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Repurposing an introductory organic and inorganic laboratory course from the focus on teaching theory to the focus on teaching practical technique

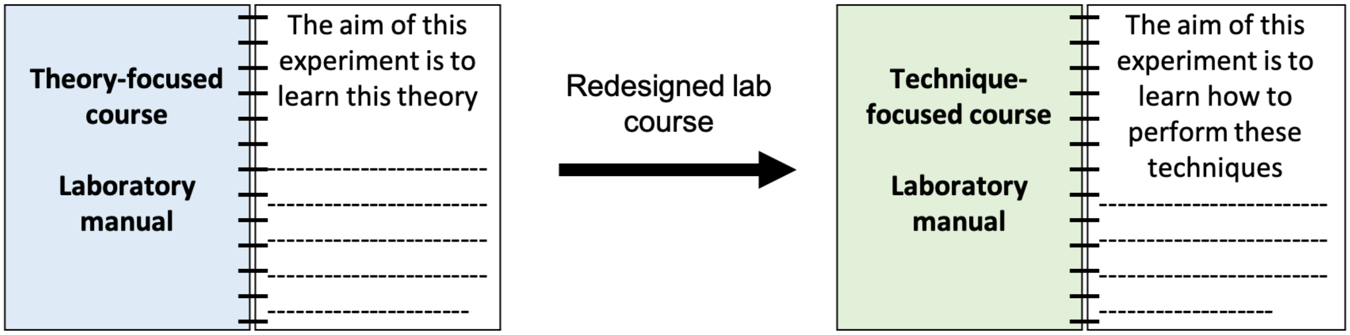
Stephen A. Gorman, Kimberly Holmes, Gemma Brooke, Christopher M. Pask and Nimesh Mistry*

School of Chemistry, University of Leeds, Leeds, West Yorkshire, LS2 9JT

ABSTRACT

A traditional laboratory course with the primary learning outcome of improving students' theoretical knowledge has received much criticism over the years due to the lack of evidence that these goals are achieved. We report our efforts to redesign a traditional first year organic and inorganic (also known as synthetic) laboratory course from having a focus on teaching theory to the development of practical skills. With better alignment between the core learning outcomes of the course and the type of experiments embedded into the curriculum, we report that the redesigned course improved students' practical skills from a number of measures, including students grades pre and post-course and from students' self-assessment of core skills in synthetic chemistry.

GRAPHICAL ABSTRACT



KEYWORDS

First-Year Undergraduate, Laboratory Instruction, Learning Theories, Hands-On Learning/Manipulatives.

INTRODUCTION

Despite laboratory courses being a fundamental aspect of undergraduate chemistry programmes, their educational value is one that continues to be debated.[1] Traditionally, the primary learning objective of practical work has been to improve students understanding of theory taught in lectures and this is where many of the criticisms of laboratory education lie.[2-5] There is little evidence that students achieve this goal. Instead of making connections to lecture material, students' primarily focus on following instructions carefully, finishing the practical in the allotted time, and gaining the necessary data for the post-laboratory assessment.[6-9] Despite performing experiments in this way, students expect laboratory courses to enhance their understanding of theory.[7, 10, 11] In physics education, exam scores between physics courses with and without a laboratory component were compared.[12, 13] It was discovered that there was no improvement in students' exam performance where there were associated practical classes, even though improving theoretical knowledge was stated as the key purpose of having the laboratory component. Recently, we investigated whether students' understanding of organic mechanisms was improved from performing associated experiments.[14] We found that an associated laboratory experiment made no difference to the level of performance for each type of mechanism. A study by Akkuzu and Uyulgan found that students understanding of functional groups in organic molecules were no better when they completed an associated experiment.[15] In this study, students' were found to possess a large number of misconceptions regardless of whether an associated experiment was performed or not.

At the University of Leeds, the organic and inorganic sections of practical modules were primarily focused on aligning theory from organic and inorganic lectures. It was believed that students' understanding of theory would be enhanced as a result of performing these experiments. In addition to the issues mentioned earlier, this was found to have negative consequences for other learning outcomes from the laboratory. In the laboratory manual, each experiment focused on background theory in the introduction with little mention of practical techniques or other learning outcomes. Experiments in the second-year organic laboratory course were organized into classes of organic reactions (e.g. cycloaddition reactions, C-C bond forming reactions) taught in the second-year organic chemistry curriculum, and students had to choose one experiment from each reaction class to perform (supplementary information). We analyzed the number of experiments chosen by students over a number of years and found that they overwhelmingly chose experiments which contained techniques taught in the first-year laboratory course, meaning students were progressing through the organic laboratory course without developing proficiency with advanced practical techniques such as inert atmosphere reactions and column chromatography which the second-year course was meant to teach. There have been many calls for laboratory curricula to cease being used as a vehicle for teaching theory.[16] Kirschner argues that laboratory education should be used to teach students how to *do* science rather than learn science[2] which forms the basis of a subsequent framework for learning in laboratory.[17] Instead of focusing on enhancing theoretical understanding, laboratory curricula should focus on skills where there is more substantial evidence to ensure there is learning value to justify the cost of running a teaching laboratory. These include the teaching of practical techniques as it is unlikely that students could learn these skills in other educational settings; requiring students to design experiments to test their own ideas; engaging students in the process of scientific inquiry and solving problems.[2, 5, 17]

Domin's taxonomy of laboratory instruction

Domin proposed a taxonomy of different types of laboratory instruction and how students behaved in each scenario.[3] Expository style laboratories, also known as 'recipe' or 'cookbook' labs are the most commonly used method of laboratory instruction by far. Here students follow a scripted procedure to synthesise a product that is known to both the student and instructor. This style of instruction has been criticized as a poor method for developing higher-order skills.[3] In the Task Analysis Guide in Science, this type of instruction is described as scripted integration, and is placed on one of the lowest cognitive levels of the framework.[18] The reason for this is that students have to make few decisions of their own. Any requirements for experimental design and problem-solving has been conducted by the instructor in the development of the procedure. What students are required to do is synthesize the correct product where yields and purity are based on how accurately they follow the procedure. As such, correct use of technique and instrumentation is important for achieving these goals. What students actually learn through expository laboratory courses can be garnered through students and staff expectations of laboratory courses.[11] As students progress through the course their experience leads to decreasing expectations of learning theory through practical work, however their expectations to learn practical skills is maintained throughout the course. Staff from the same courses expect students to primarily learn practical skills from largely expository courses. In a similar finding, faculty in the US were surveyed on their learning goals for laboratory courses.[19] In this study, practical technique was seen to be the main learning goal over higher-order skills, particularly for organic laboratory courses.

Inquiry-based experiments are more open-ended that their expository counterparts.[3] Here students have more responsibility for generating the procedure and for determining the outcomes of the experiment. Students are engaging in hypothesizing, experimental design, critical analysis and problem-solving during an inquiry-based experiment, and so can develop these skills better through this type of activity.[20, 21] There are a number of examples of inquiry-based experiments which have been incorporated into laboratory courses, or where the course itself has become fully inquiry-based.[22-25] Students find these experiments more challenging than expository experiments, but also find them more interesting and develop more positive attitudes towards the nature of science.[25] Immersing students directly into inquiry-based experiments can overwhelm students if too much demand is placed on learning new concepts.[26] An example of how to overcome this is by having structured activities where students first perform an expository experiment to become familiar with techniques followed by an open-ended, inquiry version of the experiment to develop higher-order skills.[27]

Discovery-based instruction is where students follow the procedure but the outcome is unknown.[3] This type of instruction is supposed to mimic the process of scientific discovery. The intention is that students will learn concepts by determining the outcome of the experiment. An example in a synthetic chemistry context would be conducting an experiment to deduce the mechanism. The reality is that students find this type of laboratory class overwhelming and rarely achieve the desired learning outcomes.

The final type of instruction is problem-based. Here students are given a problem to try and solve but will have to devise their own methods to do so. Often, the problem involves students applying particular concepts, so it is recommended that students are taught concepts prior to applying them in problem-based laboratories. Like inquiry-based instruction, problem-based instruction encourages higher order thinking, and a number of problem-based laboratory courses have been developed in organic and inorganic chemistry.[28-31]

OVERALL AIMS OF THE REDESIGNED SYNTHETIC LABORATORY COURSES AT LEEDS

A number of years ago, we embarked on a teaching enhancement programme to improve the learning outcomes from the organic and inorganic components of the chemistry laboratory modules at Leeds. Improved understanding of chemical theory was no longer used as a learning outcome for the courses and a driver for what experiments should be used. Instead, the primary learning outcomes were the development of practical technique, application of chemical theory (e.g. experimental design), problem-solving, scientific skills and professional skills. The organic and inorganic distinctions were no longer to be used and instead merged into synthetic chemistry. A key aspect of the redesigned curriculum was to use different types of laboratory instruction to focus on particular outcomes. Expository experiments would be used to teach practical technique, whilst more open-ended inquiry and problem-based experiments would be used to develop higher-order skills. A framework was devised where the course would focus on teaching practical technique in the introductory year (year 1) whilst more open-ended experiments and projects would be used for developing higher-order skills in years 2 and 3 respectively before students either graduate on the BSc programme, or perform an undergraduate research project on the integrated masters (MChem) programme in a research laboratory. The framework is a guide rather than a strict set of rules to follow. For example, inquiry and experimental design can still be used in year 1 to introduce these skills in a structured way, and expository experiments can be used to teach advanced practical techniques (handling syringes and needles, inert atmosphere techniques) in year 2. The structure has many similarities to an exemplar course structure proposed by Seery which used complex learning theory as a theoretical framework.[17] Although complex learning theory was not formally used in our curriculum redesign many of the principles were in our thoughts for designing our course.

Many students arrive at university with little prior experience of practical work.[32] Teaching both lower and higher-order skills from the outset risks overwhelming students. Competency with practical techniques is a necessary pre-requisite for performing open-ended laboratory investigations, so equipping students with these skills will allow student to focus on developing higher-order skills later in the course. A similar approach for a first-year synthetic courses has also been used elsewhere.[33-35]

Herein, we describe the design of the first-year synthetic laboratory course and its impact on students practical skills.

DESIGN OF THE FIRST-YEAR SYNTHETIC CHEMISTRY COURSE

The Quality Assurance Agency (QAA) Chemistry Benchmarks Statement which outlines the standards which UK Chemistry degree programmes must adhere to states that students should learn the ''*skills required for the conduct of documented laboratory procedures involved in synthesis and analysis, in relation to both inorganic and organic systems*".[36] Building on this, Royal Society of Chemistry (RSC) accreditation requirements state that ''*The practical component should be laboratory based and designed so that students are exposed to a variety of synthetic and measurement techniques*".[37] A list of fundamental practical techniques which we expect students to become proficient at the first-year level was devised. This was broadly in line with the techniques that most faculty expect students to learn at a similar level.[38]

Experiments in the course were broken down into the practical techniques they contained. Experiments which were unreliable or did not contain the desired skills were either removed, replaced or adapted so every experiment contained at least one skill or technique which we wanted students to learn (table 1). An example of this was the synthesis of paracetamol experiment where the original procedure required heating of the reaction mixture in a conical flask on a hotplate but was changed to heating by reflux so this skill could be introduced in a short experiment. The course was structured so each experiment would introduce key practical techniques. The following weeks would provide the opportunity to repeat and practice the technique, whilst they also introduced additional skills. Skills mapping was used to ensure the techniques were being introduced to students in a progressive manner, starting with simpler experiments and working towards experiments which contained more techniques. All students progress through the same sequence of experiments to gain the benefit of the course structure, and not feel overwhelmed performing more complex experiments before simpler ones.

Table 1. Skills mapping used to design the first-year synthetic chemistry laboratory course. 'X' denotes the presence of the skill in the experiment

	Experiment										
Practical Techniques	1[a]	2[b]	3[c]	4[d]	5[e]	6[f]	7[g]	8[h]	9[i]	10[j]	11[k]
Reflux				X		X		X	X		
Dropwise addition		X								X	
Hazardous chemicals			X						X	X	
Thin layer chromatography (TLC)			X	X							
Liquid-liquid extraction						X		X		X	X
Recrystallisation	X	X	X	X				X	X		X
Hot filtration	X	X							X		
Distillation						X				X	
Titration									X		
Melting point			X	X					X		
UV-vis					X		X				
Infrared (IR) spectroscopy			X	X		X	X	X		X	X
^{1}H NMR spectroscopy				X				X		X	

[a]Induction skills. [b]Iron complexes. [c]Borohydride reduction. [d]Paracetamol. [e]Cobalt complexes. [f]Esterification. [g]Copper complexes. [h]Benzocaine. [i]Tin Iodide. [j]Grignard reaction. [k]Purification design.

A guided-inquiry experiment was also introduced at the end of the course based on experimental design.[39] This was included to introduce problem-solving and experimental design skills in a structured way to prepare students for more open-ended experiments in the following years. In the first part of the experiment, students design their own work-up to isolate a desired compound from a mixture. This usually involves some form of manipulation to transfer compounds from the organic to aqueous layer and *vice versa*. The second part of the experiment involved purification of a sample by recrystallisation. Students choose their own solvent through a mixture of trial and error and understanding of solvent polarity. The laboratory manual was rewritten so references to theory were brief. Instead, the learning outcomes of each experiment specified the new and repeating practical techniques that were embedded into the experiment (for an example of an experimental procedure changed from the theory-led to technique-led format see supplementary information). Each experiment included an associated pre-laboratory activity. Pre-laboratory activities are an important tool to prepare students for the laboratory.[40] Effective pre-laboratory exercises provide students with the necessary supportive information so they have a better understanding of what they are meant to achieve in the experiment and feel less overwhelmed when they go into the laboratory.[17] Videos demonstrating technique were produced and hosted on a YouTube channel to facilitate ease of access from a variety of devices.[41] Pre-laboratory exercises required students to read through the procedure, watch the videos and answer questions based on technique, health and safety, and reagent calculations.

Lectures and workshops were also added to the practical course to support the learning of skills in the laboratory. Our rationale was similar to that used for pre-laboratory exercises in that they help to prepare students for practical work. Scientific literacy lectures and workshops guided student through the use of laboratory notebooks and how to write procedures in the standardized format used in journal articles. A practical theory lecture was given at the end of semester 2 when students had experience of the synthetic laboratories to explain the principles of experimental design and how experiments work. This was followed up with an experimental design workshop, where students learn how to design a full experimental procedure for an organic molecule, drawing upon their understanding of synthetic chemistry procedures and techniques as well as organic chemistry theory from lectures.

IMPLEMENTATION OF THE NEW COURSE

Experiments were scheduled to start on a Friday in semester 1 and a Tuesday in semester 2, with the deadline for completing pre-lab exercises by 11:59 pm the day before the experiment.

We analysed the access statistics of the practical videos channel from 24th September 2018 to 31st May 2019 which represents the full length of practical course in an academic year. The access statistics were filtered to only include views from the United Kingdom. These statistics do not capture geographical viewings at a more local level, so it is possible that some views were from non-Leeds students. However, the general pattern of views complemented the delivery of the practical course so there is confidence that it was Leeds students who were accessing the videos for the pre-lab exercise. The daily usage statistics showed a moderate number of views for most days then a spikes on the days of pre-lab deadlines (figure 1). This pattern was consistent across the academic year whilst the laboratory course was running.

Outside of term, in the Christmas and Easter vacation periods, there were very few views of the videos.

The course had 147 students enrolled in the 2018/19 academic year. For most videos, the number of times that each video was viewed exceeded the number of students on the course (table 2). This does not mean every student had watched the videos as individual data is not captured. However, when analysed with the pattern of daily usage over the course, this data suggests that most students were watching the videos and some watched them repeatedly. The extent to which students watched each video was on average between 61-84% of the entire video length. It is notable that the most popular video, recrystallisation, had the lowest percentage of views. It is possible that this is attributed to students feeling the need to re-watch this video but only for key parts rather than in its entirety. Overall, this pattern of video usage suggests that students were engaging with the practical technique videos prior to each experiment. It is likely, therefore, that these videos had an effect on students' ability to perform these techniques in the laboratory course.

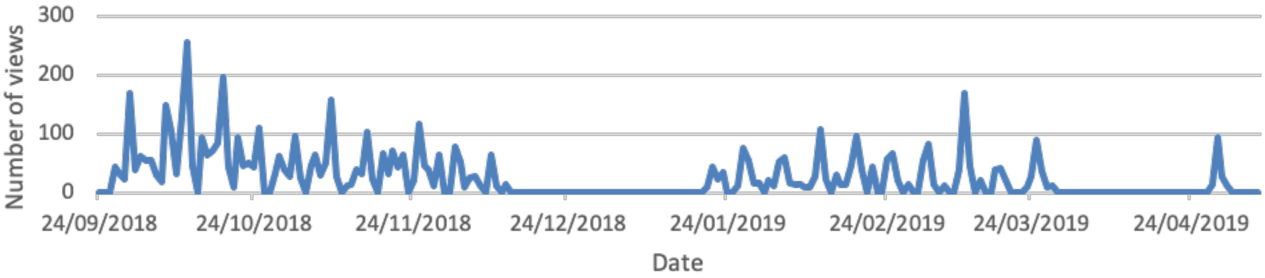


Figure 1: Viewings of laboratory practical videos hosted on the laboratory YouTube channel over the course of the 2018/19 academic year.

Table 2. YouTube analytic data for practical technique videos

	Video length	UK views	Average view duration	
	(mm:ss)		(mm:ss)	%
Reflux	2:21	197	1:52	79
Dropwise addition	1:40	183	1:08	68
TLC	1:07	196	0:56	84
Liquid-liquid extraction	3:09	160	2:40	85
Recrystallisation	2:14	297	1:22	61
Hot filtration	2:26	179	1:57	80
Distillation	2:09	131	1:27	67
Melting point	1:00	191	0:43	72
IR spectrometer	2:24	218	1:39	69

Before the changes were implemented, the laboratory felt hectic; a place where students were chasing grades by attempting multiple experiments simultaneously. By simply following the theory-led scripts students would not take the time to learn the technique or consider the justification for its use to any particular situation. This would lead to confusion and mistakes over how to perform techniques and how to consider improving them. Any effort to rectify mistakes would compound the sense of urgency. Following the changes that were made, the laboratory environment felt calmer. Having the students prepare in advance of the session and starting them with a briefing again adds to a sense of calm and that there is sufficient time to complete an activity. This communicates to the students that even when mistakes are made students know there is time to rectify it. At the beginning of each experiment students would receive a briefing from a demonstrator who would emphasise the key techniques and how to perform them correctly. In comparison to the theory-led course, students seemed to have a much better awareness of how to perform techniques correctly. Students would often ask demonstrators to check if their equipment had been set up correctly and receive other forms of formative feedback on their technique during the experiments much more often than in comparison the to the theory-led course.

EVALUATION OF STUDENTS' PERCEPTION OF SKILL DEVELOPMENT

Recently, we developed a laboratory skills survey to measure students perception of knowledge, experience and confidence of laboratory skills.[32] Students rate their skills on a scale of 1 to 5, where a score of 1 indicates low knowledge, experience and confidence and a score of 5 indicates high knowledge, experience and confidence. The survey was guided by the practical requirements of accreditation criteria to measure a set of core skills relating to scientific literacy, practical skills, health and safety, practical understanding, experimental design and problem-solving. The survey can also measure students' perceived development of higher and lower-order skills. In a previous study, we used the survey to understand the level of students' perceived skill development at the start of university, and how this could inform instructors in designing appropriate laboratory courses.[32] We found that students' perceived knowledge of skills exceeded their experience and confidence in most cases. Lower-order cognitive skills were more likely to be rated highly than higher-order skills. Many students had some knowledge of performing practical techniques such as reflux and recrystallisation as this is also a requirement for their practical skills development at high school.[42]

Ethical approval was granted by the institution's ethical approval board. The survey was administered to two cohorts of students who started the laboratory course in 2018 and 2019 respectively. Students first completed the survey at the start of the laboratory course and then following the completion of the course at the beginning of their second year of study. The survey was delivered using an online survey tool[43] and students were notified about the survey through the university virtual learning environment. Before completing the survey, students were made aware of the aims of the skills evaluation, how it did not contribute to their grades, how it was not compulsory and how they could withdraw their data at a future date if they so desired.

A total of 308 responses were received for the pre-course survey and 166 responses were received for the post-course survey. This represented 82% for the pre-course survey and 44% of the number of students over both years.

Student responses for each item were combined to give the overall percentage of students providing each rating 1 to 5. Following a method used by Towns[44] and Seery[45] independently, the pre-course percentage distribution was subtracted from the post-course distribution. A decrease in the overall percentage of students giving low ratings 1-3 and an increase in the percentage of students giving high ratings of 4-5 post course indicates an increase in student's perceived skill development from the laboratory course. Pre and post-course means for each item were calculated to be statistically significant through t-test ($p < 0.05$). The effect size for each item was determined by measuring the Cohen's d value. Following the guidelines given by Sawilosky[46], Cohen's d values below 0.2 were deemed to be a very small effect, 0.2-0.5 is small, 0.5-0.8 is medium, 0.8-1.2 is large and greater than 1.2 is a very large effect.

There are limitations that should be considered when interpreting the data. Student perceptions of their laboratory skills may not be an accurate representation of their abilities. Students may have over or underestimated their abilities, particularly for skills which they are unfamiliar with. Asking students to complete the pre-survey after they have finished the course may have provided different results.[47] Demographic data was not obtained from this survey. It is possible that there could have been differences in students based on demographics such as gender and ethnicity. As not all students responded to the survey there is a possibility that these results are not wholly accurate of the perceived skills developed by the whole cohort. In the post-course survey, the response rate was lower than for the pre-course survey. It is possible that the students who answered the post-course survey were not representative of all the students who completed the pre-course survey.

Table 3. Results of the pre-course and post-course skills assessment survey for practical techniques

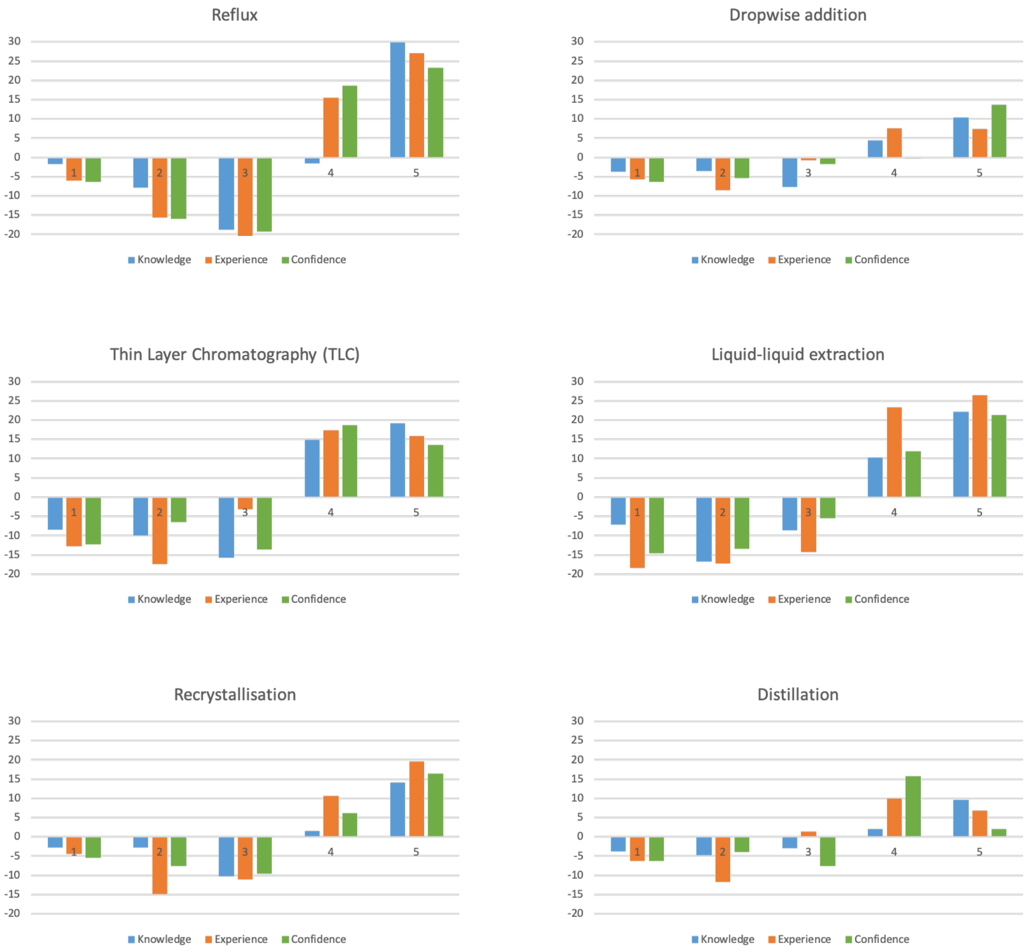
Practical Techniques		Pre-course mean[a]	Post-course mean[b]	Cohen's *d*	Effect
Reflux	Knowledge	3.60	4.31	0.82	Large
	Experience	3.23	4.21	1.04	V. large
	Confidence	3.11	4.05	1.00	Large
Dropwise addition	Knowledge	3.76	4.12	0.40	Small
	Experience	3.55	3.97	0.42	Small
	Confidence	3.45	3.91	0.45	Small
TLC	Knowledge	3.32	4.13	0.81	Large
	Experience	2.96	3.89	0.86	Large
	Confidence	3.02	3.80	0.74	Medium
Liquid-liquid extraction	Knowledge	3.16	4.02	0.84	Large
	Experience	2.75	4.05	1.24	V. large
	Confidence	2.84	3.80	0.88	Large
Recrystallisation	Knowledge	3.63	4.37	0.87	Large
	Experience	3.31	4.40	1.20	V. large
	Confidence	3.22	4.10	0.89	Large
Distillation	Knowledge	3.69	4.04	0.38	Small
	Experience	3.37	3.87	0.51	Medium
	Confidence	3.37	3.75	0.39	Small

[a]N = 308. [b]N =166.

Skill development results

Students reported large gains in their perceived skill development for reflux and recrystallisation as evidenced by their effect sizes (table 3) and their overall percentage increases being most prominent with the highest possible ratings of 5 (figure 2). These results can be attributed to the high number of experiments containing these techniques and they imply that students have learnt these skills to a high level. Therefore, it is unlikely that experiments in the second and third-year course which focus on developing these skills would be required. Instead, maintaining students' familiarity with these techniques will be the most likely benefit from future experiments, so upon graduation students can demonstrate these skills as the required level.

The focus on certain experiments teaching and practicing thin layer chromatography (TLC) and liquid-liquid extraction has also been effective in improving students' perceived competency of these two techniques demonstrated by their large effect sizes. In comparison to reflux and recrystallisation, students had less knowledge, experience and confidence of these skills at the start of the course. Therefore, a greater proportion of students self-assessed their skills to be at level 4. This is a positive outcome for the laboratory course, however it indicates that many students still feel they can improve these skills further with more practice later in the degree.



Reflux

Dropwise addition

Thin Layer Chromatography (TLC)

Liquid-liquid extraction

Recrystallisation

Distillation

Figure 2: Percentage change (post-pre course survey results for practical techniques) of students rating themselves 1-5 on the skills survey.

For dropwise addition and distillation, there were improvements in students' perceived competency of these skills. However, the percentage increases and effect sizes were smaller in comparison to the other techniques. This reflects the fact that there were fewer experiments for students to develop these skills further. This does not mean that students do not have good levels of perceived competency of these skills at this stage of their degree. These post-course means are comparable to TLC and liquid-liquid extraction. Their pre-survey means however, are higher and more comparable to reflux which explains why their effect sizes are smaller. Therefore, the overall outcome is the same as TLC and liquid-liquid extraction in that students have developed these skills to a high level but feel they can improve with more practice. For example, if the choice of a second-year experiment would be one that included a reflux and recrystallisation, and the other included a dropwise-addition and distillation, it would be preferable to choose the latter experiments to maximize the learning value from the experiment.

As an inquiry-based practical, the purification experiment gave the opportunity to develop more than just practical techniques. In our report of this experiment[39] we found students were required to apply their knowledge of chemistry to design their work-up procedures. Their understanding of the work-up process and experimental problem-solving skills was also found to be improved.

STUDENT PERCEPTIONS OF COURSE VALUE

Student feedback on module evaluations supported the observation that students were developing their practical technique. One of the most popular comments was how course provided students with the opportunity to practice and learn techniques. Students also commented on learning how to use equipment and instruments as well.

Variety of skills and opportunities to practice techniques so saw a lot of improvement over the year and feel more confident about skills developed.

I enjoyed the labs and using lots of new equipment that I hadn't used before.

A number of students also commented on how the laboratory manual was written in a helpful way to learn techniques. The original manual was theory-focused so each experiment was rewritten to highlight and focus on the skills being taught. This appears to have been noticed by these students highlighting the laboratory manual as a factor in their learning and emphasises the important role that the laboratory instructions have in influencing the learning outcomes.

Handbook was easy to use and well written for students.

Some students were able to reflect on how the whole course structure had progressively developed their skills from our design to introduce skills in key experiments with repetition in subsequent experiments that increased in difficultly. It was pleasing to see that the course design was noticeable from a student perspective.

The structure of the module progressively built up my skills by introducing new apparatus and techniques, and then using the same techniques in a range of different experiments. This structure helped to increase my familiarity and confidence with key skills required in practical chemistry.

A comment which was brought up by many students was how the length of time given to students to complete their experiments was a factor in their ability to develop practical skills. The course was designed to have simpler experiments to start with and become more difficult as students progressed through the course. The difficultly was also managed so that students would have plenty of time to complete each experiment and possibly repeat the experiment if needed. It has been seen elsewhere that if time constraints dominate in a student's thoughts then they are less likely to learn skills in the laboratory.[7] In our case students wrote how they had enough time to focus on skills with the time given to complete each experiment.

Plenty of time given for practicals, so time pressure was not too big of a stress meaning focus could be on practical skills rather than timing.

This highlights how time is an important factor for laboratory skill development. These comments also concur with the instructors' observations that the redesigned laboratory was calmer and students were focusing more on skill development.

For comparison, we also analysed module evaluation comments prior to the redesigned course. In our analysis we found no comments mentioning the development of practical techniques.

STUDENT PERFORMANCE

Students were assessed on their performance for each experiment by the data associated with the quality of the samples produced and completion of an experimental proforma. Sample data included sample appearance, yield, melting point, appearance of TLC plates, and quality of infrared and ^{1}H NMR spectra. Performing techniques well leads to high yields and high quality data, hence high marks. In each experiment the total of these criteria amounted to 60 marks out of 100. The remaining 40 marks were from laboratory notes, analysis of spectra and some questions connected to the experiment.

We analysed the grades of students who performed these experiments in the 2018/19 academic year (table 4). In our analysis we removed the marks associated with laboratory notes, analysis of spectra and questions so only the sample marks were left. This is so our analysis of grades could be correlated more with students' performance of experimental techniques. The marks reported here are the sample marks out of 60, given as a percentage. We found that for every experiment the sample marks were high. This indicates that the majority of students had performed the required practical techniques to a high standard. One experiment which had a noticeably lower average is the Grignard experiment. This experiment was one of the most technically challenging experiments as it required the preparation and use of a Grignard reagent which is moisture sensitive. There is a greater chance of students obtaining lower yields if their glassware was not dry. When comparing these scores to the same experiments that were part of the theory-focused course it was found that the practical-focused course led to higher yields and data marks. This indicates that students taking the practical-focused course were better at performing practical techniques compared to students on the theory-focussed course.

Table 4. Results of students sample grades for each experiment.

	Theory-focused course		Practical-focused course	
Experiment	% Mean[a]	Std Dev[a]	% Mean[b]	Std Dev[b]
Iron complexes	65.4	12.4	71.3	16.2
Borohydride reduction	—[c]	—[c]	74.9	16.7
Paracetamol	—[c]	—[c]	73.1	15.9
Cobalt complexes	—[c]	—[c]	72.0	17.1
Esterification	61.2		69.8	18.3
Copper complexes	—[c]	—[c]	68.4	15.8
Benzocaine	59.6	15.8	69.5	16.3
Tin Iodide	62.7	19.5	76.4	17.4
Grignard reaction	55.4	18.3	62.6	20.1
Purification design	—[c]	—[c]	72.3	19.2

[a]*N* = 204; [b]*N* = 245; [c]Experiments introduced with the course changes so there is no comparible data.

CONCLUSION

We have reported that an introductory synthetic chemistry laboratory course can be redesigned from focusing on enhancing theory to supporting the development of practical skills. Using Domin's taxonomy of laboratory instruction styles, we designed the course so that that main learning outcome of expository style experiments was the development of synthetic chemistry techniques. Students were progressively introduced to new techniques with each experiment, with the opportunity to repeat these skills in the following experiments. Pre-laboratory videos were introduced to demonstrate the correct practice of the techniques. Implementation of a laboratory skills survey pre and post-course to two cohorts who participated the redesigned course revealed students' perceived development core synthetic chemistry techniques. Observations from instructors and students indicate that students were focusing on developing practical skills. Students' grades indicated that they were developing they were performing the techniques to a high level, and were better than the students who took the theory-focussed course. These changes provide the foundation to further develop students' practical skills in later years by focusing on advanced techniques and the development of higher-order skills through open-ended laboratory activity. The effect of teaching enhancement programme to the second and third-year laboratory courses will be reported in the future.

ASSOCIATED CONTENT

Supporting Information

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

Students choice of second-year experiments, sample laboratory procedures (DOCX)

AUTHOR INFORMATION

Corresponding Author

*E-mail: N.Mistry@leeds.ac.uk

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