry for some time. A minority of students from both cohorts selected the words "*confusing, easy, nothing new, boring, pointless, not relevant*" and "*poor, bad, weak*", possibly a mix of students, some of whom found the work new and challenging, and others who had studied higher chemistry in the past so they did not feel that they learned anything new. These results are summarized in Figure 13.

LIMITATIONS

At the time of COVID-19, one limitation was the opportunity to repeat the 2020 survey during the following academic year, which would have given a valuable comparison as teaching was gradually returning to F2F classes. The limitation of not being able to deliver laboratories during COVID-19 was a challenge partly overcome by dry-labs, although this solution was not ideal from the perspective of both staff and students because their chemistry dexterity was not developed. PSP was not easy to deliver without hands on practical experiments, and students were not able to photograph parts of their experiment or equipment or make actual observations. A possible solution to this could be using videos and simulations, which are now more freely available since the pandemic.

FUTURE STUDIES

Chemists are always considering new ways to encourage the development of practical skills for new chemists, and some have been included in this manuscript. Further research into training undergraduate chemists using PSP to accompany laboratories would be an interesting follow up study. Researching the value of simulations as a preparation for forthcoming laboratories would be another valuable investigation.

CONCLUSIONS

RQ1. Investigations about reciprocal peer-teaching and laboratory simulations before, during, and after lockdown found these methodologies successful for both cohorts. Peer-teaching was useful particularly for sharing information, meeting new people, explaining procedures, and developing employability skills. Team pairing and working with others needs to be managed carefully to ensure all students gain valuable skills as both "teachers" and "learners". Dry-Labs were not ideal in developing laboratory skills for cohort A, although it was agreed they were useful in the circumstances. Laboratory simulations are valuable preparation, particularly when hands on opportunities were not available. Both cohorts were positive about using laboratory simulations as preparation and introduction to an actual lab.

RQ2. PSP is a novel idea that helps students reflect on practical skills and decide what level of confidence they have gained. Students build up a portfolio of practical skills from their practical classes, which produces a valuable reference document laying the foundation for future laboratory studies. With pictures and personal reflections students can recap skills for preparation for future practical classes away from the laboratory. PSP was beneficial for both cohorts as visual images were obtained and they could look back at actual photographs to remind them about equipment set ups and techniques. It also reminded them where they were confident and where they needed to improve. Issues about using a phone in the laboratory were a concern from both cohorts which need addressing.

RQ3. Previous experiences in practical laboratory skills from school were varied, with analytical techniques and scientific writing most likely to be gained before University. Synthetic skills and spectroscopy are not as easy to develop at school. Cohort B were found to be less confident when entering university with practical skills compared to cohort A, possibly as a result of COVID-19; however, after the laboratory course 92% of cohort B felt ready for progression. Foundation programs at university would be advised to include more practical sessions, particularly synthetic techniques together with analysis using instrumentation.

Word analysis revealed that the module was well received for both cohorts and appropriate for a course at this level. Students felt that they had gained many practical skills during this module.

An important finding from this research is that students on foundation programs would like **differentiated teaching.**[70,71] If students are separated according to entry qualifications and taught in groups with students who have similar entry qualifications instead of a mixed group with GCSE and "A"-level chemistry qualifications, this would result in a better learning environment for them. The use of reciprocal peer-teaching, laboratory simulations, and PSP supports students with different learning styles so they can learn at a speed that works for their individual learning requirements.

The main finding of this research was that students' confidence in developing practical skills was far higher for cohort B who studied laboratories F2F (92%) compared to cohort A who studied during the pandemic through dry-laboratories (41%). Students from cohort A also said that nothing can replace a hands-on laboratory. This finding supports what the sector believes about the importance of hands-on practical chemistry in a laboratory; it is really the only way to develop chemists' dexterity in becoming both competent and confident chemists with their practical skills.

AUTHOR INFORMATION

Corresponding Author

Julie Hyde − *Department of Chemistry, The University of Sheffield, Sheffield S3 7HF, United Kingdom*; orcid.org/0000-0001-8819-2411; Email: julie.hyde@sheffield.ac.uk

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.jchemed.4c01124

Notes

The author declares no competing financial interest.

ACKNOWLEDGMENTS

Thanks to Sheffield University technical staff for helping set up laboratory sessions: Richard Bottomley, Joe Quick, Sam Parkin, Simon Parker. Thanks to Graduate Teaching Assistants (GTAs) for laboratory support before and during COVID-19: Heather Carson, Francesca Dennis, Sally Morton.

Thanks to colleagues for development of the Aspirin practical before and after COVID-19: Bethany J Crowston, Francesca Dennis. Special thanks to colleagues for advice: Lee Brammer, Nimesh Mistry, Gary Wood, James S Wright. Special thanks to the SEFY Foundation Course Director for support and guidance during COVID-19: Peta Kirk. Special thanks to the SEFY Foundation Students 2019-2020 who worked hard at their studies during such exceptional circumstances.

REFERENCES

(1) Dates and Deadlines for Uni Applications. *UCAS*, 2022. https://www.ucas.com/undergraduate/applying-university/ucas-undergraduate-when-apply (accessed 2022-01-20).

(2) *GCE A level Subject Guidance for Science (Biology, Chemistry, Physics)*; Ofqual/15/5753; Ofqual, 2015. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/447167/2015-07-20-gce-subject-level-guidance-for-science.pdf (accessed 2022-01-31).

(3) *BTEC Level 3 National Extended Diploma in Applied Science*; Pearson, 2016. https://qualifications.pearson.com/content/dam/pdf/BTEC-Nationals/Applied-Science/2016/specification-and-sample-assessments/BTEC-L3-Nat-ExtDip-in-Applied-Science-Spec.pdf (accessed 2022-01-31).

(4) Chamberlain, S.; Elford, D.; Lancaster, S. J.; Silve, F. Tailored blended learning for foundation year chemistry students. *Chimia* **2021**, *75*, 18−26.

(5) Read, D.; Watts, J. K.; Wilson, T. J. Partial flipping to support learning in lectures. In *The Flipped Classroom Vol. 2: Results from Practice*; ACS Symposium Series; American Chemical Society: Washington, D.C., 2016; pp 55−79.

(6) Gonzalez, M.; Zewail-Foote, M. Crisscrossing Learning Experiences in an Undergraduate Research Based Laboratory Course to Promote Reciprocal Peer-Learning. *J. Chem. Educ.* **2023**, *100* (3), 1092−1099.

(7) Fergus, S.; Botha, M.; Scott, M. Insights gained during COVID-19: Refocusing Assessments Online. *J. Chem. Educ.* **2020**, *97*, 3106−3109.

(8) Wild, D. A.; Yeung, A.; Loedolff, M.; Spagnoli, D. Lessons Learned by Converting a First-Year Physical Chemistry Unit into an Online Course in 2 Weeks. *J. Chem. Educ.* **2020**, *97*, 2389−2392.

(9) Lab Sims. *Learning Science*. https://www.learnsci.com/products/labsims (accessed: 2022-01-19).

(10) Wright, J. S.; Read, D.; Hughes, O.; Hyde, J. Tracking and assessing practical chemistry skills development: practical skills portfolios. *New Dir. Teach. Phys. Sci.* **2018**, *13*, 1−9, DOI: 10.29311/ndtps.v0i13.2905.

(11) Read, D.; Barnes, S. M.; Hyde, J.; Wright, J. S. Nurturing reflection in science foundation year undergraduate students. In *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton*; Seery, M. K., Mc Donnell, C., Eds.; Creathach Press: Dublin, Ireland, 2019; pp 23−38.

(12) Department for Education. National curriculum in England: science programmes of study. *GOV.UK*, 2015.https://www.gov.uk/government/publications/national-curriculum-in-england-science-programmes-of-study/national-curriculum-in-england-science-programmes-of-study (accessed 2019-12).

(13) Seery, M. K. Flipped Learning in higher education chemistry: emerging trends and potential directions. *Chem. Educ. Res. Pract.* **2015**, *16*, 758−768.

(14) Petillion, R. J.; McNeil, S. Johnston's Triangle as a Pedagogical framework for flipped class instructional videos in introductory chemistry. *J. Chem. Educ.* **2020**, *97*, 1536−1542.

(15) Eichler, J. F.; Peeples, J. Flipped Classroom modules for large enrolment general chemistry courses: a low barrier approach to increase active learning and improve student grades. *Chem. Educ. Res. Pract.* **2016**, *17*, 197−208.

(16) Freeman, S.; Eddy, S. L.; McDonough, M.; Smith, M. K.; Okoroafor, N.; Jordt, H.; Wenderoth, M. P. Active learning increases student performance in science, engineering, and mathematics. *Proc. Natl. Acad. Sci. U.S.A.* **2014**, *111* (23), 8410−8415.

(17) Shapiro, M.; Solano, D. M.; Bergkamp, J. J.; Gebauer, A.; Gillian, E.; Lopez, K. M.; Santoke, H.; Talbert, L. E. Impacts of converting courses to virtual instruction midsemester at a Hispanic-Serving institution. *J. Chem. Educ.* **2020**, *97*, 2526−2533.

(18) Christiansen, M. A. Inverted Teaching: Applying a new pedagogy to a university organic chemistry class. *J. Chem. Educ.* **2014**, *91*, 1845−1850.

(19) Becker, R.; Birdi, A. Flipping the classroom: Old ideas, new technologies. *International Review of Economics Education.* **2018**, *29*, 1−5.

(20) Arico, F. R.; Lancaster, S. J. Facilitating active learning and enhancing student self-assessment skills. *International Review of Economics Education.* **2018**, *29*, 6−13.

(21) Lancaster, S.; Read, D. Flipping lectures and inverting classrooms. *Educ. Chem.* **2013**, *50* (5), 14−17.

(22) Luker, C.; Muzyka, J.; Belford, R. Introduction to the Spring 2014 ConfChem on the flipped classroom. *J. Chem. Educ.* **2015**, *92*, 1564−1565.

(23) Seery, M. K. ConfChem Conference on Flipped Classroom: student engagement with flipped chemistry lectures. *J. Chem. Educ.* **2015**, *92*, 1566−1567.

(24) Muzyka, J. ConfChem Conference on Flipped Classroom: Just-in-time teaching in chemistry courses with moodle. *J. Chem. Educ.* **2015**, *92*, 1580−1581.

(25) Pienta, N. J. A "Flipped Classroom" Reality Check. *J. Chem. Educ.* **2016**, *93*, 1−2.

(26) Ramachandran, R.; Rodriguez, M. C. Student Perspectives on Remote Learning in a large Organic Chemistry Lecture Course. *J. Chem. Educ.* **2020**, *97*, 2565−2572.

(27) Schmidt-McCormack, J. A.; Muniz, M. N.; Keuter, E. C.; Shaw, S. J.; Cole, R. C. Design and implementation of instructional videos for upper-division undergraduate laboratory courses. *Chem. Educ. Res. Pract.* **2017**, *18*, 749−762.

(28) Gallardo-Williams, M.; Morsch, L. A.; Paye, C.; Seery, M. S. Student generated-video in chemical education. *Chem. Educ. Res. Pract.* **2020**, *21*, 488−495.

(29) Stieff, M. Improving Learning Outcomes in Secondary Chemistry with Visualization-Supported Inquiry Activities. *J. Chem. Educ.* **2019**, *96*, 1300−1307.

(30) Seery, M. K. Moving an in-class module online: a case study for chemistry. *Chem. Educ. Res. Pract.* **2012**, *13*, 39−46.

(31) Hitlal, D. Virtual Chemistry Laboratories in the Caribbean - A qualitative study. *J. Chem. Educ.* **2023**, *100*, 2847−2859.

(32) Babincakova, M.; Bernard, P. Evolution after the revolution: How classical and online school chemistry teaching has changed during the COVID-19 pandemic? *J. Chem. Educ.* **2024**, *101* (3), 963−972.

(33) Lee, S.; Guo, Y. Evolution of Teaching independent undergraduate chemistry research courses and student skills developed through the COVID-19 pandemic and forward. *J. Chem. Educ.* **2024**, *101* (4), 1726−1734.

(34) An, B. G.; Abdullah, M. N. S.; Chua, K. H. Chemistry Teacher Reflections of Online teaching Platforms in Malaysia Secondary Schools during COVID-19 Crisis. *J. Chem. Educ.* **2023**, *100*, 3220−3227.

(35) Lancaster, S. J.; Cook, D. F.; Massingberd-Mundy, W. J. Peer instruction as a flexible, scalable, active learning approach in higher education. In *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton*; Seery, M. K., McDonnell, C., Eds., Creathach Press: Dublin, Ireland, 2019; pp 89−104.

(36) Brooks, B. J.; Koretsky, M. D. The Influence of Group Discussion on Students' responses and Confidence during Peer Instruction. *J. Chem. Educ.* **2011**, *88*, 1477−1484.

(37) Hyde, J. Taking Laboratory Chemistry to China: A Personal View. *New Directions in the Teaching of Physical Sciences.* **2014**, *10*, 32−35.

(38) Hyde, J. Can you teach University Chemistry Abroad? *Chem. Sri Lanka* **2014**, *31*, 18−19.

(39) Hyde, J. Design of a three-year laboratory program for international delivery. In *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton*; Seery, M. K.; McDonnell, C., Eds., Creathach Press: Dublin, Ireland. 2019; pp 405−420.

(40) Hyde, J.; Wright, J. S.; Xie, A. Progression from Chinese High School onto a TransNational Chinese-UK University joint BSc degree in chemistry: an international study focussing on laboratory practical skills. *Chem. Educ. Res. Prac.* **2024**, *25*, 151−170.

(41) Seery, M. S.; Agustian, H. Y.; Doidge, E. D.; Kucharski, K. M.; O'Connor, H. M.; Price, A. Developing laboratory skills by incorporating peer-review and digitial badges. *Chem. Educ. Res. Pract.* **2017**, *18*, 403−419.

(42) Towns, M.; Harwood, C. J.; Robertshaw, M. B.; Fish, J.; O'Shea, K. The Digital Pipetting Badge: A Method To Improve Student Hands-On Laboratory Skills. *J. Chem. Educ.* **2015**, *92*, 2038−2044.

(43) Hensiek, S.; DeKorver, B. K.; Harwood, C. J.; Fish, J.; O'Shea, K.; Towns, M. H. Improving and Assessing Student Hands-On Laboratory Skills through Digital Badging. *J. Chem. Educ.* **2016**, *93*, 1847−1854.

(44) Aguirre, J. D.; Selampinar, F. Teaching chemistry in the time of COVID-19: Memories and the classroom. *J. Chem. Educ.* **2020**, *97*, 2909−2912.

(45) Howitz, W. J.; Guaglianone, G.; King, S. M. Converting an organic chemistry course to an online format in two weeks: design, implementation and reflection. *J. Chem. Educ.* **2020**, *97*, 2581−2589.

(46) Kyne, S. H.; Thompson, C. D. The COVID Cohort: Student transition to University in the face of a global pandemic. *J. Chem. Educ.* **2020**, *97*, 3381−3385.

(47) Njoki, P. N. Remote teaching of general chemistry for nonscience majors during COVID-19. *J. Chem. Educ.* **2020**, *97*, 3158−3162.

(48) Huang, J. Success and Challenges: Online Teaching and learning of Chemistry in Higher Education in China in the Time of COVID19. *J. Chem. Educ.* **2020**, *97*, 2810−2814.

(49) Campbell, C. D.; Challen, B.; Turner, K. L.; Stewart, M. I. DryLabs20: A new Global Collaborative Network to Consider and Address the challenges of Laboratory Teaching with the Challenges of COVID-19. *J. Chem. Educ.* **2020**, *97*, 3023−3027.

(50) Athapaththu, D. V.; Ambagaspitiya, T. D.; Chamberlain, A.; Demase, D.; Harasin, E.; Hicks, R.; McIntosh, D.; Minute, G.; Petzold, S.; Tefft, L.; Chen, J. Physical Chemistry Lab for data analysis of COVID-19 spreading kinetics in different countries. *J. Chem. Educ.* **2024**, *101* (7), 2892−2898.

(51) Seery, K. M.; Agustian, Y. H.; Zhang, X. A Framework for Learning in the Chemistry Laboratory. *Isr. J. Chem.* **2019**, *59*, 546−553.

(52) Creswell, J. W. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 3rd ed.; SAGE, Thousand Oaks, CA, 2009.

(53) Thomas, D. R. A general Inductive Approach for Analysing Qualitative Evaluation Data. *American Journal of Evaluation.* **2006**, *27* (2), 237−246.

(54) Sullivan, G. M.; Artino, A. R., Jr Analysing and Interpreting Data from Likert-Type Scales. *J. Grad. Med. Educ.* **2013**, *5* (4), 541−542.

(55) Lalla, M. Fundamental characteristics and statistical analysis of ordinal variables: a review. *Qual Quant.* **2017**, *51*, 435−458.

(56) Norman, G. Likert scales, levels of measurement and the "laws" of statistics, Adv. *In Health Sci. Educ.* **2010**, *15* (5), 625−632.

(57) Jamieson, S. Likert scales: how to (ab)use them. *Med.Educ.* **2004**, *38* (12), 1217−1218.

(58) Braun, V.; Clarke, V. Using thematic analysis in psychology. *Qualitative Research in Psychology.* **2006**, *3* (2), 77−101.

(59) Braun, V.; Clark, V. *Thematic Analysis, a practical guide*, 1st ed.; Sage Publications: London, UK, 2022.

(60) Saldana, J. *The coding manual for qualitative researchers*, 4th ed.; Sage Publications: London, UK, 2021.

(61) Field, A. *Discovering Statistics Using IBM SPSS Statistics*, 5th ed.; Sage Publications: London, UK, 2018.

(62) Muijs, D. Introduction to Quantitative research. In *Doing Quantitative research in Education with SPSS*, 3rd ed.; Sage Publications: London, UK, 2013.

(63) Bryman, A.; Cramer, D. *Quantitative data analysis for social scientists*, 1st ed.; Routledge, 1990.

(64) Taber, K. S. The Use of Chronbach's Alpha when developing and reporting research instruments in science education. *Res. Sci. Educ.* **2018**, *48*, 1273−1296.

(65) Barbera, J.; Naibert, N.; Komperda, R.; Pentecost, T. C. Clarity on Cronbach's Alpha Use. *J. Chem. Educ.* **2021**, *98*, 257−258.

(66) *AS and A-Level Chemistry Specification*; AQA, 2015. https://filestore.aqa.org.uk/resources/chemistry/specifications/AQA-7404-7405-SP-2015.PDF (accessed 2022-01-31).

(67) *A Level Chemistry Specification*; Pearson Edexcel, 2015. https://qualifications.pearson.com/content/dam/pdf/A%20Level/Chemistry/2015/Specification%20and%20sample%20assessments/a-level-chemistry-2015-specification.pdf (accessed 2022-09-05).

(68) *A Level Specification Chemistry A*; Oxford Cambridge and RSA, 2017. https://www.ocr.org.uk/Images/171720-specification-accredited-a-level-gce-chemistry-a-h432.pdf (accessed 2022-01-31).

(69) *A Level Specification Chemistry B (Salters)*; Oxford Cambridge and RSA, 2017. https://www.ocr.org.uk/Images/171723-specification-accredited-a-level-gce-chemistry-b-salters-h433.pdf (accessed 2022-31-01).

(70) Carter, K. L. Differentiated Chemistry in the Junior Schools. *J. Chem. Educ.* **1930**, *7*, 845.

(71) Carter, K. L. Differentiated Chemistry in the Junior Schools. *J. Chem. Educ.* **1979**, *56*, 329.

(72) Reid, N.; Shah, I. The role of laboratory work in university chemistry. *Chem. Educ. Res. Pract.* **2007**, *8* (2), 172−185.

(73) Hill, M. A.; Overton, T. L.; Thompson, C. D.; Kitson, R. R. A.; Coppo, P. Kitson.; Paolo Coppo. Undergraduate recognition of curriculum-related skill development and the skills employers are seeking. *Chem. Educ. Res. Pract.* **2019**, *20*, 68−84.

(74) Seery, M. K.; McDonnell, C. The application of technology to enhance chemistry education. *Chem. Educ. Res. Pract.* **2013**, *14*, 227−228.

(75) Seery, M. K.; Donnelly, R. The implementation of pre-lecture resosources to reduce in-class cognitive load: a case study for higher education chemistry. *British Journal of Educational Technology.* **2012**, *43* (4), 667−677.

(76) Smallwood, Z. M.; Spencer-Briggs, J. L.; Xia Sean, X.; Ward, M. D.; Hyde, J. Design and Delivery of a Graduate Teaching Assistant (GTA) Program in a UK University: Experiences and Perspectives. *J. Chem. Educ.* **2022**, *99*, 592−602.

(77) Brandon, D. Unflipping the flipped classroom: balancing for maximum effect in minum lead-time in online education. *J. Chem. Educ.* **2020**, *97*, 3301−3305.

(78) Chen, K.; Chen, Y.; Ling, Y.; Lin, J. The Individual Experience of Online Chemistry teacher Education in China, Coping with COVID-19 Pandemic. *J. Chem. Educ.* **2020**, *97*, 3265−3270.

(79) Woelk, K.; Whitefield, P. D. As close as it might get to the real lab experience - live streamed laboratory activities. *J. Chem. Educ.* **2020**, *97*, 2996−3001.

(80) Practical resources. *Royal Society of Chemistry.* https://edu.rsc.org/resources/practical (accessed 2022-01-31).

(81) Selco, J. I. Faculty Using Hands-On Chemistry Experiments While Teaching Online. *J. Chem. Educ.* **2020**, *97*, 2617−2623.

(82) George-Williams, S.; Motion, A.; Pullen, R.; Rutledge, P. J.; Schmid, S.; Wilkinson, S. Chemistry in the time of COVID-19: Reflections on a very unusual semester. *J. Chem. Educ.* **2020**, *97*, 2928−2934.

(83) Dickson-Karn, N. M. Student Feekback on Distance Learning in the Quantitative Chemical Analysis Laboratory. *J. Chem. Educ.* **2020**, *97*, 2955−2950.

(84) Seery, M. K. Establishing the laboratory as the place to learn how to do chemistry. *J. Chem. Educ.* **2020**, *97*, 1511−1514.

(85) Bretz, S. L. Evidence for the importance of laboratory courses. *J. Chem. Educ.* **2019**, *96*, 193−195.

(86) Read, D.; Barnes, S. *Review of A-Level Chemistry Content*, ver. 1.21; University of Southampton & RSC., 2015, 1-39

(87) (a) Practical Videos | 14-16 Years. *Royal Society of Chemistry*. https://edu.rsc.org/practical/practical-videos-14-16-years/4012090.article (accessed 2024-11-09). (b) Practical Videos | 16-18 Years. *Royal Society of Chemistry*. https://edu.rsc.org/practical/practical-videos-16-18-years/4012343.article (accessed 2024-11-09). (c) Analytical Chemistry Introductions. *Royal Society of Chemistry*. https://edu.rsc.org/resources/collections/analytical-chemistry-introductions (accessed 2024-11-09).

(88) Harrison, T.; Shallcross, D.; Davey, W. Making better and wider use of undergraduate teaching laboratories in the support of chemistry in the UK. *New Directions* **2011**, *7*, 79−84.

(89) Chemistry on the Move. *Royal Society of Chemistry*, 2016. https://www.rsc.org/news-events/features/2016/jun/spectroscopy-in-a-suitcase/ (accessed 2022-01-20).