A Preliminary Study: An Evaluation and Redevelopment of Current First Year Laboratory Practices

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Keywords: expository learning, inquiry learning, problem based learning, chemistry laboratory, teaching approaches

International Journal of Innovation in Science and Mathematics Education, *22*(7), 23-34, 2014.

Abstract

This study consisted of an evaluation and redevelopment of first year laboratory experiments in a first year chemistry course at a medium-sized Australian public university, with respect to the teaching methods implemented. The teaching approaches focused on were *expository*, *guided inquiry*, and *problem-based* and these were applied to two physical chemistry experiments. The aims of this study included investigation into the engagement and input of both students and demonstrators, the understanding achieved by students through completion of the laboratory experiment, and the enjoyment of students in participating and completing the laboratory experiment.

The major outcomes of this study found that both *problem-based* and *guided inquiry* approaches had greater success than the *expository* approach in areas such as the engagement of students within the laboratory environment, and the deeper understanding the students gained in the chemical concepts. In addition, *expository* and *problem-based* approaches were found to have more acceptable workloads than the *guided inquiry* variant. The greatest contribution of this study is in providing a foundation for further investigations to be continued into this field of research.

Introduction

The primary function of chemical education is the eventual production of capable, enthusiastic scientists to join and contribute to the global scientific community (Lagowski 1990). Chemistry is widely accepted as being central to many scientific disciplines, for example, biology, medicine, physics, and the earth sciences (Abelson, 1973; Culp, 2000). Therefore the improvement of chemical education will always be a necessary and beneficial goal. As the sciences grow and evolve, so must the educational paradigms of students' learning (Gabel, 1999).

Historically, when learning chemistry, students are exposed to a variety of media in which to both learn and demonstrate chemistry knowledge. The most prevalent media are face-to-face experiences in classes, hands-on laboratory sessions, and time spent studying outside the traditional classroom (Read, 1941). Given the diversity of educational institutions, there exist many variations or alternative curricula for teaching chemistry. Curriculum reform is a topic of high interest as detailed by Rickard (1992). One example is given by Gosser (1995) who introduced a workshop-oriented curriculum where graduated students ran workshops as part of the curriculum to support current students with their studies. The focus of this study narrows the scope to university level students and is to investigate the last aspect, being the time spent learning within a laboratory environment. Laboratories as an aspect of chemical education have been central to most chemistry courses of study and are traceable as far back as Liebig's laboratory in 1820 (Pickering, 1993). Teaching within a laboratory space has, however, been a topic of debate for almost as long (Hunt, 1935). This is due to the diversity of teaching and learning approaches and the limitations of more practical needs such as time and cost (Hofstein, 2004). These variables often lead towards laboratory courses that are well suited for the institution they are implemented at, whilst the students become a lower priority (Lagowski, 2002).

Domin (1999) published a review on the types of laboratory instruction styles most commonly used and seen within the literature. The basis of this review was the increasing criticism towards the most common instruction style implemented, the *expository approach* (also referred to as 'recipe-style teaching' (Hunter, Wardell, & Wilkins, 2000; McDonnell, O'Connor, & Seery, 2007) or 'spoon-feeding' (Ellis & Allan, 2010) laboratories). Lagowski (1990, p.541) describes the evolution of this instruction style as a means to "consume minimal resources whether these be time, space, equipment, or personnel". Within his review, Domin emphasised the need to understand that *all* instruction styles featured both pros and cons for their implementation and the outcomes achieved by students. The following table highlights the key descriptors Domin used to identify each instruction style:

Table 1. Descriptors of the Laboratory Instruction Styles

Style	**Descriptor**		
	Outcome	**Approach**	**Procedure**
Expository	Predetermined	Deductive	Given
Inquiry	Undetermined	Inductive	Student generated
Discovery	Predetermined	Inductive	Given
Problem-based	Predetermined	Deductive	Student generated

Considering the implications of Domin's descriptors, one of the most common criticisms for the expository approach can be observed. Given that the outcome, approach, and procedure are either known or provided, this can lead to students simply following the instructions to obtain a result or conclusion they may not understand. It could be argued, however, that the simplified instructions allow greater focus on practice and competence in experimental techniques without increasing their workload with additional steps that may require excessive time or assistance to complete (Green & Elliot, 2004). An alternative perspective on defining the differences between instruction styles was given by Fay, Grove, Towns, and Bretz (2007) as seen in Table 2:

Table 2. Characteristics of Lab Types[#]

	Verification	**Guided-Inquiry**	**Open-Inquiry**
Order	C → D	D → C	D → C
Choice of Experiment	T	T	S
Experiment Design	T	T	S
Data Analysis	T	S	S
Data Explanation	T	S	S

[#] C: Concepts D: Data T: Teacher S: Student

Once again the main theme is the transition of the experiment being teacher-generated (expository or verification) and becoming student-generated (open-inquiry or problem-based).

The question being addressed by this study was: *which of three teaching methods (expository, guided inquiry, problem-based) is more appropriate for first year chemistry laboratory experiments?* To achieve this, the authors performed a comparative investigation into the relative merits of different teaching approaches used within a laboratory environment. There has been a large amount of research conducted on the implementation of specific teaching approaches into laboratory experiments and/or courses. Some examples include; allowing students to modify recipes to attain a higher standard experiment (Pickering, 1989), incorporating guided inquiry or discovery laboratories and making these the focus of the chemistry course (Ricci & Ditzler, 1991), or the introduction of problem-based laboratory experiments (Sandi-Urena, Cooper, Gatlin & Bhattacharyya, 2011). Many more examples can be found within the literature showing considerable efforts towards investigating and implementing these alternative inquiry-based teaching approaches (Allen, Barker, & Ramsden, 1986; Oliver, 2007; Pavelich & Abraham, 1979) and *problem-based* approaches (Browne & Blackburn, 1999; Kelly & Finlayson, 2007).

Design and Implementation

Study Context

The traditional teaching method, *expository*, has been heavily relied upon and used throughout the history of chemical education despite being criticized in several areas for being too instruction based or likened to students completing a “recipe” without understanding the process. *Problem-based* as a teaching method represents the opposite of an *expository* approach. Within this teaching method, the instructional component of teaching is removed and replace with a problem, which can be multi-layered, for the students to design a solution to. This method has many favourable outcomes including the development of: higher order learning skills; problem solving ability; and an in depth understanding of the content. There are also many drawbacks to this method including but not limited to being inappropriate for some of the learning outcomes wanted, and where the students can be faced with a problem that they may not be able to overcome with their current knowledge base. Finally, a broad range of teaching methods are known as *inquiry* teaching which could be described as everything between the two approaches discussed above. *Inquiry* is a difficult teaching method to define, as it exists as multiples levels of inquiry ranging from well-defined inquiry to open ended inquiry. This works favourably however, as it enables inquiry based teaching to be flexible to meet a large variety of different learning outcomes.

At the University of Tasmania (UTAS), a first year chemistry unit is offered in semester two, KRA114 – Chemistry 1B, where the laboratory component could largely be described as *expository*, the traditional teaching approach. This unit became the focus for this study as it had a large student pool to draw from and included students from multiple disciplines such as biology, earth science, pharmacy, medical research, plant science, and biotechnology as a result of their respective course and degree requirements. These students would mostly be undertaking a Bachelor of Science with some undertaking alternative courses such as Bachelor of Pharmacy and Bachelor of Biotechnology and Medical Research

Study Design

The initial step in the process was to decide on suitable teaching approaches that would give varied results while remaining feasible given the environment provided at UTAS. After extensive consideration of the literature it was decided to consider three different teaching approaches namely, *expository*, *guided inquiry*, and *problem-based*. In comparing these teaching approaches, it must be acknowledged that each will have specific learning outcomes unique to that approach. The aim of this study focuses upon the core experiment-specific outcomes that remain the same regardless of the teaching approach used. The *expository* approach was chosen as it relates most closely to the current laboratory methods used. *Problem-based* on the other hand, was as far removed from the *expository* approach as possible allowing a comparison between two approaches at opposite ends of the spectrum. *Guided inquiry* was treated as an intermediate between these two approaches, combining elements of both in a structured manner. Once the teaching approaches had been chosen, it was necessary to consider the experiments contained within the laboratory component of the unit. These included eight experiments centred on various topics from within the unit including: equilibrium and acid-base chemistry, chemical kinetics, coordination chemistry, separation techniques, the chemistry of organic functional groups and an introduction to lipids, carbohydrates and proteins. As this study was completed by the first author as an eight-month research project carried out as a fourth year undergraduate student, it was decided to focus on two of the experiments as the scope of the study. These included an experiment investigating the fundamentals and techniques used in basic solvent extraction and an experiment to determine the formation coefficient of the iron thiocyanate complex employing a spectrophotometric method.

Research Question

The research question investigated in this study was: '*which of three teaching methods (expository, guided-inquiry, problem-based) is most appropriate for first-year chemistry laboratory experiments?'* To unpack this question further, some points need clarification to better understand the intended outcomes. Firstly, this question is aimed at teaching methods when applied to the practical setting of a laboratory education environment. Secondly, the use of the term *appropriate* can have many meanings. In this study, by appropriate it is intended that the teaching method most appropriate would optimise not only the chemistry-specific educational outcomes for the student cohort but also their engagement with the content and the development of a broader skill set including problem-solving skills and critical thinking. Finally, by chemistry laboratory experiments, we differentiate the laboratories based on the types of skills required to complete certain experiments. In this case we are considering a calculations oriented experiment, kinetics, and a technique oriented experiment, solvent extraction.

Research Methodology

A bounded case study (Stake, 1995) took place in a single university over one teaching semester. Consistent with the study taking place in a real-life setting, a mixed methods approach was adopted (Cohen, Manion, & Morrison, 2011) that allowed for a deeper exploration of the research question.

Laboratory Design

The first teaching approach to be considered was *expository* as it is most closely related to the current teaching approach used for first-year chemistry laboratory classes at UTAS. Changes were made to the existing experimental procedures which involved systematically reviewing both experiments to remove steps requiring problem-solving or independent student planning to produce a purely instruction-based experiment. All requirements for calculations and discussions were presented in a template form at the end of the experiment. This allowed students to complete the experimental work by simply following clear, direct instructions before filling in the template report in order to present their results.

Each experiment was then considered carefully for areas that could be expanded upon to introduce more complexity in terms of the thought required to complete the experiment. This allowed the conversion of the *expository* experiment to a *guided inquiry* format through altering these points of interest. The introduction of *guided inquiry* styled questions and discussions was then interspersed throughout the experiment replacing the calculations and results template currently within the laboratory manual. This was intended to prevent the lack of independent thought that arises from following direct instructions and furthermore to provide a more beneficial student learning experience. The aim of this was to initiate discussions and "brain-storming" as the experiment occurred, allowing the students to inquire and understand the processes they were undertaking.

The final and most challenging teaching approach to be tackled was that of *problem-based*. Due to the nature of *problem-based* as a teaching approach, it becomes difficult to provide sufficient information for the experiment to be completed without compromising the nature of solving problems. Several variables were considered in the design of this experiment. The three most important variables were: the information given to the students about the equipment available for the experiment; the description of the problem; and the demonstrating staff who supervised the students. With regard to these considerations, it was decided to include a list of available reagents and laboratory equipment without specifying what each item should be used for. Additionally, each experiment was broken into sub-sections in order to transform the experiment from a "whole" problem into several parts, and the demonstrators were under instruction to act as a safety net rather than a guiding force. The list of reagents and equipment was included to not only limit the scope of the possibilities for the students but also to provide a point for the students to begin from, allowing planning and designing of the experiment before it commenced. By breaking the experiment into several sub-sections, the students were given a degree of structure to allow a systematic and logical approach to the experiment to be completed. Finally, the demonstrators held a key position in the teaching laboratories and it is obvious that a demonstrator who provides step-by-step help would instantly compromise both the advantages and disadvantages of a more intuitive form of learning such as *problem-based*. Therefore, it was necessary for the demonstrators to take a step back and act as a last resource for assistance whilst still observing the laboratory for potential hazards.

For example, the following steps have been drawn from the respective laboratory manuals for the expository, guided inquiry, and problem-based experiments. Each step is describing the same process for their respective experimental procedure but has been adapted to represent each of the instruction styles. First, the expository extract seen below has clear instructions leaving no room for deviation with understanding and interpretation to be completed after data collection.

> 'Combine 25 mL of the primary solution with 75 mL of heptane in a clean 100 mL separatory funnel. Stopper and shake gently to begin extraction. Use the stopcock to release internal pressure periodically. Repeat four to five times.
>
> Identify which layer is which.'

The next extract from guided inquiry has similar instructions, giving structure to the process they are to complete. The main difference here lies in the context provided to the students as they progress through the experiment. This context allows students to develop their understanding as they collect data and the use of questions interspersed throughout the manual furthers enables consolidation of the experiment content.

> 'We have now experimentally tested the difference in a single extraction versus a multiple extraction. Another important variable is the solvent used to extract the target compound. Previously we have used ethyl acetate to great success. It was earlier mentioned that two other common solvents used were diethyl ether and dichloromethane. Heptane is an additional solvent which serves our purposes and will be used to test the difference in extraction efficiency between solvents.
>
> Why might dichloromethane be a poor choice?
>
> What differences could be predicted by the use of heptane in favour of ethyl acetate?'

The final extract is taken from the problem-based experiment. This approach gives students a context to work within before giving a statement for the students to test. This allows a development of method in addition to the requirement of designing the variables to collect data on. For this teaching method, students are engaged prior to beginning the experiment.

'Different solvents will obviously lead to different outcomes in solvent extraction. Use a different immiscible solvent to the one used in Part 1 in a single extraction and test this statement. Attempt to explain any differences found.'

Laboratory Implementation

The experiments were undertaken by sample subsets from the student body consisting of approximately 20 students. These sample groups were formed by random selection from the student pool on each day. These students were isolated from the main cohort in a separate laboratory each with two dedicated demonstrators for their designated experiment. In total, approximately 60 students and 2 demonstrators were involved in this study. Upon arrival the students were allowed to freely choose their seating spaces. On the week that a particular experiment was completed, a modified teaching approach experiment was implemented on separate days, accompanied by a control group of students undertaking the original experiment in a separate laboratory. No students completed more than one instance of an experiment, whether modified or original.

Consent was obtained from students passively through provision of an information sheet and completion of the survey instrument. All data obtained were anonymous and were collected by the demonstrators upon completion of the laboratory session before being collated and analysed. Ethics approval was gained (UTAS Ethics reference number H0011923) for this study prior to data collection with the condition that all students are awarded pass or fail dependent on attendance to the laboratory. Any grades given by the demonstrators were purely for data collection purposes and in no way impacted upon student assessment.

Roles of Demonstrators

Demonstrators for chemistry laboratory classes at the School of Chemistry, UTAS, oversee groups of up to 16 students and act as both an instructor and a source of information for the students as they complete their experiment. Similar positions exist in other institutions under alternative titles. The demonstrators employed must have a minimum Bachelor of Science qualification, and nominate themselves to show interest in teaching. As demonstrators have a key role in the teaching of students within the chemistry laboratory, it was very important that these staff have a thorough understanding of the content of the experiment. In addition to this the demonstrators must be able to judge the amount of information or guidance students would require depending on the teaching approach for that experiment. Demonstrators participating in this study underwent face-to-face discussions with both the first author and an experienced academic staff member to develop their understanding of how to implement and manage different instruction styles. For all teaching approaches, demonstrators were required to act as an observer for unsafe practice in addition to being a source for constructive assistance. Teaching approaches such as *guided inquiry* and *problem-based,* however, required the students to devise their own theories and experimental methodologies to test. Therefore, careful supply of external information is required to prevent either restriction or direction of the students, thereby alleviating the potential for skewed results. To avoid variation in the assessment of student ability, the same demonstrators were used for each experiment. The student investigator (first author) was present for each laboratory class to support the demonstrators and oversee the experiment as it progressed.

Data Collection

Collection of data for each of the teaching approaches occurred in three ways:

- a grade out of 10 provided by the demonstrator for the student as a measure of their competence throughout the laboratory
- a post-experiment quiz (see the supplementary material) designed to assess the understanding gained by students undertaking the laboratory, both in the theory associated and the experimental techniques used. Particular care had to be taken with the quiz to ensure the experiment did not simply feed the answers to the quiz questions. As the quiz was designed to be administered immediately upon completion of the experiment, the quiz was limited in length and aimed to give insight rather than a thorough examination of understanding
- a post-experiment survey to gain insight into the student's opinion of the teaching approach used.

In comparing grades between cohorts undertaking separate teaching methods, it is important to understand the assumptions used in this comparison. Firstly, it is assumed that as the student selection for each teaching method was random, the cohorts for each teaching method are, on average, equal in ability. This is subject to potential bias by coincidence however. Secondly, it is assumed that whilst each teaching method has variable learning outcomes, each student is assessed to a common standard of performance and understanding within the laboratory experiment. These concepts also apply to the comparison of student performance on the post-experiment quiz.

The survey consisted of a variety of targeted points of interest including: engagement with the experiment, learning objectives for both clarity and achievement, development of practical skills, student workload, effort given to completing the experiment, enjoyment, and an overall rating for the experiment. These questions were derived from the investigative aims of the study. A similar survey instrument has been utilised in the ASELL, *Advancing Science by Enhancing Learning in the Laboratory,* initiative (formerly known as ACELL (Buntine, Read, Barrie, Bucat, Crisp, George, Jamie, & Kable, 2007), formerly known as APCELL).

Data Analysis
A one-way between-groups analysis of variance (ANOVA) was conducted using the statistics package SPSS Statistics to compare the means of three separate data collection instruments: a total of 8 specific survey questions and an overall experience survey question, overall quiz result, and the grades attained by students as assessed by their demonstrator. Participants were grouped into three groups, each group undertaking a single teaching method of the following: expository, guided inquiry, and problem-based.

Discussion of Results

Results
Two experiments were analysed from the KRA114 unit, the kinetics experiment and the solvent extraction experiment. Each experiment will be discussed separately below. As the majority of the results were inconclusive statistically, only those that produced significant differences or approached significant difference have been included for discussion. The entire results database can be found within the supplementary information. For all analyses approaching or indicating significant difference the effect size was calculated, using eta squared, with the smallest effect size being 0.10.

Kinetics Experiment
The kinetics experiment yielded no significant differences at the $p < 0.5$ level in any of the variables however, several variables were approaching statistical significance including: (i) grade $F\ (2, 30) = 2.8$, $p = 0.079$, effect size 0.16; (ii) survey question 2 (the full survey can be found within the supplementary materials), *the learning objectives were clearly defined,* $F\ (2, 49) = 2.9$, $p = 0.066$, effect size 0.11; and (iii) survey question 3, *the learning objectives were fulfilled through completion of this experiment,* $F\ (2, 49) = 2.7$, $p = 0.075$, effect size 0.10.

(i) A comparison of the average grade between *expository* ($M = 7.46$, $SD = 0.54$) and *problem-based* ($M = 8.06$, $SD = 0.63$) approaches indicated that the *problem-based* approach produced a significantly higher student grade average than that of *expository*. Each demonstrator provides their grade for a student for the laboratory session which acts as an indication of each student's performance in completing the experiment. In comparing grades, it was expected that *problem-based,* generally associated with higher order thinking skills, would be a more challenging experiment for students and thus may impede their progress and resulting grade. *Expository* on the other hand, is more straightforward by nature and it was expected that students would feel more comfortable in completing this version as it more closely resembled experiments that they had completed previously. The fact that this comparison approached significant difference between *problem-based* and *expository,* higher grades might indicate that deeper learning has taken place, but further investigation is required,

(ii) Question 2 of the survey, *The learning objectives were clearly defined*, targets whether there is a difference between teaching approaches giving a clear idea of the learning objectives. All three methods had the learning objectives clearly stated; this question was designed to interpret whether students grasped the objectives they were learning through completion of the experiment. Only one comparison approached significant difference indicating *guided inquiry* (M = 3.76, SD = 0.83) was close to being more efficient than *expository* (M = 3.08, SD = 0.90). This result could be explained by considering that many students may just go through the motions for *expository,* in comparison to *guided inquiry* where connections may be drawn between the learning objectives and the method as the experiment occurs.

(iii) Question 3 of the survey, *The learning objectives were fulfilled through completion of this experiment*, also produced interesting results in which both *guided inquiry* (M = 3.62, SD = 0.74) and *problem-based* (M = 3.63, SD = 0.76) approached being significantly higher than *expository*.

Solvent Extraction Experiment

The analysis of the solvent extraction experiment indicated that there were significant differences at the $p < 0.5$ level for several variables including: (i) survey question 1, *the learning format was an engaging experience,* F (2, 42) = 4.0, p = 0.26, effect size 0.16; (ii) survey question 5, *the workload was acceptable,* F (2, 42) = 6.8, p = 0.003, effect size 0.24; and (iii) survey question 6, *I deepened my understanding of chemistry through completion of the experiment in this format,* F (2, 42) = 3.9, p = 0.29, effect size 0.16.

(i) Within the first question of the survey, *the learning format was an engaging experience,* it was found that the *problem-based* (M = 4.57, SD = 0.51) approach was significantly higher than *expository* (M = 3.88, SD = 0.81). This is consistent with our expectations that students undertaking the *problem-based* approach would feel more engaged given the higher student input for the procedure.

(ii) Question 5 of the survey, *the workload was acceptable*, reported that both *problem-based* (M = 4.57, SD = 0.51) and *expository* (M = 4.19, SD = 0.91) approaches had a more acceptable workload than the *guided inquiry* (M = 3.20, SD = 1.20) approach. The difference in student opinion of workload could be attributed to the difference in the length and detail of experimental information provided to the students. The incorporation of the report template in the *expository* approach occurs at end of the experiment allowing the procedure to seem shorter and easier to approach whereas the *guided inquiry* method extends the method section of the experiment considerably by incorporating the discussion and results throughout the procedure. This could potentially be overwhelming to students as most experimental methods they had encountered previously were considerably shorter. The *problem-based* approach by its nature, allows students to construct the details of the method themselves, and therefore the method section in the experimental details provided to the students appears to be short and simple. This then becomes a trade-off between the understanding gained and the acceptableness of the workload associated.

(iii) Interestingly, question 6 of the survey, *I deepened my understanding of chemistry through completion of the experiment in this format*, gave the impression that students felt more confident in their understanding of the chemistry in the *problem-based* (M = 4.29, SD = 0.47) experiment over the *expository* (M = 3.56, SD = 0.96) approach. It was also observed that the comparison between *problem-based* and *guided inquiry* (M = 3.67, SD = 0.72) approached significant difference.

Observations of Student Performance

An important aspect of the study to be considered was the process students went through while completing the experiment. To this end, the first author was present during each laboratory to record observations of the approach students used when completing the experiments and tackling problems. It was observed that whilst the experiments were designed to be completed as pairs with results reported individually, students tended to cluster into groups, particularly in the *problem-based* experiments, to plan and brain-storm ideas. These groups were often formed of approximately six students, with most students contributing at least one idea. After an initial period of consultation these groups would then disperse to begin the experiment as individuals before reconvening on occasion to compare results or report problems they encountered. This observation was supported by the qualitative data collected through the free-text positive feedback responses from student surveys including comments such as:

[The best feature of this experiment was:] *'The increased focus on interaction to help each other solve problems.'* (Student, problem-based solvent extraction experiment)

Expectations and Limitations

It was expected that teaching approaches such as *guided inquiry* and *problem-based* would lead to a higher development of critical thinking and independent thought. These benefits, however, included drawbacks such as an increased workload or difficulty of completion for a significant number of students. The results obtained did not identify as many differences as initially hypothesised and the three teaching approaches were similar in most areas examined. This could be due to the nature of the teaching approaches, the number of students involved in the study, the students themselves, the implementation of the experiments, or an unknown variable unaccounted for. In addition to this, there were several notable limitations to the study, which could have influenced the results in either direction. In particular, the sample sizes for each class group were selected randomly but there were no other means to control who was selected. The implications from this were that as students were randomly selected from each day, there might have been an unintentional imbalance of students undertaking a particular course. No demographic information was taken from students at the time the study was completed so it is impossible to measure the effect this may have had upon the study.

Due to time constraints each version of the laboratory experiment was only held as a single instance. The limitation of only one instance may lead to potential problems as there is no way to account for the possibility of anomalous cohorts of students. Additionally, the KRA114 unit consists of students studying different degree programs, and timetable constraints meant that specific cohorts of students were required to attend nominated sessions. As such, random selection of students did not completely guarantee a mixed and representative cross-section of the total student population. As there is a large variety of students in any class population, it was expected that at least some of the students would have trouble adapting to an unfamiliar teaching approach at such short notice. Some of this variety is inherent in their personal learning styles and educational backgrounds, but another effect was the nature of the degree that each student was studying. As mentioned earlier, while the majority of students were undertaking a Bachelor of Science, with their major being one of many options, there were also students participating who were undertaking a Bachelor of Pharmacy or a Bachelor of Medical Research and Biotechnology.

Outcomes and Conclusions

While the number of significant differences observed between the outcomes of the different teaching approaches was small, sufficient evidence was produced to provide a strong foundation for the continuation of this study. In particular, *guided inquiry* showed the greatest contribution to learning and understanding of the concepts. Students, however, enjoyed the *problem-based* and *expository* styles over *guided inquiry* claiming that the workload for the *guided inquiry* approach was not acceptable in comparison. During the completion of the *problem-based* approach, and to a lesser extent the *expository* and *guided inquiry* approaches, students were observed to form small groups to brainstorm or plan the intended method to be undertaken to obtain the outcomes designated for the experiment. It was expected that problem solving at an early stage of an undergraduate degree might pose some difficulty for students who are currently only learning the fundamentals of chemistry. It was encouraging, however, to see that while the *problem-based approach* may have proven difficult, it was appreciated and enjoyed by both the students and the demonstrators, with student comments indicating that it was a beneficial learning approach.

The nature of this study was intended as a preliminary investigation to gauge the feasibility of conducting a more thorough investigation looking at a wider variety of teaching approaches in greater depth for a larger number of laboratory experiments across different levels of a science course. This project produced a limited set of very useful and meaningful results related to the differences between these three teaching approaches, but it was apparent that a further, more rigorous study with greater scope is required if meaningful results are to be found.

Each teaching approach has facets beneficial to students and their learning. The important aspect to consider is the balance and appropriateness for each teaching approach in relation to the type of experiment and the level of education the students are completing. These results are a step in the process towards improving the quality of the education provided to each student as they undertake their respective discipline. Furthermore, these results will act as foundational work and raise awareness for the use of alternative teaching approaches in chemistry laboratories. Based on these results, the teaching approaches found to be of most benefit from this study will be implemented on a larger scale to investigate robustness of these findings over different student cohorts. In addition, the processes used in this study can and will be modified to address a longitudinal study into a wider range of experiments over all three years of the undergraduate Bachelor of Science – Chemistry program. To clarify, these results do not point towards a single teaching approach being used for an entire experimental program, but rather an appropriate teaching approach could be tailored to match an individual experiment as indicated by student performance.

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