A virtual experiment improved students’ understanding of physiological experimental processes ahead of a live inquiry-based practical class

 Quiroga M, Choate JK. A virtual experiment improved students’ understanding of physiological experimental processes ahead of a live inquiry-based practical class. Adv Physiol Educ 43: 495–503, 2019; doi:10.1152/advan.00050.2019.—Physiology is commonly taught through direct experience and observation of scientific phenomena in “hands-on” practical laboratory classes. The value of such classes is limited by students’ lack of understanding of the underlying theoretical concepts and their lack of confidence with the experimental techniques. In our experience, students follow experimental steps as if following a recipe, without giving thought to the underlying theory and the relationship between the experimental procedure and the research hypotheses. To address this issue, and to enhance student learning, we developed an online virtual experiment for students to complete before an inquiry-based practical. The virtual experiment and “live” practical laboratory were an investigation of how autonomic nerves control contractions in the isolated rabbit ileum. We hypothesized that the virtual experiment would support students’ understanding of the physiological concepts, as well as the experimental design associated with the practical. Anonymous survey data and usage analytics showed that most students engaged with the virtual experiment. Students thought that it helped them to understand the practical physiological concepts and experimental design, with self-reported time spent on the virtual experiment (and not on lectures or practical class notes) a significant predictor of their understanding. This novel finding provides evidence that virtual experiments can contribute to students’ research skills development. Our results indicate that self-paced online virtual experiments are an effective way to enhance student understanding of physiological concepts and experimental processes, allowing for a more realistic experience of the scientific method and a more effective use of time in practical classes.

computer-based simulation; gut physiology; online simulation; virtual experiment, virtual laboratory

INTRODUCTION

Laboratory classes. Physiology practical laboratory classes play an important role in helping students to understand physiological concepts via collaborative and experiential learning (14, 21). The communication and social interactions between students and teaching staff during the practical classes encourages collaborative learning and enhances engagement by fostering a student’s positive sense of inclusion (6, 11). Practical laboratory classes also support the development of research skills, such as experimental design, data analysis, statistics, and report writing; expose students to experimental techniques and methodologies; and facilitate employability skills development, such as communication, quantitative reasoning, problem solving, and team work (15, 19). However, when developing practical classes for teaching, consideration needs to be given to the use of animals as subjects (23) and the expense and time commitment for running these classes, especially with large student cohorts and reduced budgets. Furthermore, the busy, social, and noisy environment of the practical class distracts students from the aims and theory of the exercise (11, 13) and can result in an over-reliance on practical laboratory notes (19).

Virtual experiments. The use of virtual experiments (or computer-based simulations) provides a way of reducing the “noise” students experience in the practical class environment by prefamiliarizing them with the ideas and concepts underlying the experiment, the apparatus and materials, the planning and sequence of actions, and the expected results (13). Virtual experiments have been shown to enhance understanding of core discipline concepts (in biosciences), as ascertained by exam and assessment performance, when used before or alongside practical work (4, 8, 10, 12, 25). They have multiple benefits for universities, faculty, and students. For universities and departments, they can drastically reduce the costs associated with practicals (e.g., animals, equipment, staff and faculty time). For faculty/academic staff, they can lead to more efficient wet laboratory classes, by ensuring the students are better prepared; they allow an expansion of the learning outcomes by enabling data collection from inaccessible populations (aging, disease, expensive or controlled substances); and they can directly address known gaps in student background knowledge. For students, they release the pressure associated with getting the “perfect” result in the laboratory, allowing the focus to shift instead to the experimental process; they help them feel better prepared for the laboratory activities; they allow each student to be fully involved in all aspects of data collection (compared with expensive equipment limitations); and they encourage flexibility in self-directed learning, allowing students to learn at their own pace, repeating as needed with their choice of timing and location for this learning activity.

Computer-based simulations are particularly beneficial for longer term experiments that would normally run over several practical classes, or experiments that are unfeasible in practical classes due to ethical or other concerns (15, 22). However, virtual experiments do not allow students to develop the collaborative and hands-on technical skills that they experience in a traditional laboratory class, they usually do not expose students to variability in scientific data, and they frequently rely on self-directed learning (and thus student time manage-
When students were surveyed about the discontinuation of either virtual or traditional laboratories, they communicated a need for both to be used together (5, 18). Furthermore, many students believed that animal laboratories were necessary to learn topics such as anatomy and physiology (9).

**Inquiry-based activities.** In recent years, there has been a focus by university educators and management on the development of students’ graduate attributes and employability skills. Within bioscience education, this has been associated with the development of inquiry-based practical laboratory classes, as this facilitates the development of skills such as problem solving and critical thinking (2, 24). Inquiry-based practical classes encourage teachers to move away from traditional recipe-based practical classes that have predictable results and that students find repetitive and boring (1). They facilitate active learning, as students investigate an open question or problem, using evidence-based reasoning and creative problem solving to reach a conclusion, with the guidance of their teacher (3, 16, 17). However, students can struggle with the autonomy, and educators need help with how to guide students with this type of learning (26). Here we propose an important role for virtual experiments in supporting inquiry-based practical classes.

**The intervention.** For the last 20 yr, we have been running an undergraduate physiology practical class investigating the neuronal control of contractions in the isolated ileum. This practical was associated with lengthy and detailed step-by-step practical notes that specified nerve stimulation and drug pipetting protocols. In 2014, students performed poorly on an exam question that required them to understand and interpret an experimental trace recorded from this practical class. This suggested that they had not understood what they were recording during the practical class and prompted the development of a prepractical class online virtual experiment. This study reports on the development of this virtual experiment and an evaluation of the impact of the virtual experiment on student learning. Anonymous student surveys were used to examine whether students’ thought that the virtual experiment contributed to their skills in experimental design and data analysis, as well as their understanding of the core physiological concepts associated with the practical class. To date, there have been no published evaluations of the effectiveness of virtual experiments for enhancing students’ scientific skills development, such as experimental design, data analysis, and presentation (15).

**MATERIALS AND METHODS**

**Context and participants.** Students involved with this research were completing the second year of their 3-yr degree program in subjects that included the “Neuronal Control of Gastrointestinal Smooth Muscle” practical laboratory class. Of these students, 421 were completing a core biomedical science subject as part of their Bachelor of Biomedical Science degree program (subject: BMS2031, Body Systems), 83 students were undertaking an integrative biomedical subject as part of their Bachelor of Nutrition and Dietetics degree program (subject: NUT2103, Integrated Science Systems), and 376 students were undertaking a physiology subject as part of their Bachelor of Science degree program (subject: PHY2032, Endocrine Control Systems). The BMS2031 subject was conducted in semester 1 (February–May 2016), and the NUT2031 and PHY2032 subjects were conducted in semester 2 (July–October 2016). Due to student numbers, the practical was repeated five times over 3 days for PHY2032 and BMS2031, whereas one practical accommodated all NUT2103 students. The link for the virtual experiment was made available to students via their online learning management system (on Moodle).

**Research design.** Each cohort of students received three relevant theoretical lectures on gut physiology in the weeks before the practical laboratory class. During these lectures, the lecturer instructed students to complete the virtual experiment that recreated the live experiments performed in the practical class. Students were also e-mailed an announcement via their learning management system (Moodle) before the practical class, prompting them to complete the virtual experiment. The virtual experiment was not part of the students’ summative assessment in these subjects.

At the beginning of the “Neuronal control of Gastrointestinal Smooth Muscle” practical class in the BMS2031 subject, one of the authors of this research (Dr. Maria del Mar Quiroga), an independent researcher not involved in the teaching of the subjects, invited students to complete a paper-based, voluntary, and anonymous survey (see Supplemental Data: All supplemental material is available at https://doi.org/10.5281/zenodo.3381651). Students completed and submitted the survey before they commenced the practical class, and for logistical reasons we were only able to run this survey in the BMS2031 subject. From here on we will refer to this survey as the prepractical survey. The survey contained four questions about how students engaged with lectures, practical notes, and the virtual experiment; and four questions (two multiple-choice questions and two written response) designed to test students’ understanding of autonomic physiology, experimental design, data analysis, and interpretation of results in the context of this practical laboratory class.

- **Question 5** (Q5) was a multiple-choice question that required students to analyze the amplitude of a sample recording taken from the virtual experiment, similar to recordings to be acquired during the practical class (data analysis and understanding of the experimental recordings).
- **Question 6** (Q6) was a multiple-choice question about interpreting experimental data (problem solving).
- **Question 7** (Q7) was a short-answer questions with two parts:
  - Q7a required a written explanation about how autonomic receptor agonists could be used to determine the type of autonomic nerves being stimulated (experimental design and understanding of autonomic physiology).
  - Q7b required a written explanation about how autonomic receptor antagonists could be used to determine the type of autonomic nerves being stimulated (experimental design and understanding of autonomic physiology).

We established a marking rubric for Q7a and Q7b, and a teaching associate with no relationship to the research project or the virtual laboratory marked the questions. For Q7a, each of the following statements was worth one point, with a maximum of three points:

1. Noradrenaline is the sympathetic neurotransmitter (0.5 if a relationship is hinted, but not specified, for example “NA = sympathetic”).
2. Acetylcholine is the parasympathetic neurotransmitter (0.5 if a relationship is hinted, but not specified, for example “ACh = parasympathetic”).
3. If noradrenaline mimics the effect of nerve stimulation, then mostly sympathetic nerves were stimulated; if acetylcholine mimics the effect of nerve stimulation, then mostly parasympathetic nerves were stimulated.

For Q7b, each of the following statements was worth one point, with a maximum of three points:

1. Phentolamine is an adrenoreceptor antagonist (sympathetic) (0.5 if a relationship is hinted, but not specified, for example “phenolamine = sympathetic”).

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2. Atropine is a muscarinic receptor antagonist (parasympathetic) (0.5 if a relationship is hinted, but not specified, for example “atropine = parasympathetic”).

3. If phentolamine attenuates the effect of nerve stimulation, then mostly sympathetic nerves were stimulated; if atropine attenuates the effect of nerve stimulation, then mostly parasympathetic nerves were stimulated.

After the practical class and before submitting their written practical reports through Moodle, students from all three subjects (PHY2032, NUT2103, and BMS2031) were invited to complete a voluntary, anonymous online survey through Qualtrics. This survey asked students to rate their responses to statements using a five-point Likert scale, from “strongly disagree” to “strongly agree.” The statements were designed to gauge how students used the online virtual experiment, whether they found it a valuable tool, and gave them the opportunity to report any technical problems and provide open-ended feedback (see Supplemental Data: https://doi.org/10.5281/zenodo.3381651). From here on we will refer to this as the postpractical survey.

Both surveys (pre- and postpractical) were approved by the Monash University Human Research Ethics Committee (CF16/1436-2016000774).

Data and statistical analysis. We performed all statistical analyses and created the corresponding graphs using the R project (https://www.r-project.org/), a free programming language and software for statistical computing and graphics. For the prepractical survey, we obtained three predictors from questions 1–4 regarding self-assessment of student engagement: time spent on the virtual experiment, time spent reading the practical notes, and the number of lectures attended. We performed a logistic regression on the proportion of correct responses for the multiple-choice questions (Q5 and Q6) as a function of the three predictors. The written response questions (Q7a and Q7b) were first scored between zero and three points (see Research design above), and we performed a regular generalized linear regression on this scored data. We used Akaike information criterion to select the best possible models with the three predictors.

To compare the students’ report grades across the years, we ran an ANOVA with a Tukey test for post hoc comparisons.

The virtual experiment. We developed a virtual experiment that mimicked the corresponding practical laboratory class, using HTML and CSS for the layout and aesthetics, and JavaScript (including the d3.js library; https://d3js.org/) to create the interactivity and graphs associated with the experiment. The recorded data in the virtual experiment, created directly in the browser using sine waves, was based on the observed characteristics of real data recorded in the practical class in 2015. We also included animations, videos, and text support for the physiological concepts and technical skills related to the practical class within the virtual experiment, accessible online at: https://ilearn.med.monash.edu.au/physiology/gastro-smooth-muscle/index.html. The website is structured across four main tabs (see Fig. 1): 1) Home; 2) Experimental Setup; 3) Simulation; and 4) Interpretation.

The Home tab contains a short description of how the autonomic nervous system controls intestinal motility and an embedded video describing the preparation, created in-house by the teaching support team.

The Experimental Setup tab contains two videos, also created in-house by the teaching support team, describing the equipment and software used to perform the experiment in a wet laboratory, as well as some instructions for preparing the organ bath. The three videos described above were originally designed to prepare students for the subsequent hands-on practical, but they could also serve to make the actual experiment more tangible, if the virtual experiment were used as a stand-alone activity.

The Simulation tab provides instructions on how to obtain an approximate measure of the changes in length of a section of ileum by measuring the amplitude of the spontaneous contractions under different conditions. It has a built-in example of the required data analysis calculations, including hints on how to measure changes in contraction “amplitude.” Only once students have worked through the example measurements correctly can they gain access to subsequent Experiment and Analysis subtabs. We made this decision based on the difficulty that students had in previous years in performing these calculations, and with the aim of ensuring they understood the procedure before moving forward with the virtual experiment.
The Experiment subtab provides an animated interactive visualization of the experimental preparation on the left, and a graph showing the measurement trace on the right (see Fig. 1). Using a drop-down box, the user chooses whether to electrically stimulate the autonomic nerves attached to the ileum section, or to add noradrenaline or acetylcholine directly to the organ bath, after which he/she can see (and measure) the effect of each of these manipulations on the spontaneous contractions of the section of ileum. Once the effects of these manipulations are measured, the user can choose to add an autonomic receptor antagonist (phentolamine or atropine) to the organ bath (by clicking on the corresponding legend entry to the right of the preparation) and repeat the measurements. Prompts to calculate the relevant amplitudes appear below the right-hand graph. Tool tips built into the graph allow the user to click on the peak values of the oscillation to display the read-out value and facilitate the amplitude calculation. Each calculation is validated behind the scenes, and values that are close enough to the true value are accepted (tolerance = 1 mV). If the user enters an incorrect value, feedback or hints display in pop-up dialogue boxes.

The percent changes in contractions, extracted and calculated from the experimental trace, transfer into a summary table in the Analysis subtab. An embedded quiz then prompts the user to interpret the results and to decide what type of autonomic nerves (i.e., sympathetic or parasympathetic) were predominantly present in their virtual preparation.

In-built variability was included in the virtual experiment, so that each time the URL is accessed (for example, when the browser is refreshed, or the student leaves the current tab and then returns), the ileum section will show a different response to the manipulations, simulating a different section of the ileum, or one obtained from a different animal. This was done so that no two students would get identical results and to encourage them all to complete the experiment.

The Interpretation tab contains an interactive animated schematic of the experimental procedure at the autonomic neuroeffector junction, created in house by the teaching support team. This interactive allows students to follow the same experimental procedures as in the preparation (and thus, indirectly, the changes in the force of contraction amplitude of a single ileum smooth muscle cell.

The “live” inquiry-based practical laboratory class. The preparation and setup for the “Neuronal Control of Gastrointestinal Smooth Muscle” practical class are almost identical to those published by Montgomery et al. (20), with some minor exceptions:

- We provided only ileum segments to students. These segments include a branch of the mesenteric artery that vascularizes the segment (with the autonomic nerves running along the adventitia). A silk thread was attached to the branch of the mesenteric artery, and this was pulled through a rubber ring containing bipolar platinum stimulating electrodes.
- We used Holman’s solution (mM): 120 NaCl, 5 KCl, 2.5 CaCl2, 1 MgSO4, 1 NaH2PO4, 25 NaHCO3, 11 glucose, and 10 sucrose, bubbled with 95% O2, 5% CO2 (carbogen).
- Students recorded isotonic contractions of the spontaneously contracting preparation. The changes in length (as the longitudinal smooth muscle contracts and relaxes rhythmically) were converted by a transducer to contractions (recorded in mV), with the amplitude of the contraction indicating the degree of length change in the preparation (and thus, indirectly, the changes in the force of contraction).

For the inquiry-based practical class, students were provided with pharmacological agents (i.e., norepinephrine, acetylcholine, the muscarinic receptor antagonist atropine, and the adrenoceptor antagonist phentolamine). They were instructed to use these drugs to design experiments that would enable them to determine what type of autonomic nerves they were predominantly stimulating to produce the changes they observed in gut motility during nerve stimulation. To make this process more challenging, the receptor agonists were not identified, and students had to work out which one was norepinephrine and acetylcholine based on their experimental results. Teaching associates checked off the hypotheses and protocols before the experiments proceeded.

RESULTS

The virtual experiment was trialed with students in 2015, and anecdotal feedback from the practical teachers indicated that it appeared to aid with student understanding of the practical objectives. This was associated with a shortening of the practical class time, presumably because students were more comfortable and familiar with the technical aspects of the experiments (as covered in the virtual experiment). This allowed the reallocation of practical time for experimental analysis and figure generation for the report, processes formerly completed independently by students after the practical class. However, the teachers indicated that students were still heavily reliant on the recipe-based nature of the practical class and its associated notes. The practical class was thus redesigned in

| Table 1. Rates of student engagement with the practical classes (attendance and practical report submission), survey response rates, and virtual experiment completion rate |
|-----------------------------------------------|
| Subject          | BMS2031 | NUT2103 | PHY2032 | Source                  |
|------------------|---------|---------|---------|-------------------------|
| Students enrolled, n | 421     | 83      | 376     | University student database |
| Practical class attendance rate, %enrolled students | 99 (417/421) | 98 (81/83) | 98 (367/376) | Entry and exit scanning of student ID cards |
| Submission attendance rate, %enrolled students | 99 (417/421) | 94 (78/83) | 89 (335/376) | No. of reports submitted |
| Response rate for the prepractical (paper-based) survey, %enrolled students | 81 (342/421) |       |         | No. of paper surveys returned |
| Response rates for the postpractical (online) survey, %enrolled students | 71 (297/421) | 86 (71/83) | 80 (300/376) | Estimation based on self-reporting from the postpractical survey |
| Completion of the virtual experiment, %student responses to postpractical survey | 92 (273/297) | 99 (70/71) | 95 (284/300) | |

n, No. of students. Nos. in parentheses are n students who participated out of n. enrolled in class for rows 2–5, and who completed the virtual experiment out of no. of postpractical surveys for row 6.
2016 such that students completed the virtual experiment first, and then attended class for an inquiry-based practical during which they designed and performed their own experiments. We also incorporated informal feedback from students on the virtual experiment to further refine and improve it.

Engagement with the practical class and virtual experiment. Response rates for all the surveys were >70% (see Table 1). Over 90% of the postpractical survey respondents from each of the three subjects reported having completed the virtual experiment. This is a high completion rate, given that the virtual experiment was optional and was not assessed. Most of the postpractical survey respondents in each subject also attended the practical class and submitted the practical report.

Data from the prepractical survey (administered only to BMS2031 students; Fig. 2) shows that only 48% of the students who responded to this survey attended or viewed all three gut physiology lectures before the practical class, with lecture attendance at each specific lecture averaging at 63% of survey respondents (data not shown). Figure 2 also shows that 87% of students reported reading the practical notes, and 89% of students reported accessing the virtual experiment. This is lower than the 92% of BMS2031 students who reported accessing the virtual experiment in the postpractical survey, presumably explained by some of the students accessing the online resource during and/or after the practical laboratory class.

As shown by Google Analytics data in Fig. 3, students from all three subjects accessed the virtual experiment before their practical class and before their practical report was due. Taken together with the survey data (Fig. 2), this shows that most students completed the virtual experiment the day before or immediately before their practical class. The data did not show increased usage of the resource before the final exam (data not shown).

Perceived value of the virtual experiment. Students indicated in the postpractical survey that the virtual experiment helped them to understand the autonomic regulation of gut smooth muscle function, and that both the virtual and the real experiments were necessary to help them understand how autonomic nerves modulate gut motility (see Table 2). They also reported that the virtual experiment helped them to prepare for the practical class, to understand the aims of the practical class, and to design their experiment during the practical class. This is supported by students’ anonymous written comments in response to the postpractical survey open-ended question: “How do you think the virtual experiment could be improved to better convey the material of the practical class?”

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**Fig. 2.** Self-reported BMS2031 student engagement (n = 421) with the “Neuronal Control of Gastrointestinal Smooth Muscle” practical class. No. of lectures (total of 3) on the practical topic attended or viewed online, time spent reading the practical notes from the practical manual, when the virtual experiment was accessed, and time spent engaging with the virtual experiment (percentage of the total survey respondents are at the top of each bar) are given.

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**Fig. 3.** “Unique views” of the virtual experiment for the Biomedical Science (BMS2031), Nutrition (NUT2103), and Science (PHY2032) students obtained from Google Analytics, with the timing of the practical classes and the practical report due date indicated in gray (practical classes were repeated over 3 days for BMS2031 and PHY2032 subjects). Each curve shows the unique page views (per device) for each day for all URLs associated with the gastrointestinal smooth muscle online activity after filtering for legitimate visits made from within Australia.
Students thought the virtual experiment was a valuable resource, as they suggested it should be completed during the practical class, or that students should not be allowed to start the practical until they had completed the virtual experiment:

“Doing it in class would be better” (BMS2031 student).
“Do not let students enter the practical if the simulation is not complete” (PHY2032 student).

However, some students felt that there needed to be better linkage between the virtual and live experiments:

“Maybe use the words ‘as in the practical’ to link it more” (BMS2031 student).

Students were asked in the postpractical survey to use three words to describe the virtual experiment. The most used words were helpful, informative, engaging, useful, interactive, and interesting (see Fig. 4).

**Table 2. Biomedical student perceptions of the virtual experiment (BMS2031)**

| Perception                                                                 | Strongly Agree and Agree | Neither | Strongly Disagree and Disagree |
|-----------------------------------------------------------------------------|---------------------------|---------|-------------------------------|
| The virtual experiment helped me understand the concepts of autonomic nerve regulation of gastrointestinal smooth muscle function. | 70                        | 26      | 4                             |
| Both the virtual experiment and the practical were necessary to understand autonomic control of gut motility. | 56                        | 32      | 12                            |
| Completing the practical was not necessary for understanding the subject content. I could have done with just the virtual experiment. | 20                        | 30      | 50                            |
| The virtual experiment helped me understand the aims of the practical class. | 77                        | 20      | 3                             |
| The virtual experiment helped me to prepare for the practical class.       | 67                        | 28      | 5                             |
| The virtual experiment made it relatively straightforward to come up with the experimental design for the practical class. | 62                        | 30      | 8                             |

Values are in percent; n = 287 students. Percentages ≥50% are in bold to simplify interpretation.

“I don’t think the simulation [virtual experiment] could be improved at all. It was sufficiently interactive enough and allowed enough problem solving to convey the material in the practical class well” (BMS2031 student).

“It’s a good application towards many practicals and gives me a much better understanding of the practicals as opposed to just reading the lab manual and basically turning up confused” (PHY2032 student).

“Very useful in helping me understanding and revise the overall concepts of the practical” (PHY2032 student).

“A clear visual way to understand and play with the mechanisms” (PHY2032 student).

Students were asked in the postpractical survey to use three words to describe the virtual experiment. The most used words were helpful, informative, engaging, useful, interactive, and interesting (see Fig. 4).

Fig. 4. Student responses to, “Write three words that you would use to describe the virtual experiments.” Each word’s size is proportional to the square root of the number of times it appeared in an answer. We used the square root instead of the actual number of repetitions to enhance the visibility of the less used words. This “word cloud” image was generated using the following online resource: https://www.jasondavies.com/wordcloud.
Effect of the virtual experiment. There was a positive correlation between the amount of time students reported spending on the virtual experiment and student performance on three out of four experimental-based questions on the prepractical survey (i.e., Q5, Q7a, and Q7b; see the Research design section for a description of these questions). This effect was not seen with the other predictors of student performance: how long they spent reading the practical class notes and how many lectures they attended or watched (see Fig. 5). It is worth noting that students completed this prepractical paper-based survey at the beginning of the practical laboratory class (before the commencement of the practical class), so the survey results were not influenced by their experiences of the “live” practical class.

Unlike the other questions on the prepractical survey, neither of the three predictors considered were significant for student performance on Q6. This question was more complicated than the other experimental questions and involved both analysis and interpretation of the data; students needed to consider both percent changes in contraction amplitude (with nerve stimulation) and the impact of the autonomic receptor blockers on this response.

We next sought to understand whether the virtual experiment and the changes in the practical activity had any effect on student’s practical laboratory report grades, on a scale from 1 to 100. Figure 6 shows the average grades for the “Neuronal Control of Gastrointestinal Smooth Muscle” written practical laboratory reports, for each subject (BMS2031, NUT2103, and Science PHY2032, shaded curves), between 2012 and 2017. Because the lecturer, lectures, and practical laboratories were the same across the three subjects in each year, we averaged grades across the three subjects to obtain one average grade per year (solid curve). The introduction of the virtual experiment had no discernible effect on grades (compare 2015 average grade to earlier years); however, there was a significant drop in the average report grade following the transition to an inquiry-based practical, accompanied by different questions and format of the practical laboratory report in 2016. The difference between any individual year from 2012 to 2015 and any individual year from 2016 to 2017 was significant ($P < 0.007$, Tukey test).

DISCUSSION

We developed a virtual experiment to support a practical laboratory class that investigates the neuronal control of gastrointestinal smooth muscle in the isolated ileum. We found that the online activity improved students’ understanding of
theory and experimental design associated with the practical class, reducing the practical duration and resulting in fewer technical issues from students’ misunderstanding of the practical notes or the equipment. This allowed us to redesign the laboratory exercise to be inquiry based, which improved engagement and helped students to develop their research skills. This finding is in line with Lewis’s recommendations (15) and is consistent with findings of other educators on the various benefits of virtual laboratories (4, 8, 10, 12, 25).

Most of the students accessed the virtual experiment for practical class preparation immediately before the practical class, with many students also accessing it before writing their practical report. This highlights how useful the students found the virtual experiment, as it was not compulsory, nor was it directly assessed. Only the amount of time students reported spending on the virtual experiments (and not lecture attendance or time reading the practical notes) was predictive of their positive performance on both conceptual and experimental (design and analysis) questions in the prepractical survey. This is the first time that virtual experiments have been documented to statistically improve students’ research skills development, including experimental design and data analysis, with previous analyses of virtual experiments focused on understanding of theoretical concepts (15).

Hughes (12) and Downie and Meadows (7) found that students who completed computer-based simulations performed as well or better than students who completed “wet” laboratory practicals in written reports and theoretical questions. Our study takes this a step further and shows that, within the same groups of students, the time spent engaging with the virtual experiment correlated with better knowledge and understanding of the conceptual and experimental skills development. In interpreting this correlation, we must consider the possibility that the more dedicated and high-performing students were more likely to engage with the virtual laboratory and spend more time on it. However, the same increased engagement of high-performing students would be expected with both the lectures and the notes from the practical manual, which did not hold predictive power. The fact that only time spent on the virtual experiment predicted improved student performance and not either of the other two potential predictors (i.e., lecture attendance/ viewing and reading the practical notes) supports the idea that the enhanced performance is due specifically to the virtual experiment.

This study was unable to determine how the virtual experiment affected student performance on the written report for the practical activity. This is because the format of both the practical class and the written reports was changed in association with the introduction of the virtual experiment. We believe that the decreased student performance on the practical reports following introduction of the inquiry-based practical class reflects an increase in difficulty for the report. In our experience, when practical activities and their corresponding reports change abruptly from year to year, there is usually a subsequent drop in student performance on the reports, although this may be due to students sharing data and reports between years.

In summary, we have developed a virtual experiment on the neuronal control of gastrointestinal smooth muscle and shown that it 1) improves students’ theoretical knowledge of the practical class, 2) facilitates students’ understanding of experimental design and data analysis, and 3) helps students to prepare for an inquiry-based practical activity. We have made the virtual experiment freely accessible to all educators and students across the world through the url: https://ilearn.med.monash.edu.au/physiology/gastro-smooth-muscle/index.html.

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

AUTHOR CONTRIBUTIONS
M.Q. and J.K.C. conceived and designed research; M.Q. performed experiments; M.Q. analyzed data; M.Q. interpreted results of experiments; M.Q. prepared figures; M.Q. and J.K.C. drafted manuscript; M.Q. and J.K.C. edited and revised manuscript; M.Q. and J.K.C. approved final version of manuscript.

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