Do-it-yourself physiology labs: Can hands-on laboratory classes be effectively replicated online?

Kay Colthorpe and Louise Ainscough
School of Biomedical Sciences, The University of Queensland, St Lucia, Queensland, Australia

Abstract

Laboratory classes are a cornerstone of physiology education, enabling students to develop essential knowledge and skills. Recent moves toward utilizing blended options to support face-to-face classes with online materials are beneficial, but using solely online classes may not produce similar learning gains. During 2020, the global pandemic meant a loss of face-to-face teaching, such that laboratory classes were rapidly transitioned to online delivery. This study explores the impact of this shift on undergraduate students, evaluating their use of the online laboratory classes and the impact this had on their examination performance and their perceptions of learning. Student use of the online laboratory classes varied, with those spending more time performing better on examinations. Students valued the online classes, finding them helpful for their learning, but also felt that the lack of face-to-face laboratory classes and interactions with peers and teaching staff was detrimental to their learning experience. Overall, academic performance of online learners was comparable to previous years but may indicate some underlying deficits.

academic performance; COVID; laboratory class; online

INTRODUCTION

The use of laboratory or “practical” classes has long been considered a cornerstone of science education, although the aims and purpose of classes may differ (1). They have been credited with the development of many of the scientific skills graduates possess, including scientific content knowledge, communication and writing skills, and team work skills (2). In addition, they can aid the development of students’ perceptions and understanding of the nature of science (3–5). Students in professional medical and health programs also benefit from laboratory classes, as these support students’ understanding of physiology and provide opportunities for them to develop scientific and clinical skills (6).

When conducted in a traditional face-to-face setting, laboratory classes allow students to work with real equipment in authentic experimental settings and to generate their own results (7). This may enable students to develop an appreciation of the differences between expected and actual results and to recognize aspects such as biological variability and experimental error (7). Introducing inquiry into laboratory classes is also considered to be highly beneficial for students in both science and professional programs. Inquiry-based approaches can improve students’ understanding of physiological concepts and the scientific approach, as well as their skills in critical thinking and evaluation of evidence (6, 8, 9).

Online or virtual laboratory experiences have also been shown to have considerable value, allowing students flexibility in the timing and frequency of access, potentially leading to deeper learning (7, 10). However, there is a lack of consensus on whether learning within online laboratory classes is comparable to face-to-face classes. Outcome measures that focus on content knowledge suggest that students perform equally well in each class type, whereas those that focus on students’ perceptions and confidence suggest greater gains from face-to-face classes (7, 11). In physiology, online laboratory classes or learning materials have often been used to complement face-to-face laboratories in blended courses (12, 13).

The combination of online and face-to-face laboratory classes may offer advantages. The online environment can allow students to explore phenomena not observable in life or to rapidly conduct multiple experiments, whereas face-to-face classes help students develop practical skills and stimulate their interest in physiology (10, 13, 14). This blended approach to laboratory classes is adopted by the coordinators of “Physiology I,” a second-year course offered during the first semester each year at the University of Queensland, a large research-intensive Australian university. The laboratory classes in the course are all face to face and are complemented by online learning materials to a greater or lesser extent.

Challenges in 2020

In March of 2020, COVID-19 was declared a global pandemic. For those of us in the Southern Hemisphere, this coincided with the first weeks of our first semester of the...
academic year. Consequently, the semester commenced as usual in late February, but after 3 wk there was a complete shutdown of all face-to-face teaching at the university. After a 1-wk unscheduled pause, teaching recommenced entirely online, under circumstances since described as “emergency remote teaching” (15).

Having commenced the course face to face brought both advantages and challenges. The first lecture modules and first laboratory class had been completed before going online, and the students had an opportunity to meet some of the teaching team, with an early rapport established. However, the preexisting learning objectives and established schedule of learning activities and assessment tasks restricted flexibility. This was particularly acute in regard to the laboratory classes. The procedures and experiments for all the classes had been designed and published in a laboratory notebook to which students had been given access before commencing the course. In addition, half the students had already completed the second scheduled laboratory class in a face-to-face setting.

Effectively recreating the laboratory classes in an online environment therefore presented a significant challenge. The existing classes had been designed to allow the students to engage with “physiology in action,” providing opportunities for them to test theoretical concepts from the lectures and to develop understanding and skills in physiological and clinical measurements in a small-group learning environment. The laboratory classes also provided the most contact between students and teaching staff, giving students opportunities to seek explanations and feedback from their teachers and from peers. Their loss created the greatest concern for teaching staff, as it is often within these classes that students become interested and excited by physiology as they begin to see its role in their future professions. In this study, we examined the impact of the move to an online learning environment for students in Physiology I. Specifically, this study focused on student use and perceptions of the online laboratory classes and the impact these had on their academic performance.

## METHODS

### Course Structure Prior to 2020

The Physiology I course is designed for students in allied health programs and provides them with an opportunity to develop an understanding of cellular physiology, including nerve and muscle cells, and physiology of the cardiovascular, respiratory, and renal systems. Under normal circumstances, the course contact consists of 3 h of face-to-face lectures every week together with a 3-h practical laboratory class in 8 of the 13 weeks of the semester. Lectures are scheduled twice a week, are recorded through Echo360 (Echo360 Inc., Dulles, VA), and are made available to students 24 h after each lecture takes place via a course Blackboard (Blackboard Inc., Washington DC) site that is available to students throughout the semester. Usually, the laboratory classes associated with this course are all face to face. In most classes, students perform “live” physiological experiments during class and are provided with small amounts of additional information online. The exceptions are two classes in which all the experiments and their associated materials are presented online, with students working on computers for the duration of the face-to-face class. For all classes, teaching staff are present in person to offer assistance and answer questions.

Course assessment includes a midsemester and an end-of-semester examination worth 20% and 55% of course assessment, respectively. These written exams are taken in a face-to-face invigilated session. Assessment of the laboratory classes is conducted through the midsemester and end-of-semester examinations, with 21.5% of all examination marks devoted to questions regarding the laboratory component. The course also includes an assignment worth 13%, four short “meta-learning” assignment tasks (16) at 2- to 3-wk intervals. These collectively contribute 12% to the assessment. These contain open-ended, self-reflective questions regarding students’ learning and experiences in the course. The assignment and meta-learning tasks are all submitted online through the course Blackboard site.

### Changes to Course Structure in 2020

As there were preexisting Echo360 recordings of lectures from previous years’ delivery of the course, these, along with their associated PowerPoint (Microsoft Corporation, Redmond, WA) slides, were provided to students on a weekly basis to replace the scheduled lectures. To supplement these, a “live” 1-h Zoom (Zoom Video Communications, San Jose, CA) question-and-answer session took place at the end of each lecture module (4–6 lectures) and again in the week before the final examination. In these sessions, lecturers and the course coordinator answered students’ questions and engaged in dialogue about the lecture material. The sessions were also recorded and made available to students for later viewing. In addition, students were encouraged to post questions on the discussion board in Blackboard, and this was monitored and responded to daily. To aid students’ self-evaluation, formative assessment tasks consisting of multiple-choice and short-answer questions from groups of three or four lectures were created and provided to students approximately weekly. Students could complete these at any time and as many times as they wished, and they were provided with answers upon completion. Students were also provided with a “study planner” to help them maintain regular study for the course and received regular weekly updates from the course coordinator.

The assessment tasks all took place as scheduled; however, the midsemester and end-of-semester examinations were delivered online, through Blackboard, with the latter being invigilated by the online proctoring service ProctorU (ProctorU Inc., Phoenix, AZ). Slight modifications to accommodate the online environment were made to a small number of questions in the examinations, for example, by removing the option to include a diagram in the answer.

### Changes to Laboratory Practicals in 2020

The remaining seven laboratory classes were all recreated as online practical modules, including the one that half the students had completed in a face-to-face class. These were all hosted on the Smart Sparrow platform (Smart Sparrow, Sydney, NSW, Australia) and were created in a linear “slide”
format, ranging in length from 15 to 32 slides. All contained embedded text, videos, images, and formative questions with feedback. Initially, during the “pause” week, the teaching laboratories were still available for staff use, providing an opportunity for pictures of equipment to be taken and short videos of procedures and experiments to be filmed. However, the time available for this phase was limited, and it was difficult to envisage all the images that might be needed. To supplement this, some online learning materials previously created by course teaching staff were adapted for use, primarily through the editing and recycling of existing videos, although these were limited in both number and scope. In addition, some videos were created at home.

The philosophy behind the creation of the online practical classes was threefold. First, they were designed to replicate the experience the students would have had if they were actually performing the procedures and experiments in the face-to-face laboratory class. Wherever possible, the videos were created in the “first person,” filmed as if the camera was performing the tasks. The videos were edited to focus on each aspect of the procedure in turn, looking at the subject (for example, the nerve-muscle preparation or the person), then at the data being acquired, and back. Second, to replicate the dialogue students would have had with the teaching staff or their peers, the online classes included “pop-up” boxes containing explanations of aspects of the experiments or results. All of the videos had an audio explanation and a written transcript of that audio (Fig. 1). There were also many formative questions included, with answers and specific feedback for each correct or incorrect choice. Finally, to engage the students in “doing” physiology, there were tasks created that students could perform at home on themselves (or someone they cohabitated with) that required little or no equipment. For example, students compared their pulse rate in a nonstressed and a stressed state (Fig. 1) or performed a forced expiration on their hand to reinforce the concept of expiratory flow (Fig. 2).

Participants in the Study

Students undertaking the course in Semester 1, 2020 were mostly undergraduate students in the Bachelor of Physiotherapy (n = 130) or Bachelor of Speech Pathology (n = 102) program who were in the second year of their program. There was also a small number of postgraduate students (n = 24) in the first year of the Masters of Speech Pathology program. Although each of these programs has demanding entrance requirements, students in the Bachelor of Physiotherapy program tend to have stronger backgrounds in science (17) and consistently outperform students in the other programs, with average marks ~10% higher than their peers. At the commencement of the course, students in the cohort had an average age of 20.9 yr, 75% were female, and 17% were international students.

Students’ Responses to Online Learning in Physiology

Students’ responses to the meta-learning question “What aspects of the learning materials for Physiology I helped or hindered your learning in the online environment?” were initially subjected to an inductive thematic analysis, followed by a qualitative content analysis process (18, 19) within the data management software NVivo 12 (QSR International, Burlington, MA). This process included an initial familiarization with data and generation of codes, then searching for, reviewing, defining, and naming themes, and finally a content analysis to produce a report on theme frequency. The meta-learning question appeared in the third meta-learning task, which students completed in week 9 of the 13-wk semester.

Laboratory Module Usage

Learning analytics data extracted from the Smart Sparrow platform for each online laboratory module included when it was opened, the duration of time open, and whether or not the module had been completed. The modules were recorded as “completed” when the students passed the final slide. These data were collected after the final examination date and were analyzed to identify the average number of times each module was accessed and the average duration of use. Data were also recorded for each student, including the individual modules opened, duration of time open for each

Figure 1. Example of an at-home activity included in an online laboratory class on blood pressure in which students compare pulse rate in a nonstressed and a stressed state. The video transcript is available as a pop-up on the page.

Figure 2. Example of an at-home activity to reinforce the concept on expiratory flow that was included in an online laboratory class on spirometry.
attempt, and module attempt number (where students opened a specific module on >1 occasion). These data were analyzed to identify the range and average number of modules students opened, the frequency of viewing of the modules, and the total and average time each student spent with the modules open.

**Academic Performance**

Individual students’ performance on the midsemester and end-of-semester examinations was collated, and the marks each student achieved on the questions regarding the laboratory classes on each examination were pooled. These questions represented 21.5% of all examination marks. In addition, their overall performance on the course (in percent) was collated. Equivalent data from the previous years’ cohort were also collated for comparison purposes. The marks were subjected to one-way analysis of variance (ANOVA) with Sidak’s multiple comparisons test. Results are expressed as mean and standard deviation (SD) and were considered significant if, when adjusted for multiple comparisons, \( P < 0.05 \).

**Ethical Considerations**

Ethics approval was received from the institutional Human Research Ethics Committee before commencement of the study. All students were invited to give written, informed consent to participate, with 152 students (60% of the cohort) doing so. A \( t \) test was used to evaluate whether any significant difference existed between the overall performance in the course of students who had consented (mean 79.0% SD 11.5) and the entire cohort (76.9% SD 11.8; \( P = 0.08 \)); as no difference existed, it can be assumed that the participating students were academically representative of the cohort. Data from consenting students in the 2019 cohort (\( n = 161 \)) have also been included in this study for comparison purposes. Consenting students’ data were assigned a deidentified code before analysis, which allowed matching of all data sources.

**RESULTS**

**Use of Online Laboratory Class Modules**

Each laboratory module was opened on average 233 times (SD 28), ranging from the most popular, “Osmosis” (opened 267 times), to the least popular, “Cardiovascular responses to exercise” (186 times). The latter was also the final class of the semester. The total duration that the modules were open exceeded 5,750 h. However, as the duration that the classes were open ranged from 1 s to >18 days, it was clear that not all this time was spent on task. To gauge a reasonable average duration, occasions when the modules were open for <30 s or >6 h were excluded from the calculation. It was reasoned that students may realistically check on specific aspects in as little as 30 s (the fastest recorded completion of a module was 39 s) but were unlikely to continue working beyond a 6-h period. On this basis, the average duration that a module was opened was 50.2 min (SD 61).

Of the students in the cohort (\( n = 254 \)), all but 15 opened at least one of the seven online laboratory modules. Altogether, the 239 students who opened the modules did so 1,630 times, finishing the module (in that they passed the final slide) on 1,315 of these occasions. A more detailed analysis of the module use by the consenting students (\( n = 152 \)) revealed that the majority (55%) opened all seven modules, with a further 16% opening six of the seven modules, giving an average of 5.7 modules (SD 1.9) opened per student. In addition, 43% of students opened at least one module on more than one occasion. After individual opening times of >6 h and <30 s were excluded, the average total time students spent with the modules open was 5.38 h (SD 4.27). The length of time each student spent with the laboratory modules open was found to be significantly related to their marks for the laboratory questions in the examinations (Pearson \( r = 0.33; P < 0.001 \)) and to their overall course performance (Pearson \( r = 0.34; P < 0.001 \)).

**Student Perceptions of Course Learning Materials**

Thematic analysis identified 18 themes within the responses of students (\( n = 149 \)) who answered the question “What aspects of the learning materials for [Physiology I] helped or hindered your learning in the online environment?” These included 10 aspects that students reported as being helpful to their learning (Table 1) and 8 aspects that hindered it (Table 2). Students could report multiple aspects that either helped or hindered their learning. There were a total of 164 comments describing helpful aspects, reported by 73% of students. In contrast, there were fewer comments describing hindrances (\( n = 106 \)); these were also reported by fewer students (60%). Over a third of students (36%) identified both helpful aspects and hindrances.

The online laboratory modules (referred to as “practicals” or “pracs” by students) featured strongly among these themes, being cited as helpful by more students (42%) than any other aspect of the course (Table 1). For example, students said “The way the practicals have been transformed to an online setting have also been super helpful as I feel like I’m getting almost the same experience with all of the videos that are included” and “The practicals have been useful though in their step by step process and their ‘real time’ assessments to make sure you understand as you go.” However, students (26%) also reported that the lack of live laboratory classes or these being online hindered their learning (Table 2), with 6% highlighting that they missed the opportunity for dialogue specifically within the laboratory classes. For example, students said “Not being able to complete the practical classes in the laboratories has hindered my learning quite a bit, as I often have difficulty understanding how the concepts work in relation to the experiments...” and “I feel that the practical sessions being online are not as helpful, however, I understand this is unavoidable. I have struggled with not being able to ask questions when I do not understand the content.”

Some students also expressed disappointment at not having the opportunity to do the live laboratory classes, saying “I wish we could have done the pracs face to face (e.g., the blood pressure one and the spirometry/lung volumes etc.), because I think they would have been quite fun to do. However, I think the online practical format has been quite good, and makes up for us not being able to do it in real life as much as possible.” and “It is disappointing (but
understandable) that we won’t get to attempt to experience the actual laboratories. It would have been great to learn to measure blood pressure. However, the online pracs are very well done.”

Responses to the meta-learning task question also demonstrated that students accepted that the shift to online learning brought about by the pandemic was necessary, and that they appreciated the efforts made by teaching staff to support them. For example, one student said, “Everything being online has definitely hindered my learning, but obviously there is not much that can be done about this and I think the staff are doing an amazing job trying to readjust the course to work within these new circumstances.”

### Table 2. Student responses regarding aspects they found hindered their learning

| Theme                              | Students, % | Example                                                                 |
|------------------------------------|-------------|-------------------------------------------------------------------------|
| Lack of live laboratory classes    | 26          | “I think the online practicals are the most difficult things. Usually in practicals we get the ability to try things for ourselves and ask questions to tutors. In this way, it feels as though we are actively participating in the content. With the online practicals, it feels as though we are taking a passive role.” |
| Lack of interaction/dialogue       | 17          | “Still being able to access lecture recordings is great! However, it’s a lot harder to seek clarification from lecturers and generally asking/collaborating with peers as well.” |
| Lecture presentation/structure     | 15          | “Recorded lectures that had diagrams pointed to/at off-screen (e.g., with in-person laser pointers that did not translate to on-screen) made it more difficult to understand what was being regarded to in images on lectures.” |
| Issues with time/workload          | 4           | “Releasing all the lectures at once can sometimes be overwhelming. It seems like we are getting more lecture hours per week than usual. I tend to want to complete them as soon as possible, and that can prove to be challenging. I sometimes feel like I am behind on all the work.” |
| Access issues                      | 3           | “I haven’t been able to access online pracs which has set me behind quite a bit as I haven’t been able to apply my understanding from lectures into practice.” |
| Lack of structure                  | 2           | “Something that has probably had a negative impact on my learning specifically is the lack of scheduling of lectures. . . flexibility is great, but I sometimes feel like I need more structure and I need either a set time or even just a set day for the lectures to be uploaded/watched.” |
| Laboratory module presentation/structure | 2       | “I would like to be able to know how long each online tutorial will be (e.g., number of slides) and to be able to see the comments about our answers to the multiple-choice questions to be left up so we can still go over them later.” |
| Exam format                        | 1           | “To be honest, I really struggled in the mid sem exam and it was unfortunately reflective on my grade, which is really disheartening to me. The single question format per page threw me off. Though I knew that this is what the format would be.” |

Student responses (n = 149) to a meta-learning question regarding aspects they found hindered for their learning were inductively coded and quantified by reporting frequency. An example of a student response to each theme is included. Students could report >1 helpful aspect with 32% doing so.
to some aspects of students' academic performance, as it reduced their ability to use their conceptual knowledge in the more applied laboratory questions in the examinations, with this deficit appearing stronger in the Speech Pathology students, who find physiology more challenging (17). Together, these findings support prior studies showing that online and face-to-face laboratory classes can aid the development of students’ content knowledge to a similar extent (7, 14). The findings also demonstrate that there are specific benefits of face-to-face laboratory classes that may be difficult to replicate in an online learning environment.

Student engagement with the online laboratory classes was high, with almost three-quarters of students opening six or more of the modules and the modules being completed on most occasions. Although attendance at live classes is not usually recorded, this level of engagement is at least as high as the level of attendance that has been observed in previous years. However, the live laboratory classes are of 2- to 3-h duration. This differed markedly from the length of time students spent on the modules, which averaged <1 h. Potentially, this difference may be accounted for by the time students would normally spend in a live class taking measurements and completing the experiments and interacting with their peers and teaching staff. The loss of these aspects of face-to-face laboratory classes was clearly a concern for students, with many highlighting that the lack of activities in face-to-face classes hindered their learning. Students also expressed concern with the loss of potential dialogue with both peers and teaching staff that occurred because of the move to online learning.

The skills that students may develop in a face-to-face laboratory class, through the physical performance of experiments, the acquisition of their own data, with its inherent biological variations, and the opportunity to see physiology more challenging (17).

### Examination Performance

The performance of students in answering questions related to the laboratory classes in the midsemester and end-of-semester examinations in 2019 (n = 161 students) and 2020 (n = 152 students), and their performance in each examination and the course overall, were collated and compared by one-way ANOVA, with Sidak's multiple comparisons tests. Students’ performance on questions relating to the laboratory classes was significantly lower in 2020, with students achieving an average of 67% (SD 17.2%) in 2020, compared with 76% (SD 16.1%; P < 0.001) in 2019 (Fig. 3). In contrast, the performance of students in each examination and the course overall did not differ significantly between the years (Fig. 3).

When separated by discipline, the difference in performance that has been consistently observed between students in each discipline was also observed in 2020. However, although the examination marks for the laboratory component for students in both disciplines were significantly lower than the previous year (Fig. 4), the impact appeared slightly greater in the Speech Pathology students. These students had on average 10.8% lower marks than the Speech Pathology students in 2019, whereas the marks for the Physiotherapy students were on average only 8.1% lower than their 2019 counterparts (Fig. 4).

#### DISCUSSION

It was gratifying to see that the academic performance of students in this course overall was not adversely affected by the shift to the online learning environment. The students’ success perhaps reflects their acceptance of the circumstances, their recognition of the need to manage their learning process, and their willingness to do so despite the upheaval brought on by the global pandemic. However, it was also clear that the lack of live laboratory classes was detrimental to some aspects of students' academic performance, as it reduced their ability to use their conceptual knowledge in

![Figure 3](image-url) Academic performance for examination questions related to laboratory classes (Lab questions), midsemester examination (Mid-semester), end-of-semester examination (End-of-semester), and the course overall of consenting students in 2019 (n = 161 students; black bars) and 2020 (n = 152 students; gray bars). Data are expressed as mean % and standard deviation of the marks available. ***One-way ANOVA with Sidak’s multiple comparisons test: P < 0.001.

![Figure 4](image-url) Academic performance for examination questions related to laboratory classes of Bachelor of Physiotherapy students in 2019 (n = 97 students) and 2020 (n = 95 students) or Bachelor and Masters of Speech Pathology students in 2019 (n = 64 students) and 2020 (n = 57 students). Data are expressed as mean % and standard deviation of the combined marks available from the midsemester and end-of-semester examinations. One-way ANOVA with Sidak’s multiple comparisons test: a differs significantly (P < 0.001) from Physiotherapy students’ performance in 2019; b differs significantly (P < 0.001) from Speech Pathology students’ performance in 2019; c differs significantly (P < 0.001) from Physiotherapy students’ performance in 2020.
physiology laboratory classes do exist, often being designed to simulate many of the processes undertaken during a laboratory class, such as including elements that demonstrate individual variation (20). When evaluated, such tools have been shown to produce learning that is equivalent to that seen in face-to-face classes (20). However, very few are publicly available, as they are often produced either within an institution or by a commercial entity (10, 21).

The dialogue that takes place between peers and with teaching staff during a face-to-face class provides opportunities for students to develop a deeper understanding of the content and aids their critical thinking. Collaborative learning is a key component of many laboratory classes, as it is associated with improvements in students’ performance and attitude toward science (22, 23). Fostering interactions with teaching staff in laboratory classes is also important, both for student understanding of content knowledge and also for the role staff play in mentoring and motivating students (24). Designs of online laboratory classes that include opportunities for student-staff dialogue may help alleviate some of these deficits (11), although opportunities for dialogue with either peers or staff during an asynchronous online class may be very challenging to create.

One additional concern for academic staff was the substantial workload associated with the development of the online modules, which was exacerbated by the speed at which the transition to online learning took place. Although there are proprietary online physiology learning resources available, many of these can only be procured through purchase or licensing arrangements that may take a considerable period to organize or may simply be too expensive. The specific requirements of the laboratory classes and the immediacy of the need brought about by the pandemic meant that these could not be readily adopted for use in this course. Consequently, the majority of the material was newly created in less-than-ideal conditions that put considerable strain on staff. Fortunately, it appears that despite these conditions, the learning materials produced were helpful to students’ learning. In addition, this material will be readily adapted for future use, either to replace or supplement future face-to-face offerings of these laboratory classes.

Conclusions

The extraordinary situation that occurred at the commencement of the academic year in 2020 created significant challenges to staff and students alike. However, it appears that despite these challenges, both groups were able to adapt to the rapid pace of change and cope in these difficult circumstances. One encouraging outcome of this study was that it highlighted that students do value face-to-face laboratory classes. This may potentially influence the way they engage with them in the future. These challenges also presented a unique opportunity, effectively a broadband experiment on the possibilities offered by online physiology laboratory classes. As we gradually return to on-campus learning it is likely that the limitations on face-to-face classes, with smaller groups and physical distancing, will be with us for a considerable time. Consequently, our experiences, the resources we’ve created, and the lessons we’ve learned in delivering these online physiology laboratory classes are likely to serve us well into the future.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

K.C. conceived and designed research; K.C. performed experiments; K.C. analyzed data; K.C. interpreted results of experiments; K.C. prepared figures; K.C. and L.A. drafted manuscript; K.C. and L.A. edited and revised manuscript; K.C. and L.A. approved final version of manuscript.

REFERENCES

1. Hofstein A, Lunetta VN. The laboratory in sci education: foundations for the twenty-first century. Sci Educ 88: 28–54, 2004. doi:10.1002/sect.10109
2. Hodgson Y, Varsavsky C, Matthews KE. Assessment and teaching of science skills: whole of programme perceptions of graduating students. Assess Eval High Educ 39: 515–530, 2014. doi:10.1080/02602938.2013.842539
3. Coil D, Wenderoth MP, Cunningham M, Dirks C. Teaching the process of science: Faculty perceptions and an effective methodology. CBE Life Sci Educ 9: 524–535, 2010. doi:10.1187/cbe.10-01-0005.
4. Russell CB, Weaver GC. A comparative study of traditional, inquiry-based, and research-based laboratory curricula: impacts on understanding of the nature of science. Chem Educ Res Proc 12: 57–67, 2011. doi:10.1039/C1RP90008K.
5. Zimbardi K, Loyle-Langholz A, Kideli J, Colthorpe K. Using inquiry-based practicals to promote students’ critical evaluation of the scientific literature and maturation of their understanding of the nature of scientific knowledge. Intl J Innov Sci Math Educ 23: 91–103, 2015.
6. Casotti G, Riester-Danner L, Knabb MT. Successful implementation of inquiry-based physiology laboratories in undergraduate major and non-major courses. Adv Physiol Educ 32: 286–296, 2008. doi:10.1152/advan.00100.2007.
7. Brinson JR. Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: a review of the empirical research. Comp Educ Train 87: 218–237, 2015.
8. Colthorpe K, Zimbardi K, Bugarcic A, Smith A. Progressive development of scientific literacy through assessment in inquiry-based biomedical science curricula. Intl J Innov Sci Math Educ 23: 52–64, 2015.
9. Zimbardi K, Bugarcic A, Colthorpe K, Good JP, Lluca LJ. A set of vertically integrated inquiry-based practical curricula that develop scientific thinking skills for large cohorts of undergraduate students. Adv Physiol Educ 37: 303–315, 2013. doi:10.1152/advan.00082.2012.
10. Lewis DI. The Pedagogical Benefits and Pitfalls of Virtual Tools for Teaching and Learning Laboratory Practices in the Biological Sciences. York, UK: Higher Education Academy: STEM, 2014.
11. Barbeau ML, Johnson M, Gibson C, Rogers KA. The development and assessment of an online microscopic anatomy laboratory course. Anot Sci Educ 6: 246–256, 2013. doi:10.1017/ase.1347.
12. Dantas AM, Kemm RE. A blended approach to active learning in a physiology laboratory-based subject facilitated by an e-learning component. Adv Physiol Educ 32: 65–75, 2008. doi:10.1152/advan.00006.2007.
13. Elmer SJ, Carter KR, Armga AJ, Carter JR. Blended learning within an undergraduate exercise physiology laboratory. Adv Physiol Educ 40: 64–69, 2016. doi:10.1152/advan.00144.2015.
14. de Jong T, Linn MC, Zacharia ZC. Physical and virtual laboratories in science and engineering education. Science 340: 305–308, 2013. doi:10.1126/science.1230579.
15. Hodges C, Moore S, Locke B, Trust T, Bond A. The difference between emergency remote teaching and online learning. Educause Rev 27, 2020.
16. Colthorpe K, Sharifirad T, Ainscough L, Anderson ST, Zimbardi K. Prompting undergraduate students’ metacognition of learning: implementing ‘meta-learning’ assessment tasks in the biomedical
17. Ernst H, Colthorpe K. The efficacy of interactive lecturing for students with diverse science backgrounds. Adv Physiol Educ 31: 41–44, 2007. doi:10.1152/advan.00107.2006.
18. Braun V, Clarke V. Using thematic analysis in psychology. Qual Res Psychol 3: 77–101, 2006. doi:10.1191/1478088706qp063oa.
19. Mayring P. Qualitative content analysis. Forum Qual Soc Res 1: 20, 2000.
20. Dobson JL. Evaluation of the virtual physiology of exercise laboratory program. Adv Physiol Educ 33: 335–342, 2009. doi:10.1152/advan.00040.2009.
21. Brinson JR. A further characterization of empirical research related to learning outcome achievement in remote and virtual science labs.
22. Corter JE, Esche SK, Chassapis C, Ma J, Nickerson JV. Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories. Comp Educ 57: 2054–2067, 2011. doi:10.1016/j.compedu.2011.04.009.
23. Springer L, Stanne ME, Donovan SS. Effects of small-group learning on undergraduates in science, mathematics, engineering, and technology: a meta-analysis. Rev Educ Res 69: 21–51, 1999. doi:10.3102/00346543069001021.
24. Good J, Colthorpe K, Zimbardi K, Kafer G. The roles of mentoring and motivation in student teaching assistant interactions and in improving experience in first-year biology laboratory classes. J Coll Sci Teach 44: 88–98, 2015.