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Analytical Thinking, Analytical Action: Using Prelab Video Demonstrations and e-Quizzes To Improve Undergraduate Preparedness for Analytical Chemistry Practical Classes

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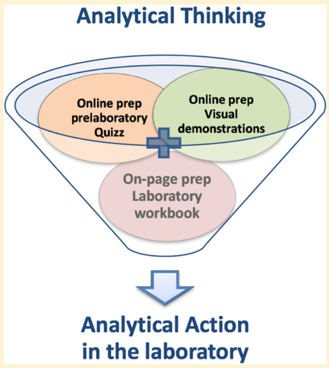
ABSTRACT: This project utilizes visual and critical thinking approaches to develop a higher-education synergistic prelab training program for a large second-year undergraduate analytical chemistry class, directing more of the cognitive learning to the prelab phase. This enabled students to engage in more analytical thinking prior to engaging in the analytical action in the laboratory, motivating students to arrive at classes prepared to engage in the material rather than the mechanics (physical processes) of the practical exercises. This reduced the likelihood of cognitive overload at the beginning of the class. Video demonstrations were developed providing both visual demonstrations with audio explanations to reinforce each concept, and students were guided to these through compulsory prelab e-quizzes. The effectiveness of the program was evaluated by academic performance and an attitudinal survey. Attitudes toward the prelab program were very positive, particularly for the e-quizzes. There was no improvement on academic performance in laboratory reports; however, students reported that the prelab material had a positive effect on their learning, and that they were able to enter the laboratory with high levels of perceived preparedness. Given that student experiences in the laboratory are arguably as important as assessable outcomes, an attitudinal study such as this is extremely important.



KEYWORDS: *Second-Year Undergraduate, Analytical Chemistry, Laboratory Instruction, Demonstrations, Internet/Web-Based Learning, Multimedia-Based Learning*

INTRODUCTION

Laboratory classes form an integral part of undergraduate science courses.[1,2] Well-designed laboratory work offers an opportunity for students to develop technical and manipulative skills, practice careful observation, reinforce theoretical concepts, develop problem-solving skills, and learn how to interpret observations, and offers an opportunity to stimulate interest.[2,3] However, students often suffer from cognitive overload in laboratory classes, reducing the likelihood that the intended learning outcomes will actually be achieved.[4,5] Reid and Shah[3] identified multiple sources of cognitive overload for students in a typical science laboratory class: the laboratory manual, verbal instructions, unfamiliar equipment or materials, theoretical background, technical skills, and time management. Given this list of demands, it is not surprising that, without adequate preparation, students tend to be preoccupied with technical details and thus mechanically follow instructions for laboratory work.[2,5−7] This results in an inability to relate the tasks being completed to the concepts underpinning the class exercise.[8]

Prelaboratory preparation facilitates reducing the amount of new information students are exposed to when they enter the laboratory.[3,9] The time spent in class preparation frees space in the limited capacity working memory during the laboratory class, reducing the likelihood of cognitive overload and enabling deeper engagement with the material.[5,10] Johnstone and Al-Shuaili[2] state that a "prepared mind" will be more likely to separate important experimental observations from extraneous "noise" caused by a preoccupation with technical issues. However, it is important that prelaboratory exercises are designed in a way that will facilitate students' engagement and encourage effective preparation.[9] A traditional approach, in which the details of the experimental work are explained briefly at the beginning of the class, has been found to contribute to information overload because of the large amount of information conveyed to students in a short period of time.[11] In contrast, prelaboratory exercises designed for students to complete before the class allow students to engage with the material at their own pace. Unsurprisingly, prelaboratory exercises have been found to increase students' understanding of the theory and aims underpinning the practical work, and to enhance their experience during laboratory classes because they have had the opportunity to think through the experimental design and procedures.[6,12]

Technology is now a prominent educational tool of university courses; many subjects now contain significant online components. In this investigation, the effect of introducing online prelaboratory learning resources to a second-year undergraduate analytical chemistry subject was examined. Previously in this subject, students were required to read the laboratory manual and complete a paper-based prelab exercise before commencing the laboratory class. In this study,

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these exercises were replaced by online prelab quizzes containing a series of guided calculations and multiple choice questions, which were supported with video demonstrations that illustrated the use of the actual laboratory equipment and general laboratory techniques relevant to that class. An online approach offers several potential advantages over the hardcopy method: it prevents students from simply copying answers from each other prior to the class;[13] it allows for automated correction of the quizzes; it frees time at the beginning of the laboratory class which was previously occupied by teachers checking prelabs; it allows rapid tracking of student access to the material[14] and progress; and it facilitates development of interactive exercises, in which students can be guided through calculations and receive immediate feedback. Students tend to be encouraged by receiving feedback prior to the laboratory class, as they gain confidence that they are "on the right track" with their thinking.[15] In addition, evidence suggests that guided instruction, such as that provided through guided calculations, facilitates learning.[16]

Students generally have favorable responses to online course material which supplements the more traditional course material.[14,17,18] Previous studies have indicated that students feel more prepared for laboratory classes when online prelab activities are available.[4,15,19,20] Interactive prelab activities have also been shown to reduce the technical and analytical errors made by students in the laboratory.[21] In one study of first-year biology students, students reported having a greater sense of confidence and clearer picture of the required tasks when online prelab exercises (including visual representations of required procedures) were available.[4] In the same study, the availability of prelab exercises appeared to increase students' motivation to prepare for laboratory classes, with students spending longer periods on laboratory preparation when the exercises were available.

The use of photographs and videos which illustrate the use of instrumentation or the setup of experiments has also been found to be an effective prelaboratory preparation strategy.[4,13,21] Visual representations allow students to develop a mental picture of what they will be doing in laboratory classes, which may increase student confidence.[13] Inclusion of visual materials also caters to students who identify as visual learners.[4] Instructional materials which combine visual and audio components ("dual-mode" materials) have been found to facilitate more effective learning than either approach alone, provided that the two modes of presentation occur simultaneously.[22−24] McKelvy[20] described the introduction of web-accessible prelaboratory videos (accompanied by quizzes) for a first-year university introductory chemistry course. These videos were used to present information about the aims of experiments, clarify procedural details, explain calculations, and highlight safety considerations, and were found to significantly enhance the flow of laboratory classes.[20]

The online tools developed in this study were designed to enhance student experience and learning in the second-year chemistry laboratory, with a student cohort that has very diverse degree programs. The study aimed to gauge the effectiveness of online prelab quizzes and instructional videos with respect to students' feelings of preparedness for laboratory classes, as well as on student performance in laboratory reports.

One potential drawback of online learning materials is that technical difficulties may be faced by students in the form of access problems or difficulties with using the material itself. Technical difficulties encountered during computer-based or online learning have been found to have a significant negative effect on learning outcomes[25] and on student attitudes.[26] Therefore, this study also aimed to assess whether this was a factor in the effectiveness of the online materials.

■ CONTEXT

Online prelaboratory exercises and videos were developed for each of the laboratory classes in a second-year, second-semester analytical chemistry subject at the University of Wollongong, Australia. The subject is a core chemistry subject at the university and must be completed by students in general chemistry degrees as well as in a number of interdisciplinary degrees including medicinal chemistry, nanotechnology, biotechnology, environmental science, and environmental engineering. It also caters to students enrolled in nutrition and marine science degrees, as well as students from arts, education, and law. Completion of first-year introductory chemistry subjects is a prerequisite for entry to this subject, meaning that students have had previous experience in chemistry laboratories (although the level of experience does vary significantly). The subject comprises 3 h of lectures per week (total duration 39 h over 13 weeks), as well as a weekly 3 h laboratory class. The laboratory component of the course is organized into two themes: titrations and instrument-based measurements, each consisting of a set of four experiments. Prior to commencing each set theme, students complete a one-week practical workshop which allows them to practice the central techniques relevant to that theme (i.e., (i) titrations which focused on concepts of mass, moles, and concentrations, and (ii) instrumentation which centered on calibration techniques).

For the five years prior to this initiative, the subject had (mean ± SD) 120 ± 13 students of which 97 ± 5% were under 30 years old (31 ± 5% under 20 years old) and males formed 60 ± 10% of the cohort. During the study, 148 students enrolled in the subject, with 129 students completing the subject. 98% of this cohort had access to the Internet at their place of residence, and 76% had a personal copy of the subject textbook. First-year chemistry subjects at the University of Wollongong require compulsory completion of online prelab activities, and as expected, the majority of students (91%) reported having completed online prelaboratory exercises in previous chemistry subjects.

■ METHODS

The online prelab quizzes and videos were made accessible to students through the WebCT Vista e-learning platform. Completion of a total of eight prelab quizzes was required, one for each laboratory class. These exercises did not form part of the assessment for the subject, but it was compulsory for students to complete each quiz successfully (at least 80% correct) at least 24 h before attending the corresponding practical class. Two attempts at each exercise were allowed, and while students were provided with immediate feedback as to which questions had been answered correctly/incorrectly, they were not provided with the correct answer for those questions which were answered incorrectly. Students were encouraged to seek assistance from teaching staff if difficulties were encountered when undertaking the prelab exercises. The content of the online prelabs was similar to the content of the hardcopy prelabs used previously in the subject, and was supported by the recommended textbook. Each exercise was

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tightly integrated with the content of the corresponding experiment, and consisted of a number of multiple choice questions designed to test conceptual and procedural understanding, as well as guided calculation questions which reflected those required in the upcoming experiment. Each quiz also contained a risk assessment question to stimulate students to consider the safety aspects of each laboratory.

The prelabs encouraged students to view the associated instructional videos, although doing so was not compulsory. These videos were designed to illustrate various aspects of each experiment: the setup and use of instruments (for example, the UV−vis spectrophotometer); practical analytical techniques (for example, titrations and quantitative transfers); and relevant calculations. Each video was accompanied by an audio explanation, consistent with the concept that "dual-mode" materials are more effective than representations using a single mode.[22−24]

Students were surveyed twice during the semester to assess changes in behaviors and attitudes resulting from the use of the online resources. Surveys were completed anonymously during practical classes and were voluntary. Survey 1 was conducted in the first week of the semester, before commencement of the practical classes; survey 2 was conducted in week 12, after completion of all prelabs and both themes of laboratory work. In survey 1, students were asked to answer questions based on their experience in previous chemistry subjects. Both surveys asked students to specify the time and manner spent preparing for laboratory classes, their preferred methods for learning, and how prepared they felt for laboratory classes. In addition, survey 2 contained questions related to the perceived value of the online videos. Questions were also included to assess whether any technical difficulties were encountered in accessing the online materials.

Student usage of the online materials was monitored quantitatively using the counters available within WebCT. To determine whether the online resources had an effect on student laboratory performance, the results from the assessed postlaboratory reports were compared with those from the two preceding years.

■ RESULTS

Time Devoted to Laboratory Preparation and Perceived Preparedness for Laboratory Classes

In the first survey (conducted before commencement of the laboratory classes), students were asked to report how much time they had typically spent preparing for previous laboratory classes, based on their experience in other chemistry subjects. The second survey (conducted at the end of the semester) asked students to report the time they had spent preparing for laboratory classes in this subject. Comparison of the responses from the two surveys indicated that students reported spending considerably more time preparing for laboratory classes in this subject than they had previously (Figure 1). In the initial survey, 45% of students reported spending 30 min or less preparing for lab classes, with 10.1% reporting that they spent less than 15 min on preparation (Figure 1). Only 4.7% of students stated that they spent over an hour in preparation, with the remaining 50% preparing for between 30 and 60 min. In the second survey, only 21% of students stated that they had spent 30 min or less on lab preparation, with just 2.8% reporting less than 15 min of preparation. There was a dramatic increase in the number of students who, during the last week of semester, reported spending an hour or more on laboratory preparation: 29.2%, compared to 4.7% in the initial survey.

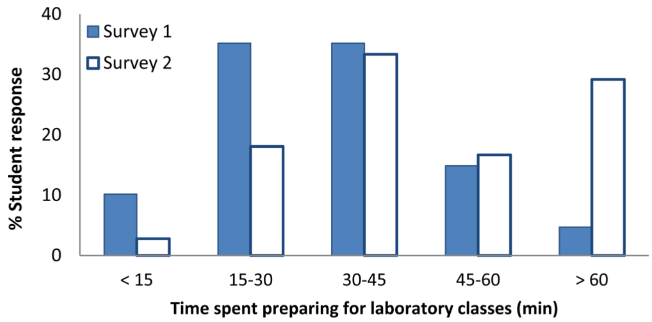

Figure 1. Reported laboratory preparation time by students before commencing the subject (survey 1; $n = 128$) and following completion of the laboratory component of the course (survey 2; $n = 72$).

The surveys also asked students to report how well-prepared they felt for laboratory classes, on a Likert scale from 1 (*very prepared*) to 5 (*not prepared at all*). Again, the initial survey requested that students use their experience in previous chemistry subjects to answer the question, while the second survey applied specifically to the current subject. In the first survey, students indicated that they had generally felt prepared in previous laboratory classes: 60% of students reported feeling "somewhat prepared"; however, only 11% reported feeling "very prepared" (Figure 2). Just 2% of students stated that they felt "not prepared at all". The second survey revealed that students felt more prepared for the laboratory classes in this subject than they had felt in previous subjects (Figure 2). Again, the most common response from students was that they felt "somewhat prepared" (65%), but the proportion of students who reported feeling "very prepared" doubled to 24%, almost one-quarter of the cohort. Thus, the vast majority of students (89%) perceived feeling at least somewhat prepared for the laboratory classes in this subject. On the other hand, the students feeling "not prepared at all" or "not very prepared" decreased from 15% to 3% after completion of the subject.

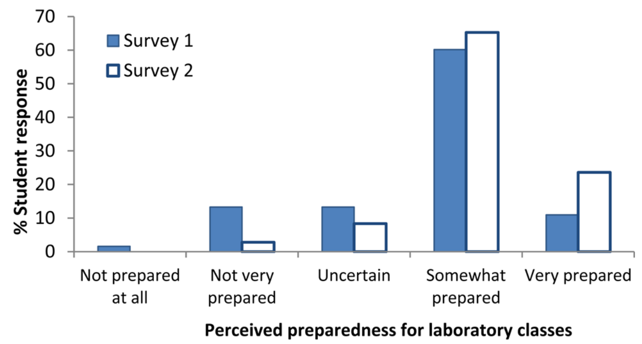

Figure 2. Students' perceived preparedness for laboratory classes in previous chemistry subjects (survey 1; $n = 128$) and in this subject (survey 2; $n = 72$).

Preferred Learning and Preparation Styles

In the first survey, students were asked to rank their preferred styles of study, given five options:

- Group study with class mates
- Independent study with Internet materials and quizzes
- Independent study using textbooks, notes and the Internet

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- Class-based group tutorial work
- Paid private tutoring

The majority of students favored learning by studying independently with textbooks, lecture notes and the Internet, with 40% of students ranking this as their most preferred option (Table 1). Paid tutoring was by far the least favored learning method: only 3% of students chose it as their most preferred study option, with 81% ranking it as their least favorite, most likely due to the financial demands associated with private tutoring. Although independent study with online materials and quizzes was only chosen as the most preferred study method by 15% of students, it was nonetheless a popular option, with 38% and 25% of students ranking it as their second or third most preferred method, respectively. Studying with class mates outside of class was also popular, with 24% of students choosing this method as their most preferred. Overall, however, independent study options (either with text or online resources, 55%) were favored over group study methods (either in-class or external to class, 42%). The surveys also explored the methods used by students to prepare for laboratory classes, beyond any compulsory prelaboratory exercises. Students were asked to specify whether they utilized the following activities "always", "sometimes" or "never" when preparing for laboratory classes:

Table 1. Preferred Learning Methods Identified by Students Ranking the Five Options According to Preference[a]

Preference	Group Study Outside Class	Independent Study: Online Materials and Quizzes	Independent Study with Text and Notes	Group Tutorial Class	Paid Private Tutoring
1st	24	15	40	18	3
2nd	16	38	22	22	2
3rd	29	25	20	18	8
4th	26	19	15	34	6
5th	5	3	3	8	81

[a]Students choosing these learning methods, % (n = 128).

- Reading the relevant part of the textbook
- Revising (studying or reviewing) the relevant lecture notes
- Reading the laboratory manual
- Watching online media—videos or animations
- Doing additional relevant calculations
- Doing additional calculations available on the textbook Web site

Students reported preparing in largely similar ways in both the initial and postsubject surveys (Figure 3). In both cases, the vast majority of students (93% in the initial survey, 90% in survey 2) reported that they always read the laboratory manual in preparation for laboratory classes, with the remainder reading the manual "sometimes". The other preparation

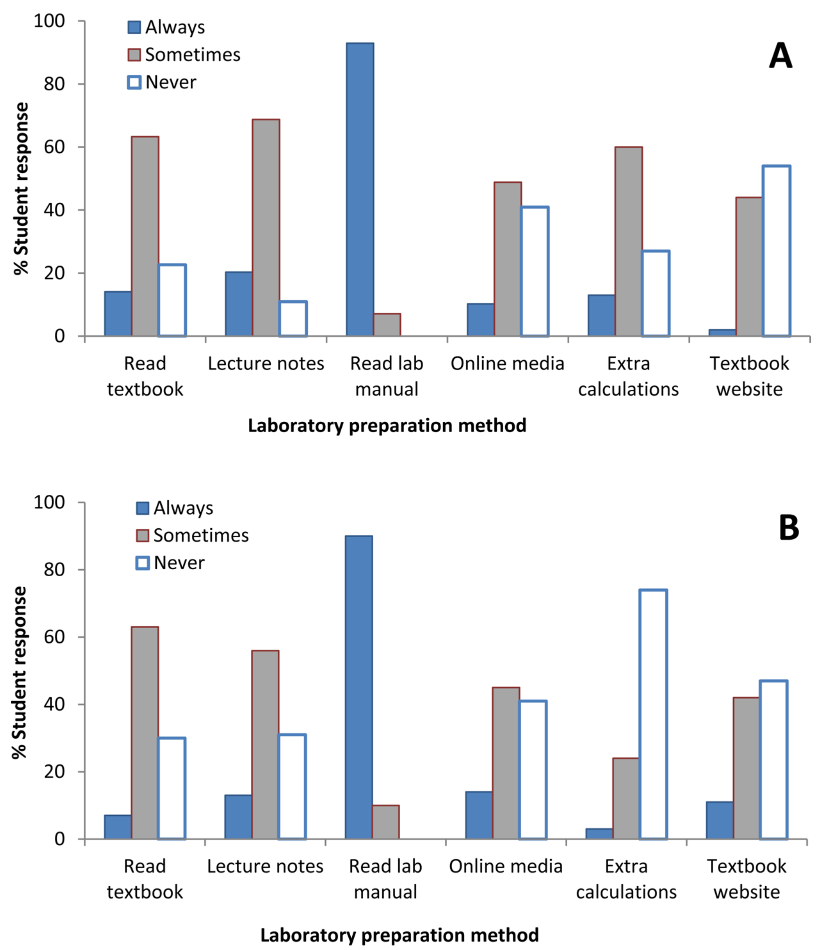

Figure 3. Reported laboratory preparation methods used by students in previous chemistry subjects (A) and in this subject (B). The sample sizes were 128 and 72, respectively.

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methods were utilized less frequently: only a small proportion of students reported using any of them "always". However, a substantial proportion of students utilized each of the methods "sometimes". One notable difference between the two surveys was in the proportion of students doing additional practice calculations as preparation: after completion of the subject, only 27% reported sometimes or always doing additional calculations, which is a decrease of 46% from the initial survey (73%). The proportions using the textbook, lecture notes, and online media to prepare were relatively similar in both surveys.

Perceived Usefulness of Prelaboratory Exercises and Videos

Following completion of the laboratory component of the subject, students were asked to indicate how valuable they had found the online prelaboratory exercises for assisting their understanding, on a Likert scale from 1 (*very valuable*) to 5 (*not valuable at all*). The student response was overwhelmingly positive (Figure 4), with 54% of students reporting that the quizzes were "very valuable" and a further 44% finding them "somewhat valuable". Only 3% of students responded negatively, reporting that they were "not very valuable".

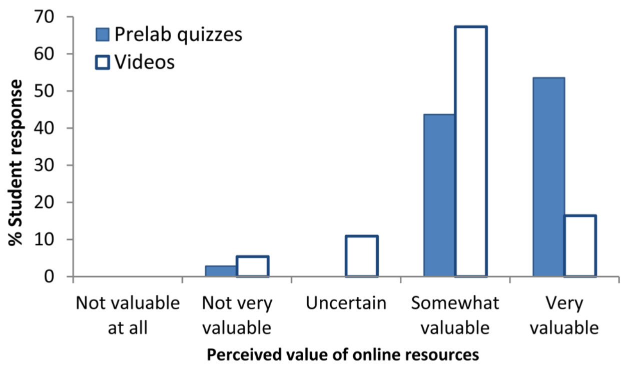

Figure 4. Perceived value of the prelaboratory quizzes (compulsory activity; n = 71) and online videos (optional activity; n = 55) in assisting understanding during the laboratory class, reported by students.

Students were also asked to indicate whether or not they had watched the online demonstration videos, how many times they had viewed each one, and how valuable they had found the videos in assisting understanding (using the same Likert scale as above). Overall, 78% of students reported watching the videos, and of those, 59% watched the videos once, 38% twice, and 4% three or more times. This was broadly consistent with data from the WebCT counters, which show around 70% of the class looking at the videos, with the more familiar instruments (e.g., UV−vis) being viewed less than those that were less familiar (e.g., GC−MS). Of the students who watched the videos, 84% responded positively to their learning value (Figure 4): 16.4% reported videos to be "very valuable" in assisting understanding; a further 67.3% found them "somewhat valuable". Only 10.9% and 5.4% were uncertain of their value or did not find them valuable, respectively.

Student Performance in Laboratory Reports

Results from individual laboratory reports (completed and submitted subsequent to each laboratory class) were compared for the two years prior and the study cohort (Figure 5). There were slight year-to-year fluctuations evident in the results, but no overall trend was observed. The average total mark for laboratory performance in the study semester was 75.7 ± 1.1% (mean ± standard error, $n \geq 107$), which was not significantly different from two and one years prior (77.9 ± 1.1% and 74.3 ± 1.6%, respectively). On the basis of this data, the quality of the reports submitted in the study semester was not significantly higher (or lower) than that of the reports submitted in the previous two years. Further, there was no correlation with introduction of the online prelabs and videos and the proportion of students withdrawing after week 1 of the semester (9.5%, 22%, 13%, respectively) or receiving a failing grade (15, 15, 16%, respectively) in the subject 2 and 1 year prior or during the study semester.

Interpreting these results alongside the data in Figure 3 raises some questions. A decrease of 46% in the proportion of students doing additional practice calculations as preparation for laboratory classes was observed, yet there was no significant change in overall student grades in the subject over the three sequential years. It is possible that the guided structure of the combined online prelab and video required more class preparation time (Figure 1), and as such students felt that the additional calculations within the quizzes were sufficient for learning.

Technical Difficulties

Technical difficulties in accessing the online material did not appear to be a major factor. Prior to commencing the subject, 95% of students declared that they were confident in their ability to access online quizzes, with 94% reporting that they "never" (28%) or "occasionally" (66%) encountered technical difficulties with previous online assessments. A small number of students reported experiencing technical problems "half the time" (2%) or "often" (3%). In a second survey, 94% of students reported feeling confident in accessing the online quizzes, and 61% reported that they never experienced any technical difficulties related to the quizzes. 31% reported occasional problems, but few students reported more frequent difficulties, either half the time (3%) or often (6%). Specific comments received from students indicated that some students encountered difficulties with the audio component of the videos, or were not able to view the videos on certain computers.

■ DISCUSSION

The surveys indicated that students reported spending significantly more time preparing for the laboratory classes in this subject than they had spent in previous subjects. Potential reasons for this increase are that the content of these laboratories was more challenging than that encountered in previous subjects, and that the prelaboratory exercises in this subject (which were compulsory) demanded the additional time commitment in order to complete the exercises satisfactorily. However, student responses also indicated a general increase in perceived preparedness for laboratory classes in this subject relative to previous subjects. This suggests that the nature of the preparatory material available for this subject may have encouraged students to prepare more thoroughly than they had done previously. Student enthusiasm for the laboratory classes was high, with comments received from students in the surveys reflecting a positive attitude toward laboratory classes, for example: "I find them very valuable, and they are usually where most of my learning for the subject occurs". Comments from students also indicated that they felt confident completing the laboratory classes in the

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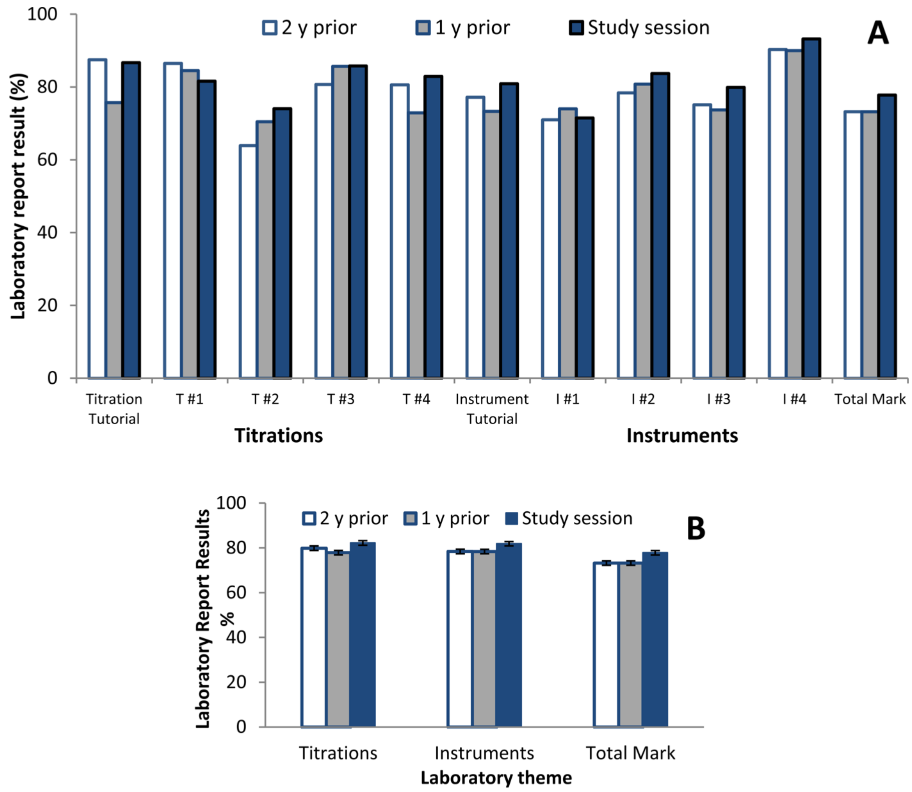

Figure 5. Mean laboratory report performance (percent ± S.E., $n \geq 107$) in 2 and 1 year prior or during the study session: (A) individual laboratory reports; (B) report performance grouped by laboratory themes.

allotted time: "good content for time available"; "labs are not rushed or stressful". These comments are consistent with the high levels of perceived preparedness for laboratory classes reported by students, and suggest that the majority of students were indeed able to avoid cognitive overload (and mechanical instruction-following) and obtain a positive learning experience from the laboratories. One motivation for moving to an online-based prelaboratory system was to remove the time burden of teachers having to check hardcopy prelab answers at the start of the lab, before work could commence. This permitted teachers to engage with students upon class commencement, immediately addressing any individual student concerns or queries, further ensuring student preparedness for the given activity. Comments from students regarding the time available and nonrushed nature of the laboratory classes indicate that this outcome was successfully achieved.

Galloway and Bretz[27] stated that the manner in which a student chooses to act (psychomotor) in the undergraduate teaching laboratory depends on how they think about (cognitive) and feel toward (affective) their laboratory experiences. They describe the nature of an undergraduate laboratory being activity packed, with demonstrators rarely allowing students to stand inactive; however, this inactive time may be important for the cognitive reflection of their laboratory task. Galloway and Bretz[27] considered that if the *doing* is inherent in the laboratory, the following question must be asked: To what extent do students integrate their thinking and feeling with the *doing*? However, in our study, we have attempted to redirect a significant proportion of the cognitive aspects of each laboratory topic to the prelab phase, such that the students engage in a significant portion of analytical thinking prior to engaging in the analytical action in the laboratory. The positive responses from the students indicate that the online prelab quizzes and videos have consequently improved their psychomotor and affective experiences in these classes.

The prelaboratory quizzes were received very positively by the vast majority of students, who declared that they made a valuable contribution toward their learning. Thus, although the prelab exercises were compulsory, students did not view them as an onerous exercise to complete, and actively engaged with the content and used them as a learning tool. This attitude is also reflected in the large proportion of students who utilized the online videos, and is consistent with the findings of Jones and Edwards[4] who noted that students enthusiastically embraced optional online prelaboratory exercises, even when there were no direct external motivating factors (such as assessment) associated with them. The motivation of students to utilize the videos may stem from maturity (these are a fourth semester cohort); perhaps their intrinsic motivation (want to learn) is developing, and their learning is not solely driven by extrinsic motivation (want to pass the subject). Although the reception for the videos was slightly less enthusiastic than that for the prelab quizzes, those students who viewed the videos generally found them helpful. One student reported that they were "especially helpful for the instrumental laboratories". This reflects previous research in which visual presentations of experimental setups have been found to reduce student anxiety associated with using new equipment in the laboratory.[13] The visual nature of the videos may be appreciated to varying degrees by individual students, depending on their learning styles.[22] The use of online materials to guide prelaboratory learning appears to fit well with the preferred styles of learning identified by students. Most students prefer independent study

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methods, illustrating that the flexibility to study when convenient and ability to go at their own pace is important. Again, this reflects previous research into online learning, which identifies its flexible nature as a key strength.[14,15]

Although the methods of laboratory preparation reported by students were largely similar at the start and end of the subject, at completion of the subject fewer students reported doing additional calculations beyond those within the prelab exercises. This suggests that the prelab exercises were well-integrated with the laboratory material, and that students gained enough confidence from doing the prelabs to not need to carry out additional calculation work. However, this may also be the result of increased workload during second-year level subjects, and warrants further investigation.

Student academic performance in laboratory reports was not significantly increased in the semester following the introduction of the online prelab resources. This is supported by Lewis[28] who found that in a first-year undergraduate physics laboratory students responded positively to video introductions but student performance was not improved. In our study, and perhaps Lewis',[28] many of the desired learning outcomes in the laboratory were not necessarily measured in the assessed laboratory reports. As students complete their report outside of the laboratory class time, they have additional time to perform analyses and develop an understanding that they may not have necessarily possessed while performing the experiment. Given that student experiences in the laboratory are arguably as important as assessable outcomes, students' feelings in the laboratory are just as integral to their learning as the design of the analysis and report questions to elicit cognitive processing, and as such an attitudinal study such as this is extremely important. In fact, the 2012 National Research Council[29] report on Discipline-Based Education Research (DBER) directly states that "cognitive and affective development needs to be considered together by instructors". This study demonstrated that student attitudes toward the online material were very positive, particularly for the online prelab quizzes. The use of online materials provided a flexible learning platform, and enabled students to study independently which fit well with the preferred styles of learning identified by students. Students report that the online prelab material had a positive effect on their learning, and that they were able to enter the laboratory with high levels of perceived preparedness. Through this prelaboratory preparation program, the likelihood of cognitive overload at the beginning of the class was reduced, enabling students with the opportunity for deeper engagement with the material. However, quantifying these outcomes remains a challenge. Teo and co-worker[30] undertook a comprehensive content analysis of 650 empirical education research papers in six top-tier discipline relevant chemistry journals between 2004 and 2013, identifying that there were relatively few studies that reported on educational technologies. This is unexpected considering that the use of videotapes to introduce experiments in a first-year undergraduate physics laboratory was reported over 20 years ago by Lewis.[28] More research is required in both the technologies and how we can quantify if better analytical results were achieved, and if the student experience is significantly improved. Galloway and Bretz[27] describe a novel assessment tool "Meaningful Learning in the Laboratory Instrument" (MLLI) that was designed to measure students' cognitive and affective expectations and experiences across a semester. This is particularly important in an undergraduate chemistry laboratory course because the "doing" of chemistry laboratory work is obvious and visible to students and instructors; however, the domains of thinking and feeling while performing chemistry laboratory experiments are equally important.

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Notes

The authors declare no competing financial interest.

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