**Assessing the practical skills of undergraduates: The evolution of a station-based practical exam**

Laura M. Hancock\* and Martin J. Hollamby

Keele University, Keele, Staffordshire, ST5 5BG, UK

Abstract

Laboratory education is a defining feature of chemistry degree courses, with one of the fundamental aims being acquiring competency in a range of chemistry-specific practical skills, yet there are still limited reports of direct assessment of these skills. Here, we present the development, implementation and evaluation of a station-based practical chemistry exam for first year undergraduate students. We have designed the exam to explicitly assess a range of practical chemistry skills, that we highlighted as being essential for subsequent chemistry laboratory work in our degree programme, including many final year independent research projects. Details are provided on the logistics of implementing this exam, which has run for cohorts of 50-120, and is suitable for cohorts of up to 200 students. Introducing the practical exam into our course has received positive feedback from both staff and students, and has contributed to increased motivation to learn and retain practical chemistry skills.

Graphical Abstract



Keywords

Audience: First Year Undergraduate/General

Domain: Curriculum, Interdisciplinary/Multidisciplinary

Pedagogy: Hands-on learning/Manipulatives, Testing/ Assessment

Topic: IR Spectroscopy, Quantitative Analysis, Thin Layer Chromatography, UV-Vis Spectroscopy

INTRODUCTION

The purpose and effectiveness of laboratory education in chemistry degree courses has long been the subject of scrutiny.1-4 The aims of laboratory work can be broadly split into three areas: practical skills; transferable skills; and intellectual stimulation.5 The term ‘practical skills’ may itself be wide-ranging incorporating operation of specific equipment and instrumentation, observation and interpretation of methods, and adherence to safety procedures. In the context of this article, we assign ‘practical skills’ to the specific techniques commonly found in chemistry laboratories including operation and manipulation of equipment and instrumentation.

Poor engagement with chemistry laboratory classes in higher education is a common complaint; there are many reports of students merely aiming to finish their laboratory class as quickly as possible with little regard for the skills they might be acquiring.6,7 Failing to effectively learn practical chemistry skills at lower levels of a degree course may hinder performance in subsequent modules (where proficiency in such skills might be "expected"), including final year research projects, and potentially hinder future employment as laboratory chemists.8 Another consequence of lacking basic practical skills at higher levels of a degree course is reduced opportunity to develop the plethora of important scientific and transferable skills that a practical chemistry course should provide, if the focus remains on explicit procedures, glassware handling and instrumentation operation. Furthermore, in the UK, one of the key requirements of Royal Society of Chemistry accredited degree courses is ‘*students must develop a range of practical skills’*.9

In recent years there has been significant focus on improving the effectiveness of chemistry laboratory classes, partly with the aim of enhanced learning and retention of practical skills.1-3 The key factor that has been identified as a barrier to learning in the laboratory, especially for students in the early years of their degree, is cognitive load.10,11 Learning any underpinning theory is significantly more challenging in an unfamiliar environment, for example where competence in new or unlearned practical skills is also required.9 At Keele and elsewhere, pre-laboratory exercises have been widely used in an attempt to reduce cognitive load and increase students’ preparedness.12-14 For example, pre-laboratory video demonstrations, often coupled with a short related quiz have been used to prepare students for new practical techniques they will meet in the lab.13 In a related approach, Fung has used ‘first person’ videos created through the student wearing a camera when carrying out a technique.15 Pre-laboratory exercises involving videos of specific techniques have been popular with students, shown to be effective at increasing students’ understanding of the purpose of the technique,14 but do not necessarily lead to enhanced academic performance.13 More recently, Blackburn *et al*. have integrated laboratory themed simulations allowing students experience of experiments without the associated risk of a laboratory setting.16 Zeiner *et al*. have replaced standard laboratory instructions with photocomics, combining photographs of the steps of laboratory procedure with short sentences.17 The photocomic lab manuals were found to promote greater student independence and efficiency in laboratory classes.

All attempts to enhance practical chemistry skills may be futile if the students do not perceive their efforts to be rewarded i.e. practical skills must be assessed.18 The assessment associated with practical courses in chemistry degrees is commonly related to the experiment write-up, or the final result (for example, quality of data analysis, product appearance and/or yield)19 rather than proficiency in the skills developed during practical sessions. While analytical and reporting skills are of great importance for chemistry graduates, this type of assessment only indirectly assesses practical skills.20-24

The direct in-course assessment of practical chemistry skills is still not commonplace in higher education, but there are some examples. Hyde *et al*. have introduced practical skills portfolios as a means to record and reflect upon techniques learnt in the laboratory, however there does not appear to be direct observation of students completing the techniques.25 Chen *et al*. have used a skills based scoring rubric for an organic chemistry experiment that comprised demonstration of various practical skills, for example ‘heating a reaction at reflux’.26 In order to ensure consistency in marking by teaching assistants, each skill comprised a series of subskills (e.g. selecting clean and dry glassware to use). In the work of Graham *et al*. the ability of students to successfully carry out a purification technique was assessed through the purity of the product, as determined by the spectral analysis obtained.27 Elsewhere, there have been reports whereby students are asked to create video recordings of basic skills (e.g. pipetting) that lead to the award of digital badges.28-30 In the example of Seery *et al*. each student-produced video is reviewed and feedback provided. However, the range of techniques is presently limited. If it were to be expanded to include a wide range of skills, marking and feedback provision may become unfeasible.

Specific examinations to assess practical skills remain rare, although there are examples at high school level,31 testing proficiency in one particular technique (for example use of a burette). Fergus *et el* have reported a structured chemistry examination (Schems) for first year pharmacy and life sciences students, incorporating the testing of competency in a range of techniques alongside important graduate skills.8 Neeland has developed a 2nd year organic chemistry practical exam comprising a series of very short (~4 min) stations where students are required to demonstrate various competencies.32However, the short timescale for each station precludes the examination of techniques that may require longer to demonstrate (for example, recrystallization).

Herein, we report the design and evolution, over 7 years and 2 distinct versions, of a station-based practical exam to exclusively assess a range of practical skills of first year undergraduates, for a cohort that has ranged from 50 - 120 students. Introducing the practical exam coincided with major curriculum redevelopment in the chemistry department at Keele, including the formation of a distinct practical chemistry module. The four intended learning outcomes (ILOs) assessed through the practical exam for the practical module (See Table S1 in the Supporting Information for further module details) are listed below:

1. Identify, assemble, and select appropriate standard chemical apparatus for chemical procedures.
2. Demonstrate competence in the use of standard chemical apparatus, procedures, and instrumentation.
3. Analyze and interpret 1H and 13C NMR, IR, and UV–vis spectra to evaluate the outcome of experimental investigations.
4. Manipulate and analyze experimental data, using spreadsheets, to create appropriate graphs and extract scientific parameters.

The practical exam comprises the principal assessment for ILO 1 and 2, while ILO 3 and 4 are also assessed through additional assessment items.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 1. “Desirable” Practical Skills for 1st-Year Chemistry Undergraduates and the Station in the Practical Exam Where They Are Assessed | | | | | | | | | | | | | |
| Practical Skills | Practical Examination Stations*a* | | | | | | | | | | | | |
| Liquid–Liquid Extraction | Recrystal-lization | UV–Vis Spectroscopy*b* | IR  Spectroscopy*c* | COSHH*d* | NMR & Yield Calc.*e* | NMR Prep. & Analysis*e* | Melting Point | Acid–Base Titration | Rotary Evaporation | TLC*f* | Reflux | Standard Solutions |
| Clamping QuickFit glassware | X |  |  |  |  |  |  |  |  |  |  | X |  |
| Accurate weighing |  |  |  |  |  | X |  |  |  |  |  |  | X |
| Mass/mole/concentration/ yield calculations |  |  |  |  |  | X |  |  |  |  |  |  | X |
| Use of micropipettes |  |  | X |  |  |  |  |  |  |  |  |  |  |
| Use of volumetric glassware (burettes, volumetric flasks, etc.) |  |  | X |  |  |  |  |  | X |  |  |  | X |
| Use of a separating funnel for liquid–liquid extraction | X |  |  |  |  |  |  |  |  |  |  |  |  |
| Gravity filtration | X |  |  |  |  |  |  |  |  |  |  |  |  |
| Drying an organic solution with MgSO4 | X |  |  |  |  |  |  |  |  |  |  |  |  |
| Recrystallization |  | X |  |  |  |  |  |  |  |  |  |  |  |
| Buchner filtration |  | X |  |  |  |  |  |  |  |  |  |  |  |
| Operation of a UV–Vis or IR spectrophotometer |  |  | X | X |  |  |  |  |  |  |  |  |  |
| Calculation of parameters from UV–Vis Spectra, including use of Beer–Lambert plots |  |  | X |  |  |  |  |  |  |  |  |  |  |
| Interpretation of IR spectra |  |  |  | X |  |  |  |  |  |  |  |  |  |
| Preparation of sample for NMR spectroscopy |  |  |  |  |  | X | X |  |  |  |  |  |  |
| Interpretation of NMR spectra |  |  |  |  |  |  | X |  |  |  |  |  |  |
| COSHH risk assessment |  |  |  |  | X |  |  |  |  |  |  |  |  |
| Melting point determination |  |  |  |  |  |  |  | X |  |  |  |  |  |
| Operation of rotary evaporator |  |  |  |  |  |  |  |  |  | X |  |  |  |
| Heating a reaction at reflux |  |  |  |  |  |  |  |  |  |  |  | X |  |
| *a*Further details relating to the exact requirements of each station are given in Table S3 in the Supporting Information. *b*UV–Vis: ultraviolet–visible. *c*IR: Infrared. *d*NMR: Nuclear magnetic resonance. *e*COSHH: Control of substances hazardous to health (Risk Assessment) *f*TLC: Thin-layer chromatography. | | | | | | | | | | | | | |

We have identified key practical chemistry skills that we perceive that undergraduate students should acquire in the first year of their chemistry degrees and have designed practical exam stations that directly assess of a selection of these skills (Table 1). These skills were identified by examining the techniques already used in our chemistry laboratory classes and through numerous discussions with colleagues, especially those teaching at higher levels of the degree course. Laboratory classes sat by students in their first semester at Keele now focus primarily on practical skills, many of which are backed up by theory covered in the lecture courses (for example, spectroscopy), to reduce cognitive load and promote skills retention. The experiments have been designed to allow opportunity to learn and practice the key skills identified in Table 1 (See Supporting information, Table S2) before the practical exam takes place. Redesign of the laboratory course and introduction of the practical exam have ensured the intended learning outcomes, teaching and learning activities, and assessment are all appropriately aligned.

PRACTICAL EXAM DESIGN

The undergraduate practical exam runs at the end of semester 1 for students in the first year of their chemistry or medicinal chemistry degree programme at Keele, UK (equivalent to freshman year in the US). Students may either be studying single honours chemistry or completing a combined honours degree programme, which in the first year equates to 50% chemistry and 50% a different subject. Figure 1 outlines the basic form of the two primary versions of practical exam that have been in place since 2012. **Version 1 (V1)** of the practical exam ran 2012/13 – 2014/15 with a typical cohort of less than 80 students. It included 5 sequentially assessed stations, each lasting 22 min and examining one or more key practical skills. The total time of 22 min includes an initial 2 min for reading the COSHH assessment and script (for example scripts, see Supporting Information Figure S1), and 20 min to complete the task. Typically, 20 - 30 students were assessed per exam, so by varying the starting station for an individual, 4 - 6 students occupied each station simultaneously. In total, including the pre-exam briefing, station reset time and time required for movement between stations, the exam lasted a little over 2 hours and as such fitted into our 3 hour laboratory slots. The exams included a combination of station types, assessing a range of skills and intended learning outcomes as outlined in Supporting Information Table S3. Depending on the constituent stations, the required staff:student ratio ranged between 1:5 and 1:4. Students have ample opportunity throughout semester 1 to practice the assessed skills, as detailed in Supporting Information Table S2.

**Version 2 (V2)** of the practical exam has run at Keele since 2015/16. A significantly increased cohort size (>100 students) meant that **V1** would not fit within the confines of the timetable. In **V2**, up to 36 students can sit their practical session in a 3hr lab session, meaning that it is now possible to examine up to 108 students in 2 × 3 hr + 2 × 2 hr sessions with greater flexibility in timetabling (this is specific to our timetable, and accounts for the provision of ‘extra time’ for students with disability adjustments), where previously a maximum of 90 could be examined. To do this, the number of stations was cut from 5 to 3, which allowed a more focused approach towards key lab skills (Figure 1 and Table S3). Other than this, the exam is run in much the same way as **V1**, with similar staff:student ratios.



Figure 1: Practical exam stations in Versions 1 (**V1**) and 2 (**V2**) of the chemistry practical exam.

Since 2016, we have continued to revisit the structure of **V2** and the way in which the exam is communicated to the students. For example, where in 2015/16 we informed the students that the three stations could each assess one or more skill from the full list, since 2016/17 we have informed them that station A assesses either liquid-liquid extraction or recrystallization, station B assesses either UV-vis spectrophotometry or IR spectroscopy and that station C assesses one or more other skill (Figure 1). This seemingly minor disclosure encouraged the students to focus their revision on what we believe to be particularly important laboratory skills (*i.e.* those assessed in stations A and B). In 2018/19, in response to student feedback, a mock practical exam was introduced midway through semester 1 in order to provide students with experience of carrying out practical chemistry under exam conditions. The mock was well received by the students, who appreciated the insight it allowed into the real exam.

Exam Preparation

Each experiment undertaken prior to the exam has an associated pre-laboratory exercise which requires students to watch and answer a series of questions on a selection of skills videos (for example from the RSC Interactive Lab Primer33). The marks from these pre-labs are summative to ensure completion, but low stakes, each worth ≈2% of the module mark. Students are told that they will complete a skills-based practical exam in the module induction, and laboratory staff refer to the exam throughout the semester. The logistics and requirements are communicated to the students at a briefing session that is typically held 1-2 weeks prior to the first exam. During this briefing, timings (as above) are explained, an example script is shown and the techniques that potentially will be examined (Table 1) are described. Finally, some ideas for preparation are given (*e.g.* read through notes made during practical sessions and work done prior to them, watch online videos that have been linked to *etc.*). Slides from the briefing session are uploaded onto the virtual learning environment allowing details to be rechecked nearer the exam.

Logistics

Students are assigned a specific practical exam slot that they must attend. Before the exam commences, students are given coversheets with their name and the station order. At each station students are provided with a script (*e.g.* Supporting Information Figure S1) that they are required to leave at the station when the allocated time period for that station ends. In addition to the normal requirements of key stationary and a calculator, they must bring their own laboratory coat and glasses. The exam is then held under normal University exam conditions. No discussion with other students is permitted. Requiring help from examiners, where permitted, is penalized by a loss of up to 25% of the marks available at that station.

Exam Equipment Preparation

The equipment requirement is station-specific, but typically sets of glassware and chemicals are prepared in trays for each space on a station for the entire session. For example, in **V2**, for a 3hr session during which 2 separate exams take place (for 2 × 18 = 36 students), each of the three stations will have 6 trays prepared, each containing sufficient equipment for 6 students to complete that station. An example of the equipment requirement for the liquid-liquid extraction station in the above scenario is provided in Supporting Information Table S4.

Grading

|  |  |  |
| --- | --- | --- |
| Table 2. Observation Level and Staffing Requirement for Different Types of Stations | | |
| Observation Level | Minimum Examiners, per station *N* | Skills |
| Direct observation by examiner | 1 per 1 or 2 students | Recrystallisation, liquid–liquid extraction, rotary evaporation |
| Station observation | 1 or 2 per station | UV–vis spectrophotometry, IR spectroscopy, Acid–base titration |
| No observational skills assessed by the result of the station | 0*a* | All other skills listed in Figure 1 and stations listed in Table 1 |
| *a*A “patrolling” examiner was present to troubleshoot. | | |

Having a 1:1 staff:student ratio is unrealistic, therefore it was important to design the practical exam such that not all stations require assessment *via* direct observation of the technique being performed, but still explicitly assess practical skills. In terms of observation, stations are generally split into three types, shown in Table 2.

To ensure consistency between examiners, each station has a detailed mark scheme, broken down into specific points. An example for the recrystallisation station is provided in Supporting Information Figure S2). For directly observed stations (Table 2), examiners are only required to tick whether the student has completed each stage and provide some notes for feedback. This makes examining as straightforward as possible, and therefore importantly, as fair and consistent as possible for the students.

EVALUATION

Marks

The marks for the practical exam over seven academic years is presented in Table 3. Mean marks are clustered around 60-65% and the failure rate is relatively low. While in **V1** (Supporting Information Table S5), students performed poorly on certain stations (e.g. standard solution preparation, UV-Vis spectroscopy), in **V2** (Table 3) marks have been more evenly distributed. We speculate that the main reason for this is more focused revision, as discussed above in “practical exam details”, but in the case of solution preparation and UV-Vis spectroscopy additional practice has also been recently introduced (see Supporting Information Table S2).

For those students who fail their first attempt, reassessment is offered late in the second semester. To-date, no student has failed the practical exam upon reassessment. Issues of, for example, over-reliance on a stronger lab partner in semester 1, can be addressed via this mechanism.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 3. Mean Practical Exam Marks ± One Standard Deviation and Failure Rates from 2012–2013 to 2018–2019 | | | | | | | | |
| Practical Exam Versions | Academic Year | Students, *N* | Stations (each worth 20 marks) | | | Mean Mark, % | Failing Grade (<40%) | |
| A*a* | B*b* | C*c* | *N* | % |
| Version 1, V1 | 2012/13 | 71 | —*d* | —*d* | —*d* | 68 ± 13 | 3 | 4.4 |
| 2013/14 | 56 | —*d* | —*d* | —*d* | 61 ± 13 | 2 | 3.3 |
| 2014/15 | 78 | —*d* | —*d* | —*d* | 60 ± 10 | 3 | 5.0 |
| Version 2, V2 | 2015/16 | 97 | 11 ± 3 | 11 ± 5 | 13 ± 4 | 58 ± 14 | 11 | 11.3 |
| 2016/17 | 112 | 14 ± 4 | 13 ± 3 | 13 ± 5 | 66 ± 14 | 5 | 4.4 |
| 2017/18 | 67 | 13 ± 5 | 11 ± 4 | 14 ± 5 | 64 ± 16 | 6 | 9.2 |
| 2018/19 | 59 | 13 ± 4 | 12 ± 4 | 13 ± 5 | 63 ± 17 | 4 | 6.8 |
| *a*Station A is LLE/Recrystallization. *b*Station B is IR spectroscopy/UV–vis spectroscopy. *c*Station C is thin-layer chromatography/NMR spectroscopy/Yield calculation/Titration. *d*Individual station marks for V1 are found in Table S5 in the Supporting Information. | | | | | | | | |

Student Perceptions

The data presented within this section was obtained from an anonymous questionnaire administered by electronic voting devices from 68 students (out of a cohort of 112) (2016-17 cohort) directly after the practical exam had taken place. The questionnaire responses are presented in Figure 2. Pleasingly, students were generally satisfied with the clarity of the practical exam instructions and deemed this a fair way to assess their practical skills. They were satisfied that the teaching and learning activities provided during the semester leading up to the practical exam were appropriate preparation. Although the majority of students felt intimidated being directly observed by an examiner, feelings were mixed over whether this was a more nervous experience than a written exam. Despite these factors, almost 80% of respondents stated a preference for the practical exam rather than another written assignment, which is interesting as student preference is generally for coursework over exams (albeit written exams).34 It may be that the effort of completing a practical exam is perceived to be lower than, for example, a laboratory report. To succeed in a practical exam, effort is required throughout the semester by engaging in learning appropriate skills in the laboratory classes.

In addition to students’ perceptions of the practical exam, they were also asked how they prepared for the practical exam (see Supporting Information Table S6 for complete answers). The most commonly cited preparations were the videos they were asked to watch as part of their pre-lab activities (47/68), the laboratory diaries (notebooks) that they are required to complete throughout semester, and being encouraged to make notes on the various practical techniques they learn (47/68). It is pleasing that students are engaging in the scaffolding we have constructed within the module to facilitate the learning of practical skills.

Finally, students were asked which practical techniques they did not feel confident in completing now that they had sat the practical exam. (Supporting Information Table S7). Answers that attracted 15+ responses were UV-Vis spectroscopy, NMR spectroscopy, graphical analysis using Excel, recrystallization and liquid-liquid extraction. Historically, stations combining UV-Vis spectroscopy and Excel graphical analysis have tended to attract lower marks (e.g. Supporting Information Table S5), and as noted above positive action has been taken to combat this, which has already seen some success (e.g. Table 3). However, the high response rate for recrystallisation and liquid-liquid extraction may just be due to the fact all students are assessed on one of these skills, since the marks for these stations tend to agree with the mean exam mark.



Figure 2: Questionnaire responses given as a % of number of respondents (n = 68).

Staff Perceptions

We believe that the introduction of the practical exam has had a positive impact in terms of changing student attitude to laboratory classes, with students observed to have greater motivation to develop appropriate laboratory skills in advance of the exam. In the second semester of first year, it is our belief that students generally demonstrate better retention of practical skills they have learnt in the first semester, and less staff intervention is required.

Introduction of the practical exam has also allowed focus upon the skills and related concepts that students find particularly difficult, and allow greater focus on these elsewhere in the course. All practical exam invigilators are directly involved in first year laboratory class teaching; being able to observe issues with technique allows these to be quickly addressed in future laboratory classes.

The explicit assessment of practical skills has also required us to more thoroughly examine our practical classes to ensure that they are adequately preparing the students for their practical exam, and subsequent laboratory classes for the remainder of their course. For example, as noted above, in 2018/19 we introduced a new laboratory experiment focusing on development of solution preparation and UV-Vis spectroscopy skills (Supporting Information Table S2).

Implementing the practical exam has been logistically challenging, requiring significant commitment from various members of academic and technical staff. As previously discussed, an increase in student cohort number in 2016/17 lead to **V2** being developed. Despite **V2** comprising fewer stations than **V1**, we do not believe that this has compromised the rigor of the exam, as broadly reflected by the marks in Table 3, instead revealing that some of the assessed stations (for example, preparation of a COSHH form, NMR analysis) could be assessed via other mechanisms. The current form of **V2** is appropriate for large cohorts of students (18 students can be assessed in 1.5 hours in our laboratory which has 16 fumehoods and a maximum capacity of 64).

Conclusion

The introduction of a skills-based practical exam as a means of assessment in our first year undergraduate curriculum has had a significant positive impact upon both the practical skills of our students and their application in laboratory classes. It has also acted as a motivator for us to ensure that the activities we provide in laboratory classes allow for adequate development of practical skills. Our practical exam has undergone various stages of evolution over the seven years of implementation, including redesign of the stations to ensure purely practical techniques are tested, and the introduction of a mock exam. It continues to evolve. We thoroughly recommend the implicit examination of practical chemistry skills at an early stage in chemistry degree courses to focus students on the importance of being a competent practical chemist, to reduce the cognitive load in future laboratory sessions of having to combine the learning of theory with the use of still unfamiliar equipment. We are pleased to report that other UK university chemistry departments are starting to adopt our approach to explicitly assess the practical skills of chemistry departments.35

Associated content

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX. [ACS will fill this in.] Example brief descriptions with file formats indicated are shown below; customize for your material.

Notes for Instructors (DOCX)

AUTHOR INFORMATION

Corresponding Author

\*E-mail: l.m.hancock@keele.ac.uk

Acknowledgments

The authors would like to thank the chemistry and medicinal chemistry students at Keele for providing valuable feedback. We also thank numerous members of the chemistry teaching team (academic staff, technicians and demonstrators) at Keele for assistance, especially Nicola Jervis for providing technical support.

REFERENCES

1. Boud D., Dunn J. and Hegarty-Hazel E., Teaching in laboratories, Surrey, UK: Society for Research into Higher Education & NFER-Nelson Guildford, **1986**.

2. Johnstone A. H. and Al-Shuaili A., Learning in the laboratory; some thoughts from the literature, *Univ. Chem. Educ.,* **2001***,* 5(2), 42–51.

3. Hofstein A. and Lunetta V. N., The laboratory in science education: foundations for the twenty-first century, *Sci. Educ.*, **2004**, 88(1), 28–54, DOI: [10.1002/sce.10106](http://10.1002/sce.10106).

4. Reid N. and Shah I., The role of laboratory work in university chemistry, *Chem. Educ. Res. Pract.*, **2007**, 8(2), 172–185, DOI: [10.1039/B5RP90026C](http://xlink.rsc.org/?DOI=B5RP90026C).

5. Carnduff J. and Reid N., *Enhancing undergraduate chemistry laboratories: pre-laboratory and post-laboratory exercises*, Royal Society of Chemistry, Burlington House, Piccadilly, London. **2003**.

6. DeKorver B. K. and Towns M. H., General Chemistry Students’ Goals for Chemistry Laboratory Coursework, *J. Chem. Educ*., **2015**, *92*(12), 2031–2037. DOI: [10.1021/acs.jchemed.5b00463](https://doi.org/10.1021/acs.jchemed.5b00463)

7. DeKorver B. K. and Towns M. H., Upper-level undergraduate chemistry students’ goals for their laboratory coursework, *J. Res. Sci. Teach.*, **2016,** *53*(8), 1198–1215. DOI: [10.1002/tea.21326](https://doi.org/10.1002/tea.21326)

8. Kirton S. B., Al-Ahmad A. and Fergus S., Using Structured Chemistry Examinations (SChemEs) As an Assessment Method To Improve Undergraduate Students’ Generic, Practical, and Laboratory-Based Skills, *J. Chem. Educ*., **2014**, 91(5), 648–654. DOI: [10.1021/ed300491c](https://doi.org/10.1021/ed300491c)

9. RSC (2017), Accreditation of degree programmes <https://www.rsc.org/images/Accreditation%20criteria%202017-%20update%20july%2017_tcm18-151306.pdf> (*accessed Nov 2019*)

10 Johnstone, A. H. Chemistry Teaching - Science or Alchemy. *J. Chem. Educ*. **1997**, 74 (3), 262.

11. Johnstone, A. H. and Wham, A. J. B. The demands of practical work, Education in Chemistry, **1982**, ***19***, 71-73.

12. Winberg, T. M. and Berg, C. A. R., Students' cognitive focus during a chemistry laboratory exercise: effects of a computer-simulated prelab, *J. Res. Sci. Teach.*, **2007**, 44(8), 1108–1133. DOI: [10.1002/tea.20217](https://doi.org/10.1002/tea.20217)

13. Jolley D. F., Wilson S. R., Kelso C., O’Brien G. and Mason C. E., Analytical Thinking, Analytical Action: Using Prelab Video Demonstrations and e-Quizzes To Improve Undergraduate Preparedness for Analytical Chemistry Practical Classes, *J. Chem. Educ.*, **2016**, 93(11), 1855–1862. DOI: [10.1021/acs.jchemed.6b00266](https://doi.org/10.1021/acs.jchemed.6b00266)

14. Stieff, M., Werner, S. M., Fink, B. and Meador, D. Online pre-laboratory videos improve student performance in the general chemistry laboratory. *J. Chem. Educ*. **2018**, 95, 1260−1266. DOI: [10.1021/acs.jchemed.8b00109](https://doi.org/10.1021/acs.jchemed.8b00109)

15. Fung, F. M. Using first-person perspective filming techniques for a chemistry laboratory demonstration to facilitate a pre-lab. *J. Chem. Educ*., **2015**, 92(9), 1518-1521. DOI: [10.1021/ed5009624](https://doi.org/10.1021/ed5009624)

16. Blackburn, R. A. R., Villa-Marcos, B., and Williams, D. P. Preparing Students for Practical Sessions Using Laboratory Simulations. *J. Chem. Educ.* **2019**, 96, 1, 153-158. DOI: [10.1021/acs.jchemed.8b00549](https://doi.org/10.1021/acs.jchemed.8b00549).

17. Zeiner, M., Viehauser, P. and Steiner-Friedmann, C. Teaching Laboratories at a slower pace: Introduction of photocomics as easy-to-use laboratory instructions. *J Chem. Educ*., **2019** 96(11), 2518-2523. DOI: [10.1021/acs.jchemed.9b00142](https://doi.org/10.1021/acs.jchemed.9b00142)

18. Johnstone, A. H., Al Shuaili, A. Learning in the Laboratory: Some thoughts from the literature, *U. Chem. Ed*., **2001**, *5*, 42–51.

19. Graham K. J., Johnson B. J., Jones T. N., McIntee E. J. and Schaller C. P., Designing and Conducting a Purification Scheme as an Organic Chemistry Laboratory Practical, *J. Chem. Educ.,* **2008**, *85*(12), 1644–1645. DOI: [10.1021/ed085p1644](https://doi.org/10.1021/ed085p1644)

20. Hill, M. A., Overton T. L., Thompson, C. D., Kitson, R. R. A. and Coppo, P. Undergraduate recognition of curriculum-related skill development and the skills employers are seeking, *Chem. Educ. Res. Pract.,* **2019***, 20,* 68-84. DOI: 10.1039/C8RP00105G

21. Hanson, S.; Overton, T. Skills Required by New Chemistry Graduates and their Development in Degree Programmes, **2010**.

<http://www.rsc.org/learn-chemistry/resources/business-skills-and-commercial-awareness-for-chemists/docs/skillsdoc1.pdf> (*accessed Feb 2020*).

22. Sarkar M., Overton, T., Thompson, T. and Rayner, G. Graduate Employability: Views of Recent Science Graduates and Employers, *Int. J. Innovation Sci. Math. Educ.*, **2016** *24*(3), 31-48.

23. Galloway, K. W. Undergraduate perceptions of value: degree skills and career skills, *Chem. Educ. Res. Pract*, **2017**, 18, 435–440. DOI: 10.1039/C7RP00011A

24. Capel N. J., Hancock L. M., Haxton K. J., Hollamby M., Jones R. H., McGarvey D. and Plana D., **Developing Scientific Reporting Skills of Early Undergraduate Chemistry Students. In *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton*; Seery, M. K., McDonnell, C., Eds,;** Creathach Press, Dublin, **2019**, 333-348.

25. Wright, J. S., Read, D., Hughes, O. and Hyde, J. Tracking and assessing practical chemistry skills development: practical skills portfolios, New Directions in the teaching of physical sciences **2018**, 13, Available at: <<https://journals.le.ac.uk/ojs1/index.php/new-directions/article/view/2905/2664>>. (*accessed Nov 2019*) doi:[10.29311/ndtps.v0i13.2905](https://doi.org/10.29311/ndtps.v0i13.2905).

26. Chen H.-J., She J.-L., Chou C.-C., Tsai Y.-M. and Chiu M.-H., Development and Application of a Scoring Rubric for Evaluating Students’ Experimental Skills in Organic Chemistry: An Instructional Guide for Teaching Assistants, *J. Chem. Educ.,* **2013***,* *90(*10), 1296–1302. DOI: [10.1021/ed101111g](https://doi.org/10.1021/ed101111g)

27. Graham, K. J., Johnson, B. J., Jones, T. N., McIntee, E. J. and Schaller, C. P. Designing and Conducting a purification scheme as an organic chemistry laboratory practical, *J. Chem. Educ.*, **2008**, 85(12), 1644-1645. DOI: [10.1021/ed085p1644](https://doi.org/10.1021/ed085p1644).

28. Towns M., Harwood C. J., Robertshaw M. B., Fish J. and O’Shea K., The Digital Pipetting Badge: A Method To Improve Student Hands-On Laboratory Skills, *J. Chem. Educ.,* **2015**, 92(12), 2038–2044. DOI: [10.1021/acs.jchemed.5b00464](https://doi.org/10.1021/acs.jchemed.5b00464)

29. Hensiek S., DeKorver B. K., Harwood C. J., Fish J., O’Shea K. and Towns M., Improving and Assessing Student Hands-On Laboratory Skills through Digital Badging, *J. Chem. Educ*., **2016**, 93(11), 1847–1854. DOI: [10.1021/acs.jchemed.6b00234](https://doi.org/10.1021/acs.jchemed.6b00234)

30. Seery, M. K., Agustian, H. Y., Doidge, E. D., Kucharski, M. M., O’Conner, H. M. and Price A. Developing laboratory skills by incorporating peer-review and digital badges *Chem. Educ. Res. Pract.*, **2017**,*18*, 403-419. DOI: [10.1039/C7RP00003K](https://doi.org/10.1039/C7RP00003K)

31.Rhodes, M. M.,[A Laboratory Practical Exam for High School Chemistry](https://pubs.acs.org/doi/abs/10.1021/ed100200k) *J. Chem. Ed.*  **2010,** 87 (6), 613-615. DOI: [10.1021/ed100200k](https://doi.org/10.1021/ed100200k)

32.Neeland, E. G. A One-Hour Practical Lab Exam for Organic Chemistry. *J. Chem. Educ.* **2007**, *84* (9), 1453−1455. DOI: [10.1021/ed084p1453](https://doi.org/10.1021/ed084p1453)

33.<http://www.rsc.org/learn-chemistry/resource/res00001064/the-interactive-lab-primer?cmpid=CMP00007674> *(accessed Apr 2019)*

34. [Richardson, John T. E.](http://oro.open.ac.uk/view/person/jr96.html) Coursework versus examinations in end-of-module assessment: a literature review. *Assess. Eval. High. Educ.*, **2015**, 40(3) 439–455. DOI: [10.1080/02602938.2014.919628](https://doi.org/10.1080/02602938.2014.919628)

35. We are aware that, in the UK, the University of York and University of Birmingham have introduced summative assessments of direct skills assessment in their chemistry course in 2017/18 and 2019/20 academic years, respectively.