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ARTICLE

What laboratory skills to students possess at the start of University?

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Nimesh Mistry*[a] and Stephen G. Gorman [a]

To be able to design a laboratory course it is important to know what laboratory skills students possess before the course starts. This way the course can focus on developing skills in areas that are lacking. Despite the extensive literature on laboratory education, there are few studies on what laboratory skills students have at this stage of their education. In this work, we aimed to address this by surveying students' knowledge, experience and confidence of a range of laboratory competencies at the start of a chemistry degree. Our key findings were that students had some knowledge, experience and confidence of performing lower-order competencies such as how to perform certain practical techniques, but lacked the knowledge, experience and confidence to perform higher-order competencies such as designing experiments. Using our results, we propose that instructors should be aware that experiments which focus on certain practical skills are not teaching students how to perform that technique but are providing more experience and confidence. We also propose instructors should use laboratory courses in higher-order skills such as experimental design and problem-solving where these skills are more evidently lacking.

Introduction

Since it was first postulated by Piaget, constructivism has gained significant importance in chemistry education as a model for how students learn (Bodner, 1986). Under the constructivist model, learners are not blank slates who absorb knowledge intact from the instructor. Instead knowledge is constructed in the mind of the learner (Cooper and Stowe, 2018). What this implies is that new knowledge is integrated through what the learner experiences and it integrates with their pre-existing knowledge structures.

The importance of prior knowledge in the constructivist model has been highlighted by Ausubel, who stated that for students to construct knowledge in a meaningful way ''*students must have appropriate prior knowledge to which the new knowledge can be connected''* and *''new knowledge must be perceived as relevant to this prior knowledge*'' (Ausubel, 1968; Bretz, 2001). Vygotsky proposed that the amount of new knowledge a student can learn is inextricably linked to what they know already, which is termed the zone of proximal development (ZPD) (Vygotsky and Cole, 1978).

In field of laboratory education there has been a great deal of discussion concerning the skills that students should learn through laboratory education (Kirschner and Meester, 1988; Hofstein and Lunetta, 2004; Reid and Shah, 2007; Bruck*, et al.*, 2010; Bruck and Towns, 2013; George-Williams*, et al.*, 2018). Recently, a framework for learning in the laboratory has been proposed, based upon the prior literature (Seery*, et al.*). Using complex learning theory as a theoretical framework, Seery proposes that learning in the laboratory should have the following components:

1. The overarching purpose of the laboratory is to teach learners how to 'do' science.
2. Preparing students for learning in the laboratory is beneficial.
3. Explicit consideration needs to be given to teaching experimental techniques.
4. Consideration of learners' emotions, motivations, and expectations is imperative in laboratory settings.

In the UK, the Quality Assurance Agency (QAA) provides a benchmark statement for chemistry degree, which includes guidelines of the laboratory skills that University chemistry students should learn (Quality Assurance Agency, 2014). The Royal Society of Chemistry (RSC) also provides accreditation for chemistry degrees as a further benchmark for the quality of the programme (Royal Society of Chemistry, 2017). To receive accreditation, University chemistry departments have to teach the laboratory skills specified by the RSC.

Using constructivism as a model for learning, prior knowledge should also be considered by instructors who design and deliver laboratory courses. This was recognised by Reid (2007) who stated that ''*it is important that those directing university chemistry laboratories are aware of what is currently happening at schools… In this way, it is possible to plan university chemistry laboratories so that they can avoid repeating school laboratory experiences but also build on the kind of thinking skills which school courses seek to inculcate.*''

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[a] *School of Chemistry, University of Leeds, Leeds, West Yorkshire, LS2 9JT, UK*
Email: N.Mistry@leeds.ac.uk

Many students enrolled onto a chemistry degrees will have had some prior laboratory experience and possess certain laboratory skills before the course starts. The majority of students in the UK, for example, will have completed an 'A' level qualification in chemistry. The UK government provides the specifications to which exams boards must follow to provide an 'A' level qualification (Department for Education, 2014). Included in these specifications are details of the laboratory skills students should develop in a chemistry 'A' level qualification. These specifications can therefore be used to determine what laboratory skills students have prior to enrolling on a chemistry degree programme.

At the beginning of a chemistry degree, George-Williams (2018) investigated the skills that students expected to learn through a University laboratory course. Most students expected to enhance their understanding of theory, learn how to apply theory, and develop practical skills. This study helps to inform laboratory instructors of students' perceptions looking forward. However, it would also be useful to have students look back at what they have learnt previously so instructors can determine how prepared students are for laboratory courses at University. A better understanding would also help universities plan their laboratory curricula accordingly.

Herein we describe our work to understand what laboratory skills students possess at the start of University and how this can be used to inform instructors of how to design the laboratory curriculum at University.

Our research questions for this study are:

1. What laboratory skills do students possess at the start of University?
2. To what level do students possess these skills?
3. How should this inform the curriculum design of a University level laboratory course?

Methodology

Survey Design

For the purpose of this study a quantitative approach was used based upon students' self-assessment of laboratory skills. Having students self-assess their knowledge, experience and confidence of laboratory skills has been used previously to evaluate the development of laboratory curricula (Hensiek*, et al.*, 2016; Seery*, et al.*, 2017). We felt this approach would be a suitable method to evaluate laboratory skills for our study.

The survey focused upon laboratory skills in synthetic chemistry (organic and inorganic) laboratory courses (table 1). Survey items (questions) were designed around laboratory skills relating to synthetic chemistry that were specified in the relevant documents for 'A' level chemistry (Department for Education, 2014) and for UK Higher Education chemistry (Quality Assurance Agency, 2014; Royal Society of Chemistry, 2017).

The 'A' level guidelines were used to design survey items for laboratory skills which students would be expected to have learnt before arriving at University. The QAA benchmark statement and RSC accreditation criteria were used to design survey items of skills that students could be expected to develop through the laboratory course.

It is interesting to note that there is some considerable overlap between specified laboratory skills in both secondary and tertiary criteria. Most of the overlap occurred when criteria at both levels specified certain practical techniques that students should learn. These skills could be considered to be of a lower-order nature. However, both secondary and tertiary level specifications placed an emphasis on developing problem-solving skills which, to the authors at least, could be considered to be a higher-order cognitive skill.

The survey items fell into six general categories of literacy, health and safety, practical technique, practical theory, experimental design and problem-solving.

In some categories, there are lower and higher-order questions within them. For example, the health and safety category has the survey item '*Following health and safety information given in the manual for experiments*' requires little independent thought so is considered lower-order. However, the category also contains the item '*Assessing the risk of a particular situation in the laboratory and deciding how to deal with it in a safe manner*' requires more independent thought and is considered to be higher-order.

Some categories were mostly made up of lower or higher order items, with the categories themselves linked together to provide a progression from lower to higher-order skills. An example of this is the way the categories of practical skills, practical theory and experimental design were linked. Performing practical techniques can be considered lower-order as students can develop those skills with no understanding of how or why they are used. Practical theory requires some understanding so is higher-order in relation to practical skills, whilst experimental design requires the application of that understanding so could be considered higher-order than practical theory.

For most survey items, students were asked to rate their knowledge, experience and confidence to align with Novak's theory of meaningful learning (Novak and Gowin, 1984; Bretz, 2001). This theory builds upon Ausubel's concepts of meaningful learning to provide a framework for how students can integrate new knowledge and skills. Novak argued that meaningful learning occurs when new knowledge and skills connects to students across the cognitive (thinking), affective (feeling) and psychomotor (doing) domains.

For this survey, students' knowledge of particular laboratory skills aligns with the cognitive domain, their experience aligns with the psychomotor domain, and their confidence aligns with the affective domain (Hensiek*, et al.*, 2016). The practical theory category was slightly different in that students only had to rate their knowledge and confidence. Students were asked to rate their knowledge, experience and confidence from a numerical value on a scale of 1-5. A score of 1 indicates low knowledge, experience, confidence, where as a score of 5 indicates high knowledge, experience, and confidence.

Table 1 Details of the survey given to students the start of University and results given as mean scores (*N* = 308)

Category	Survey item	Knowledge	Experience	Confidence
Literacy	Recording experimental details in your laboratory notebook.	3.32	3.27	3.11
	Writing a full laboratory report.	2.42	2.27	2.22
Health and Safety	Following health and safety information given in the laboratory manual for experiments.	4.13	3.97	4.06
	Handling and disposing chemicals safely in the laboratory.	3.60	3.26	3.45
	Assess the risk of a particular situation in the laboratory and deal with it in a safe manner.	3.63	3.48	3.17
	Being able to work safely in the laboratory.	4.24	4.16	4.17
Problem-solving	Using demonstrators (laboratory teaching assistants) to help me solve problems I encounter during an experiment.	3.77	3.36	3.79
	Understanding how the advice given to me by a demonstrator (laboratory teaching assistant) will solve my problem.	3.90	3.55	3.86
	Being able to make my own assessment of a problem I encounter during an experiment.	3.44	3.22	3.21
	Being able to devise my own solution to a problem I encounter during an experiment.	3.17	2.91	2.91
Practical skills	Setting-up and running a reaction under reflux.	3.60	3.23	3.11
	Setting-up and running a reaction under controlled (dropwise) addition of reagents.	3.76	3.55	3.45
	Monitoring the progress of a reaction by thin layer chromatography (TLC).	3.32	2.96	3.02
	Isolating a crude product by liquid-liquid extraction (work-up) using a separating funnel.	3.16	2.75	2.84
	Purifying a solid by recrystallisation.	3.63	3.31	3.22
	Purifying a liquid by distillation.	3.69	3.37	3.37
Practical theory	The chemical theory that underpins thin layer chromatography.	3.31	N/A	3.06
	The chemical theory that underpins liquid-liquid extraction (work-up) using a separating funnel.	2.94	N/A	2.75
	The chemical theory that underpins recrystallisation.	3.13	N/A	2.90
Experimental design	Choosing a suitable set-up of a reaction (i.e. choice of glassware) if this information has not been given in a procedure.	3.07	2.60	2.71
	Choosing suitable reaction parameters (e.g. solvent system) for monitoring reaction progress by thin layer chromatography.	2.36	2.07	2.08
	Designing a procedure to purify a mixture by liquid-liquid extraction (work-up) with a separating funnel.	2.55	2.20	2.27
	Finding an appropriate solvent to purify a solid by recrystallisation.	2.49	2.16	2.25
	Choosing analytical methods that will verify if my reaction was successful or not.	3.10	2.69	2.75

Data Collection

Ethical approval was granted by the institutions ethical review board. The University of Leeds is a large research intensive university in the UK. The survey was administered to first year Chemistry and Natural Science students over a two year period (2017 and 2018). The survey was only available to students in the first two weeks of semester 1 of their first year to eliminate the possibility of responses after the first year laboratory course had started. The survey was delivered using the online survey tool (www.onlinesurveys.ac.uk) and students were notified of the survey through the University Blackboard tool. Before completing the survey students were made aware of the aims of the study, 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.

Data Analysis

To determine if the results from each year group were comparable and hence could be combined, an *F*-test was performed for each item using Microsoft Excel. All questions returned *F*-Test values that indicated no significant differences between any of the survey questions ($p \leq 0.05$) so results will be presented and discussed as the combined responses. The analysis of survey items was conducted through the mean and distributions of responses as a percentage of the total responses. The results are given in table 1, figures 1 and 2, and in the Appendices.

There is some debate about the use of averaging Likert data in this type of analysis (Lalla, 2017). However this centres on primary data being converted from ordinal (e.g. agree/disagree) statements into numerical values, then treating those responses as values on a continuous scale. In our study, students provide their primary data as numerical values on a continuous scale, so we believe averaging these scores is a valid method to interpret the data. It should be noted that we have also analysed the distribution of responses which is commonly accepted for Likert data.

A total of 308 responses were received from two cohorts of first year students in 2017 and 2018. The response rates for each year were 84% and 78% respectively. We believe that the high response rate provides an accurate representation of first year students' self-assessment of laboratory skills for our institution and for other UK higher education institutions. We believe the general findings in this report can have some implications further afield.

Results and discussion

Literacy

Under the category of literacy we wanted to determine students' ability to record experimental data in a laboratory notebook and write scientific reports. These are arguably the two most important forms of written communication that a chemistry student should develop in a laboratory course.

The most common ratings for *recording experimental details in a lab book* were 3 and 4 (Figure 1) with mean values for knowledge, experience and confidence ranging 3.11-3.32 (table 1). This indicates that students have reasonable to good levels of this skill. This is pleasing as the 'A' level specifications state that students should be able to *keep appropriate records of experimental activities*. Nevertheless, the self-assessment of this competency suggests that students would still be able to improve from further instruction and use of a laboratory notebook in University laboratory courses.

In comparison, ratings for *writing a full laboratory report* was much lower, with the majority of students selecting low ratings (figure 1), giving mean values between 2.22-2.42 (table 1). The 'A' level specifications state that students should learn to report findings from experimental activity but is not explicit that this should be in the form of a written report. Both the QAA benchmark statement and RSC accreditation criteria include the requirement that students develop written communication skills. Our results indicate students need to develop these skills at University.

Fig. 1: Percentage distribution of responses for items in the literacy category (N =308. K = Knowledge; E = Experience; C = Confidence.

Health and safety

Learning how to handle chemicals safely is a key competency which was highlighted in both 'A' level and University level practical specifications. Under this category students rated their ability to *follow health and safety information given in the manual for experiments* and *being able to work safely in the laboratory* as highly as any item in the survey, with the majority of students giving high ratings of 4 and 5 (Appendix 1), and with mean scores ranging from 3.87-4.24 (table 1).

Other health and safety items, *handling and disposing chemicals safely in the laboratory* and *assessing the risk of a particular situation in the laboratory and deciding how to deal with it in a safe manner* require higher levels of practical competency in comparison to the two previously discussed. Student ratings were lower but still relatively high in comparison to ratings in other categories. The most common ratings were 3 and 4 (Appendix 1) with mean scores ranging 3.17-3.63 (table 1). It is interesting to note that in these two items, students rated their knowledge higher than experience or confidence.

In the 'A' level criteria, the specification explains how students must be able to *safely and correctly use a range of practical equipment and materials* and *follow written instructions*. It seems students prior to University have had experience of dealing with hazards in experiments by following instructions. The ability of high school students to self-assess their own hazards is also explicitly stated in the 'A' level specifications. The ratings students gave suggest that many of the students had knowledge of this skill to some extent but lacked the confidence and experience.

Problem-solving

The ability to ''*solve problems in practical contexts*'' was clearly specified in the 'A' level specification. The QAA benchmark statement and RSC accreditation guidelines both have extensive detail about how students should develop problem-solving skills through a chemistry degree. Whilst the HE criteria does not explicitly say that these skills have to be developed through practical work, the laboratory provides an important environment for students to develop problem-solving skills.

Survey items in the problem-solving category asked to students to self-rate their ability to solve problems using different levels of cognitive ability. The lowest level is asking a demonstrator (laboratory teaching assistants) for help solving a problem. For this item a majority of students gave high ratings between 3-5 (Appendix 2) and mean values ranging between 3.36-3.79 (table 1). Students gave very similar ratings for understanding the advice that demonstrators would give.

Higher ability problem-solving skills where students can diagnose and solve their own problems, were rated lower, with the majority of ratings being between 3 and 4 (mean scores 2.87-3.42). With these two items, experience and confidence ratings were lower than the equivalent knowledge ratings.

Practical skills

Items in this category were not meant to be exhaustive list of practical techniques, but cover the fundamental practical skills that students would develop in a synthetic laboratory course. Recent changes to the ‘A’ level specifications have led to more focus on the development of practical skills through the completion of at least 12 practical activities. The techniques chosen in the survey were all techniques that were explicitly mentioned in the ‘A’ level specification. The QAA benchmark statement and RSC accreditation documents also state that students should learn practical skills to be able to perform organic and inorganic synthesis.

The results for this category indicate that the most students know how to perform a reflux, recrystallisation and distillation before starting university. The majority of students gave high ratings of 3-4 for these skills (Figure 2 and Appendix 3) leading to mean values between 3.60-3.69 (table 1). Experience and confidence was rated slightly lower in comparison giving mean scores between 3.11-3.55.

More students gave slightly lower ratings for their knowledge, experience and confidence for performing a liquid-liquid extraction and thin layer chromatography. These more expensive/hazardous techniques might have limited their exposure to these at ‘A’ level. As with the previously mentioned practical skills the mean values for knowledge (3.16 and 3.32) were higher than their comparative experience and confidence values (2.75-3.02). It is unclear why these two skills were rated lower than the other skills.

However, the overall results from this category show that a majority of students have learnt how to perform standard synthetic chemistry techniques before starting University. Therefore experiments with these skills may provide value to students by providing more experience and confidence of performing these techniques rather than teaching them how to do it.

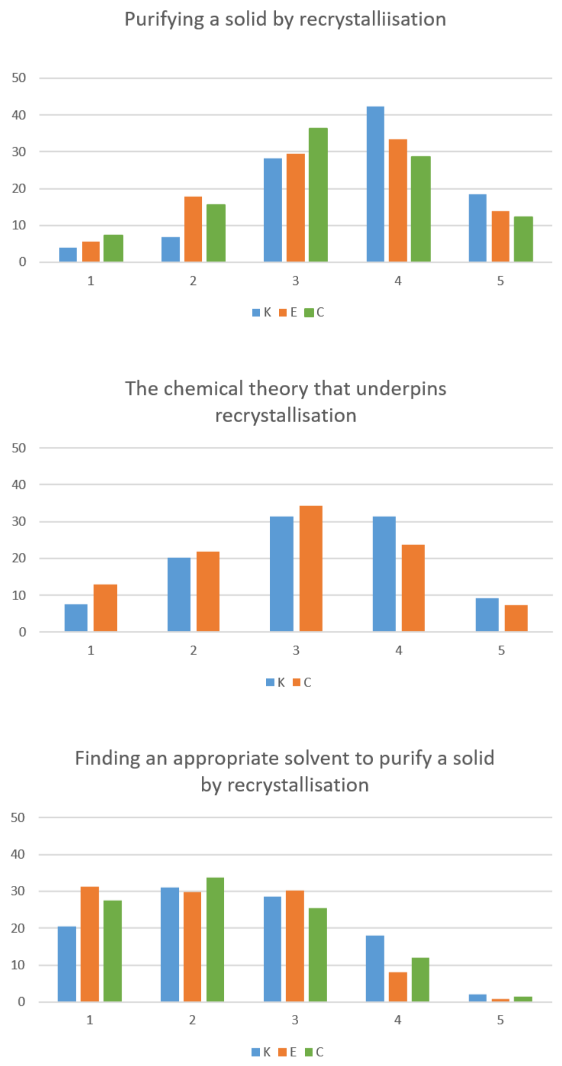


Fig 2: Percentage distribution of responses for items relating to recrystallisation (N=308) going in increasing order of cognitive demand (K = Knowledge; E = Experience; C = Confidence).

Practical theory and experimental design

The specification for ‘A’ level states that students should be able to ''*comment on experimental design and evaluate scientific methods*''. The QAA Benchmark statement states that Bachelor's students must have ''*the ability to plan experimental procedures, given well defined objectives*'', whilst Master's students should also have *the ''ability to select appropriate techniques and procedures*'' and display ''*competence in the planning, design and execution of experiments.*''

For all these objectives, an understanding of how the experiments are being performed and how techniques work is required. We categorised this section as practical theory, and designed the survey items to evaluate student understanding of the same practical techniques that were included in the practical skills category. These same objectives from the secondary and tertiary specifications influenced the design of survey items under the experimental design category. Experimental design items were also linked to practical techniques and practical theory categories by asking students if they could choose the appropriate techniques or conditions to design a synthetic chemistry experiment.

Students ratings of practical theory were lower than in comparison their practical skills (Figure 2 and Appendix 4). As a result, mean values were also lower ranging between 2.71-3.31 for their understanding of how recrystallization, liquid-liquid extraction and thin layer chromatography works. This shows that many students are be able to perform these techniques but have little understanding as to how they work.

In the experimental design category, students were asked to rate their ability to choose a suitable reaction set-up, choose the appropriate solvent system for thin layer chromatography and recrystallisation, design a liquid-liquid extraction, and choose the appropriate analytical technique for a synthetic chemistry experiment. The majority of students gave low ratings between 1 and 3 for these skills (Figure 2 and Appendix 5) leading to mean scores between 2.04-3.10 (table 1). These results show that students lack the skills to design experiments and therefore

University laboratory courses need include experimental activities to develop these skills.

Implications for University laboratory courses

Our results and analysis from surveying students' practical skills at the start of a University chemistry degree show that students have developed laboratory skills to various degrees, depending on the type of skill. Those involved in designing and delivering laboratory courses should take students' abilities into consideration.

In the Framework for Learning in the Chemistry laboratory proposed by Seery (ASAP), one of the four principles stated that laboratory courses should have some focus on practical techniques. Most instructors' expect students to learn lower-order skills such as practical techniques in a laboratory course (Bruck*, et al.*, 2010; Bruck and Towns, 2013; George-Williams*, et al.*, 2018). Here we have shown students already possess the knowledge of how to perform certain techniques. Therefore, University instructors should be aware that the value of experiments whose learning objectives are to teach practical techniques may in fact not be teaching students how to perform these skills, but are providing them with more experience and confidence.

The laboratory is a complex learning environment (Seery, ASAP), and this can lead to students feeling overwhelmed with the amount of information they have to deal with, particularly at the start of a laboratory course (Reid and Shah, 2007). Laboratory induction activities can help to reduce the cognitive overload for students by familiarising them with the laboratory environment before having to perform assessed experiments. We recommend asking students to perform techniques such as recrystallisation and distillation, because students already have knowledge of these skills and can therefore focus on becoming familiar with the new laboratory surroundings.

Whilst students feel they can perform techniques, their understanding of why they are being asked to use them or being able to plan and design an experiment with them is lacking. This is likely to be because students will have performed expository (cookbook) experiments (Domin, 1999) before University. This style of experiment has been widely criticised for their inability to develop students' higher order skills (Kirschner and Meester, 1988; Hofstein and Lunetta, 2004). We have shown that first-year students can improve their understanding of practical techniques and develop experimental design skills through structured guided-inquiry experiments (Mistry*, et al.*, 2016). Other ideas for improving experimental design skills include a two-stage experiment, where the first experiment introduces the technique in an expository experiment, whilst the second is more open-ended (Seery*, et al.*, 2019).

One of the other main advantages of performing experiments that are more open-ended is that they improve other higher order skills such as problem-solving. The level of detail devoted to the development of these skills in HE specifications indicates how important it is that students learn to problem solve. In a laboratory context, it is important that students can ask demonstrators for help if needed, but our results show that students could be better at solving problems independently. If, as indicated by our results, students do not need the whole of a laboratory course to focus on teaching practical techniques, then courses could look to include open-ended experiments and projects to develop higher-order problem-solving skill (Berg*, et al.*, 2003; Hofstein*, et al.*, 2005; Flynn and Biggs, 2012; Sandi-Urena*, et al.*, 2012; Bertram*, et al.*, 2014).

It is pleasing that students at the start of a laboratory course have the skills to work safely by following instructions. Given the importance of health and safety we recommend that University instructors should assess students' ability to do this for themselves in introductory experiments and also with chemicals which are more dangerous than the students will have had exposure to in secondary education. However at some point the students will need to be given more independence to make their own decisions relating to health and safety. For example, students could be asked to perform their own COSHH assessment for certain experiments once instructors are happy that students can follow the health and safety procedures in their laboratory.

Finally, for literacy skills there is a clear need to develop students' ability to communicate scientific experiments through written reports. Many traditional experiments assess laboratory skills through student's ability to write laboratory reports. These have been criticised as they do not directly relate to laboratory skills, leading to other forms of laboratory assessments being reported (Kirton*, et al.*, 2014; Seery*, et al.*, 2017). The authors support these forms of assessment but laboratory courses should still teach students to learn how to write written reports. One idea is that report writing could be the form of assessment for open-ended experiments or projects.

Conclusion

In summary we have used a self-assessment survey of laboratory skills that students would be expected to gain either before or during a chemistry degree. Students indicated that they have developed some of the skills expected of them before starting University, but there is scope for them to gain more experience and confidence through laboratory course at degree level. Students were also more likely to rate their ability to perform lower-order laboratory skills more highly than for higher-order skills. Many students believed they had not developed some higher order skills such as experimental design at the start of University.

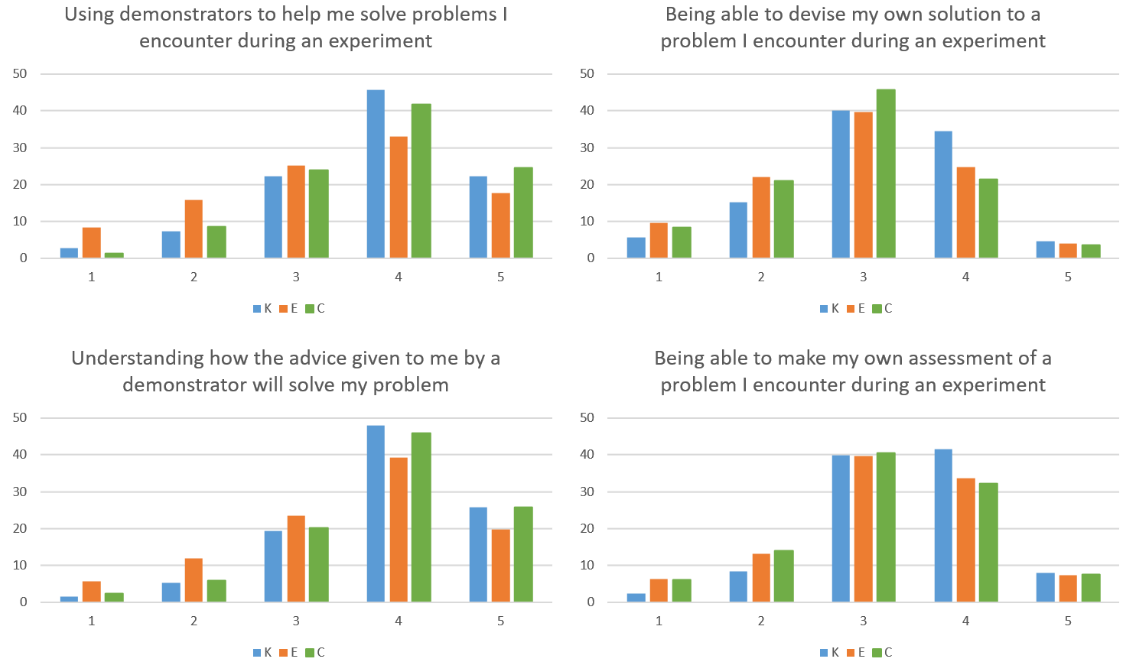
These results and findings can help Higher Education instructors plan and design laboratory courses that provide the appropriate type of practical activities which will develop skills where students are lacking.

We are continuing our use of this survey to monitor the development of these skills in our own laboratory courses and will disseminate the findings in due course.

Appendices:

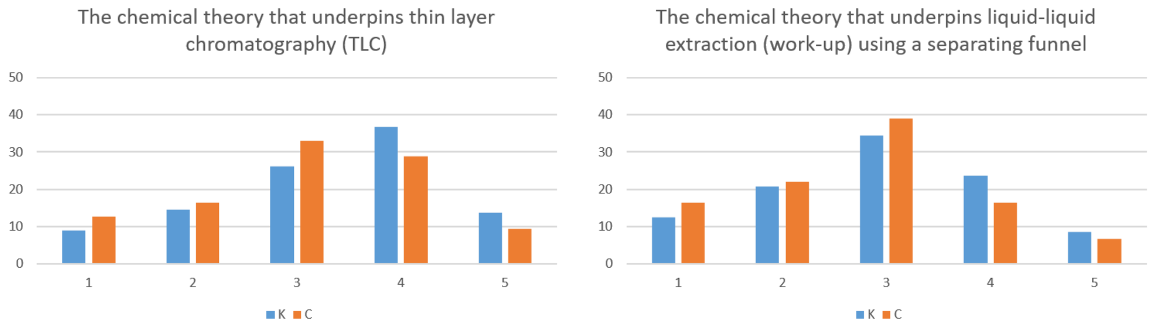
Appendix 1: Percentage distributions from the Health and Safety category; *N* = 308; K = Knowledge; E = Experience; C = Confidence

Appendix 2: Percentage distributions from the Problem-Solving category; *N* = 308; K = Knowledge; E = Experience; C = Confidence

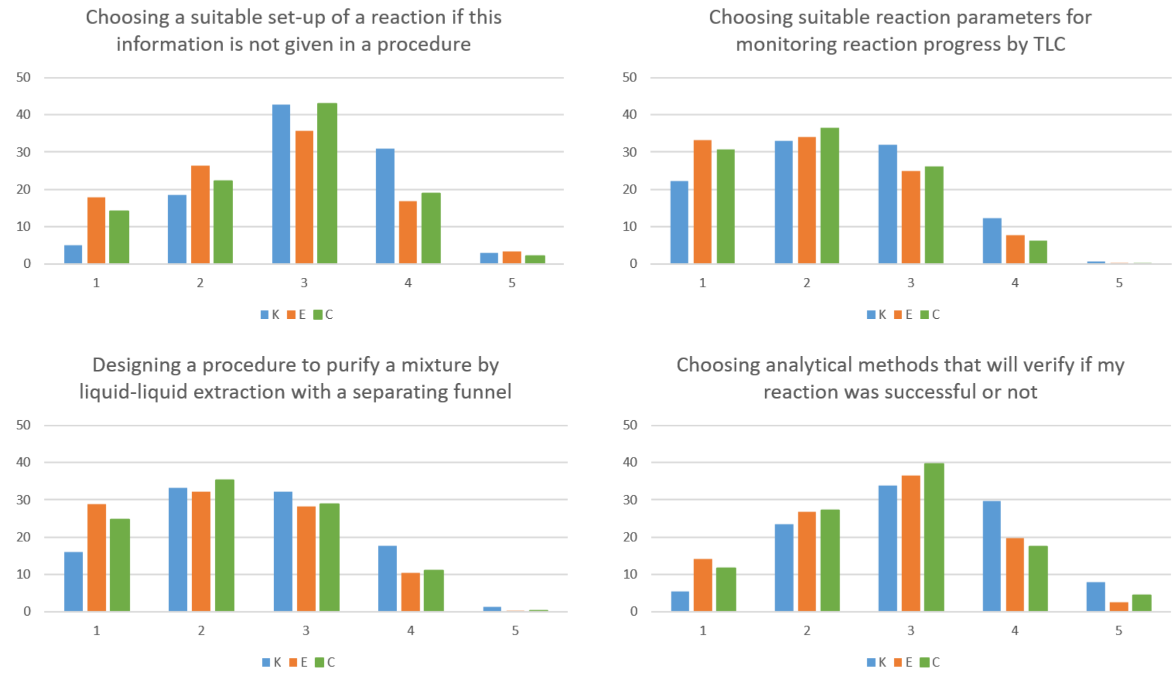


Appendix 3: Percentage distributions from the Practical Skills category; *N* = 308; K = Knowledge; E = Experience; C = Confidence

Appendix 4: Percentage distributions from the Practical Theory category; *N* = 308; K = Knowledge; E = Experience; C = Confidence



Appendix 5: Percentage distributions from the Experimental Design category; *N* = 308; K = Knowledge; E = Experience; C = Confidence



Choosing a suitable set-up of a reaction if this information is not given in a procedure

Choosing suitable reaction parameters for monitoring reaction progress by TLC

Designing a procedure to purify a mixture by liquid-liquid extraction with a separating funnel

Choosing analytical methods that will verify if my reaction was successful or not

Conflict of interest

There are no conflicts to declare.

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