CJLT RCAT
Canadian Journal of Learning and Technology
La Revue canadienne de l'apprentissage et de la technologie

Volume 46 (3) Fall/Automne 2020

# Virtual Lab Integration in Undergraduate Courses: Insights from Course Design and Implementation

# Intégration d'un laboratoire virtuel dans les cours de premier cycle : Aperçu de la conception et de la mise en œuvre des cours

***Maria Papaconstantinou****, University of Toronto*
***Dawn Kilkenny****, University of Toronto*
***Christopher Garside****, University of Toronto*
***William Ju****, University of Toronto*
***Hedieh Najafi****, University of Toronto*
***Laurie Harrison****, University of Toronto*

**Abstract**

The instructors of four biology-related courses at a Canadian university integrated Labster virtual labs in their courses as a pre-lab activity, lecture substitute, or to provide lab experience in courses with no on-site labs. The instructors used a backward design approach to align the labs with the learning objectives of their courses and to connect the labs with their course assessments. A study was conducted to examine students' perceptions of the usefulness of the virtual labs in terms of content knowledge and lab skills. At the end of each course, the instructors administered an anonymous survey in their classes. In total, 370 students participated. Across all four courses, survey results showed that at least 77% of the students found that virtual lab simulations helped them understand course concepts. At least 74% of the students navigated the virtual labs with no issues and 58% of the students found the simulations to be of high quality.

*Keywords*: Undergraduate course design; Biology course; Virtual training environment; Virtual lab simulation

**Résumé**

Les instructeurs de quatre cours liés à la biologie dans une université canadienne ont intégré des laboratoires virtuels *Labster* dans leurs cours comme activité préalable au laboratoire, comme substitut

de cours, ou pour fournir une expérience de laboratoire dans les cours sans laboratoire sur place. Les formateurs ont utilisé une approche de conception à rebours pour aligner les laboratoires avec les objectifs d'apprentissage de leurs cours et pour relier les laboratoires aux évaluations de leurs cours. Une étude a été menée pour examiner les perceptions des étudiants de l'utilité des laboratoires virtuels en termes de connaissance du contenu et de compétences en laboratoire. À la fin de chaque cours, les formateurs ont administré un sondage anonyme dans leurs classes, et 370 étudiants au total ont participé. Les résultats de l'étude ont montré que dans les quatre cours, au moins 77 % des étudiants ont trouvé que les simulations de laboratoire virtuel les avaient aidés à comprendre les concepts du cours. Au moins 74 % des étudiants ont navigué dans les laboratoires virtuels sans problème et 58 % des étudiants ont trouvé que les simulations étaient de haute qualité.
*Mots-clés* : Conception de cours de premier cycle, cours de biologie, environnement de formation virtuel, simulation de laboratoire virtuel.

## Objectives

In this paper, we share the findings of a pilot study that examined students' perceptions of and experiences with two-dimensional virtual labs that were integrated into four undergraduate biology-related courses at a Canadian university. This pilot study was part of a year-long initiative to increase opportunities for active learning through virtual lab integration, specifically virtual labs developed by Labster (https://www.labster.com/). To contextualize the findings of this pilot study, we also explain the curriculum design process of virtual lab integration into these four courses informed by active learning strategies.

## Related Literature

Virtual labs, where students use screen or head-mounted devices to conduct a simulated experiment, can foster active learning (Bonwell & Eison, 1991) as the students can engage in higher-order thinking skills to make meaning from the findings of their experiment. Previous studies have investigated potential changes in students' content knowledge, lab skills, and motivational factors resulting from using virtual labs. Here, we present evidence from studies that have explored cognitive and motivational effects of integrating virtual labs in a variety of undergraduate courses.

In an undergraduate clinical microbiology course, 97 students had access to an optional virtual lab that was integrated with other course activities (Goulding et al., 2016). Perceived effectiveness of the virtual labs was measured using a seven-point Likert scale survey administered towards the end of the semester, with a 66% response rate. For these students, the mean score of six survey items that explored the impact of the virtual lab was at least 6.1 (Goulding et al., 2016) suggesting that the students believed the virtual lab prepared them for on-site labs.

Ramos et al. (2016) provide a more in-depth account of the impact of virtual labs in preparing students for on-site labs. In an undergraduate chemistry course, 32 out of 120 students agreed to complete a virtual lab before an on-site lab and answer two questionnaires about the usefulness and effectiveness of the virtual lab and their perceived impact of the virtual lab on their performance in the on-site lab (Ramos et al., 2016). According to Ramos et al. (2016), responses to the post-virtual lab survey indicated that 96% of the students found the lab helped them learn about the experiment and 79% of the students anticipated that their virtual lab experience would prepare them for the on-site lab. Moreover, Ramos et al. (2016) observed that after completing the on-site lab, 87% of the students found the virtual lab activity positively contributed to their performance in the on-site lab. These results, however, were not corroborated with the students' on-site lab performance in their study.

Another study explored different facets of learning and motivation in two undergraduate biology-related courses, Course 1 and Course 2, that each used two virtual labs as supplemental resources (Dyrberg et al., 2016). Students in Course 1 were required to complete their two assigned labs before conducting on-site labs, whereas the students in Course 2 could complete the labs at any time before the course final exam. In total, 58% of the students in the two courses answered an end-of-term questionnaire that measured the impact of engaging with virtual labs on their self-reported self-efficacy, task value, and attitude towards Labster labs (Dyrberg et al., 2016). While Dyrberg et al. (2016) did not detect a significant increase in self-efficacy and task value as a result of completing virtual labs, students in Course 1 and Course 2 reported a significant increase in two subscales of self-efficacy: confidence in conducting lab procedures and comfort while using lab apparatus. As for the usefulness of the labs, 58% of the respondents believed that Labster labs could be a useful supplement to on-site labs, compared to 27% of the students who thought Labster labs could be used to replace on-site labs (Dyrberg et al., 2016).

Researchers have also compared the effects of virtual labs vs. instructor-led tutorials. To examine differences in the students' applied knowledge and skills, and the quality of their lab reports in relation to using a virtual lab, a virtual chemistry lab was developed for a mandatory undergraduate course (Bortnik et al., 2017). Fifty students in this course were randomly assigned to two groups: the experimental group which completed the virtual lab, and the control group which received traditional instructor-led tutorials in preparation for an on-site lab. Data sources for this study included students' lab reports from both groups and a post-lab content knowledge test administered to both groups. Bortnik et al. (2017) reported that the experimental group outperformed the control group in 5 out of 10 quality criteria for lab reports and gained significantly higher scores in the post-lab knowledge-based test.

Existing research suggests that virtual labs can facilitate equivalent learning outcomes, improve the student learning experience, and increase certain aspects of learner self-efficacy in undergraduate science courses. Yet, research on the effects of virtual labs on student learning is still in its infancy, with more to be explored regarding the implications of course design decisions and students' perceptions of their learning experience with virtual labs.

In this pilot study, we integrated virtual labs developed by Labster into four biology-related undergraduate courses at a Canadian university and investigated students' perceptions of the learning value, usability, and the overall effectiveness of the integrated labs.

## Curriculum Design and Pilot Study

Instructors who participated in this project taught courses in the Institute of Biomaterials and Biomedical Engineering, the Department of Cell and Systems Biology, and the Human Biology Program. The virtual labs used in this pilot study were created by Labster, a company that specializes in developing interactive two-dimensional and immersive virtual labs (Figure 1). Labster two-dimensional labs include theory pages that explain the conceptual foundations of the labs and incorporate assessment activities to reinforce learning. Students can access the labs as many times as they require during the semester. A built-in analytic system (Figure 2) allows the instructors to monitor students' access to the labs and their performance in the integrated assessments.

**Figure 1**

*Screenshot of a Smooth Muscle Lab*

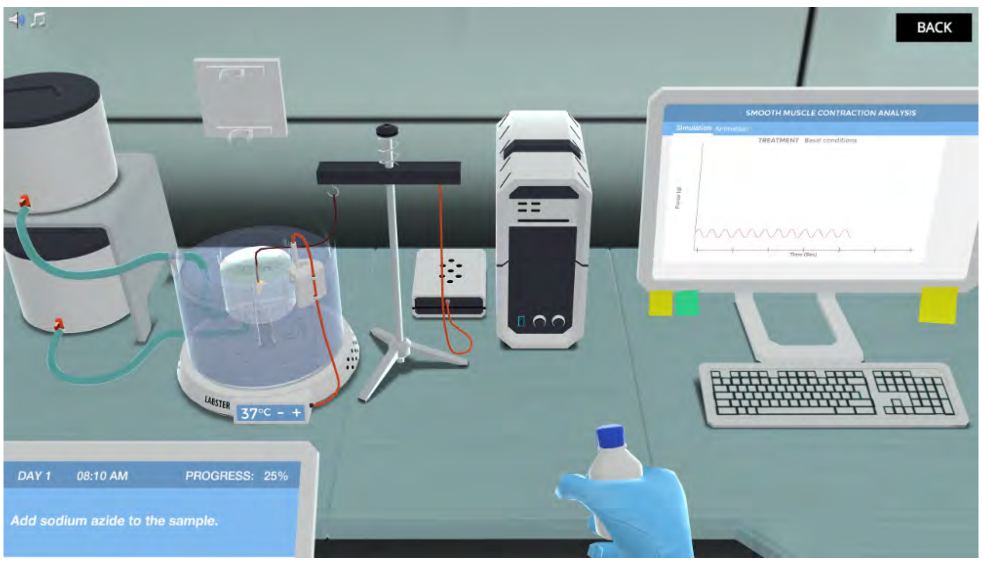


**Figure 2**

*Labster Dashboard Data Showing Students' Performance in Integrated Assessments*

| E-mail | Attempt Nur | Started at (U | Finished at (l | Time taken | Score | Max Score | Score in % | Completion % |
|---|---|---|---|---|---|---|---|---|
| 123@labster | 1 | 30-09-16 | 30-09-16 | 0:35:26 | 110 | 160 | 69 | 100 |
| 456@labster | 2 | 30-09-16 | 30-09-16 | 0:28:48 | 126 | 160 | 79 | 100 |
| 456@labster | 3 | 30-09-16 | 30-09-16 | 0:10:17 | 0 | 160 | 0 | 6 |
| 456@labster | 4 | 30-09-16 | 30-09-16 | 0:08:28 | 18 | 160 | 11 | 22 |
| 789@labster | 1 | 24-08-16 | 24-08-16 | 0:00:23 | 0 | 160 | 0 | 2 |
| 789@labster | 2 | 24-08-16 | 24-08-16 | 0:00:35 | 0 | 160 | 0 | 2 |
| 101@labster | 1 | 20-12-16 | 20-12-16 | 0:08:32 | 152 | 160 | 95 | 100 |
| 102@labster | 1 | 06-11-16 | 06-11-16 | 0:19:59 | 130 | 160 | 81 | 100 |
| 103@labster | 1 | 17-03-17 | 17-03-17 | 1:03:51 | 142 | 160 | 89 | 100 |
| 104@labster | 1 | 10-10-16 | 10-10-16 | 0:14:57 | 146 | 160 | 91 | 100 |
| 105@labster | 1 | 20-09-16 | 20-09-16 | 0:04:40 | 30 | 160 | 19 | 24 |
| 106@labster | 1 | 27-07-16 | 27-07-16 | 0:08:56 | 20 | 160 | 13 | 33 |
| 107@labster | 1 | 26-07-16 | 26-07-16 | 0:31:43 | 152 | 160 | 95 | 100 |
| 108@labster | 2 | 14-03-17 | 14-03-17 | 0:24:50 | 154 | 160 | 96 | 100 |
| 109@labster | 1 | 23-08-16 | 23-08-16 | 0:15:08 | 154 | 160 | 96 | 100 |
| 110@labster | 2 | 24-08-16 | 24-08-16 | 0:10:30 | 80 | 160 | 50 | 48 |
| 112@labster | 3 | 25-08-16 | 25-08-16 | 0:22:01 | 156 | 160 | 98 | 100 |
| 113@labster | 4 | 09-11-16 | 09-11-16 | 0:02:26 | 30 | 160 | 19 | 25 |
| 114@labster | 1 | 06-02-17 | 06-02-17 | 0:02:01 | 0 | 160 | 0 | 14 |
| 115@labster | 1 | 09-03-17 | 09-03-17 | 0:13:33 | 82 | 160 | 51 | 66 |

## Labster Labs Integration: Course Redesign

The course redesign process to integrate Labster labs in four undergraduate biology-related courses (Table 1) started in the summer of 2017. Guided by the Understanding by Design approach (Wiggins & McTighe, 2005), the instructors integrated relevant Labster labs into their courses. In a group meeting, the instructors used an alignment table template inspired by a backward design process (Wiggins & McTighe, 2005). Figure 3 shows the alignment table for one of the courses.

**Figure 3**

*An Example of a Completed Alignment Table used for Labster Lab Integration*

| Learning Outcomes | Contextualization | Labster Labs | Related Assessment |
|---|---|---|---|
| overarching learning outcomes: <br>• discuss and evaluate the progress made in understanding the genetic basis of human disease | -lecture based on the hereditary basis of cancer diagnosis, prognosis, and related therapies; --> can be flipped: lab before lecture | medical genetics simulation | questions on exam related to both lecture and lab |
| more specific learning outcomes related to the lab: <br>• compare and contrast tumor suppressor and oncogenes <br>• explain the genetic mechanisms of hereditary breast cancer <br>• examine how cancer is diagnosed i.e. tools and techniques used <br>• differentiate between Mendelian and complex traits <br>• outline how and why linkage analysis is performed | create a course wrapper around the lab, contextualize the lab in the syllabus and on blackboard ==> describe to students the importance or value of the lab and how it fits within the course. | | |

Having reviewed available Labster labs, the instructors first identified at least one desired learning outcome in their courses that would be reinforced with a Labster lab activity, then they designed new assessments or revised their existing assessments to account for the Labster lab content and learning activities. The instructors then revised their course syllabi to include an introduction to Labster labs and to reflect changes in grading policy as a result of virtual lab integration.

**Table 1**

*Undergraduate Courses Included in the Study in the 2017-2018 Academic Year*

| Course topic | Level | Class size | Labs used |
|---|---|---|---|
| Biomedical Engineering | 3rd year | 36 students | • Smooth muscle<br>• Diabetes |
| Animal Physiology I | 2nd year | 200 students | • Smooth muscle<br>• Cellular respiration<br>• Diabetes*<br>• Carbohydrates*<br>• Enzyme kinetics*<br>• Protein denaturation* |
| Neurogenomics | 3rd year | 95 students | • iPSCs & viruses<br>• Next generation sequencing |
| Genetics of Human Disease | 4th year | 50 students | • Next generation sequencing<br>• Medical genetics<br>• Gene regulation |

* Optional labs

Labster lab integration served different purposes across the four courses: pre-lab activity; lecture substitute; extending current teaching; or providing lab work opportunity where no labs were previously available. For each course, we highlight Labster lab integration rationale and specific changes in grading policy where relevant.

In the Biomedical Engineering course, two labs were integrated. The Smooth Muscle Lab replaced one lecture to prepare students for the upcoming lecture. This lab provided an inverted activity where students completed the Smooth Muscle Lab on their own and later discussed the simulation in class. Completion of this lab contributed to 10% of the grade for a project-based learning activity. The Diabetes Lab was integrated as a pre-lab activity prior to an on-site lab and contributed 25% to the on-site lab assessment grade. The final exam contained questions specific to the two Labster labs.

The Animal Physiology course had two required and four optional Labster labs. The two required labs contributed 2% participation points if the students completed them with a minimum score of 50% for each lab. Note that the students could attempt the labs multiple times before submitting their results and marking the labs as completed. This allowed them ample opportunity to gain proficiency with the lab activity and to improve their answers to the integrated questions. Both the midterm and final exams included questions specific to the two Labster labs.

Three Labster virtual labs were integrated in the Genetics of Human Disease course in an inverted manner as pre-lecture activities. With a minimum score of 50% required for each lab, Labster lab completion counted as participation and contributed 10% in total towards the final course grade. Questions related to lab content were included in both midterm and final exams.

The instructor of the Neurogenomics course integrated Labster labs as supplemental material that students could complete before the end of the semester. The final exam included questions related to the two integrated labs.

Labster labs were integrated via single sign-on within course shells in the Blackboard Learning Management System (LMS), the university's main LMS at the time of conducting this pilot study. Students could access the labs through their course website and the instructors retrieved student access and performance data from the LMS dashboard.

### Data Collection

The instructors obtained ethics approval to examine students' overall perception of the labs. Data was collected through an anonymous end-of-semester survey with 10 multiple-choice questions and one open-response question (Appendix 1). The survey questions asked students to rate Labster lab integration from "Excellent" to "Very poor" on two dimensions: learning affordance and user experience. The instructors slightly modified the survey for each course. The survey response rate for each course was: 100% in the Biomedical Engineering course, 96.8% in the Neurogenomics course, 80% in the Genetics of Human Disease course, and 24.5% in the Animal Physiology course. Note that the Animal Physiology course had the largest number of students enrolled and the voluntary survey in this course was administered online.

## Findings

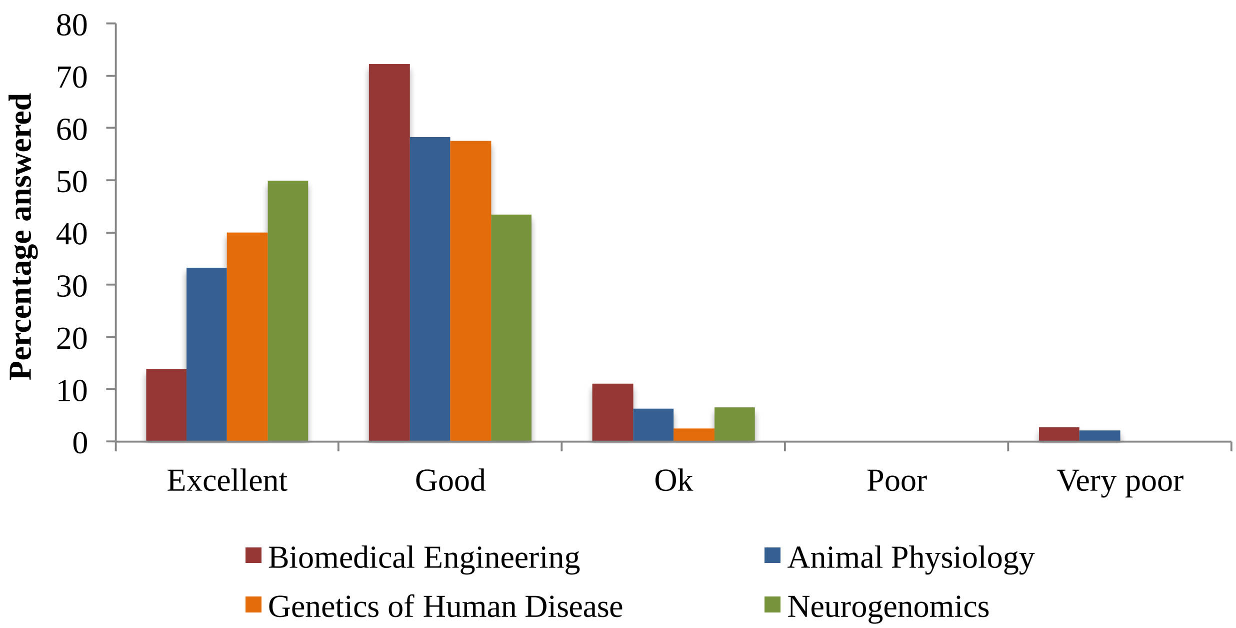
We presented our findings in three sections: students' perception of the integrated Labster labs' learning affordance, students' perception of user experience with the integrated Labster labs, and students' reflections on learning with virtual labs. We complemented the quantitative data from close-ended questions with qualitative data from the open-response question.

### Learning Affordance

Labster virtual labs included a theory section that explained the conceptual underpinnings of the labs. In their meetings, the instructors pointed to the high quality of the theoretical content. One survey question elicited students' perception of the effectiveness of the theory pages regarding understanding course concepts. Figure 4 shows that on average and in all four courses, almost 58% of the students rated the quality of theory pages as "Good", with an average of 34% of the students in the four courses rating the theory pages as "Excellent".

**Figure 4**

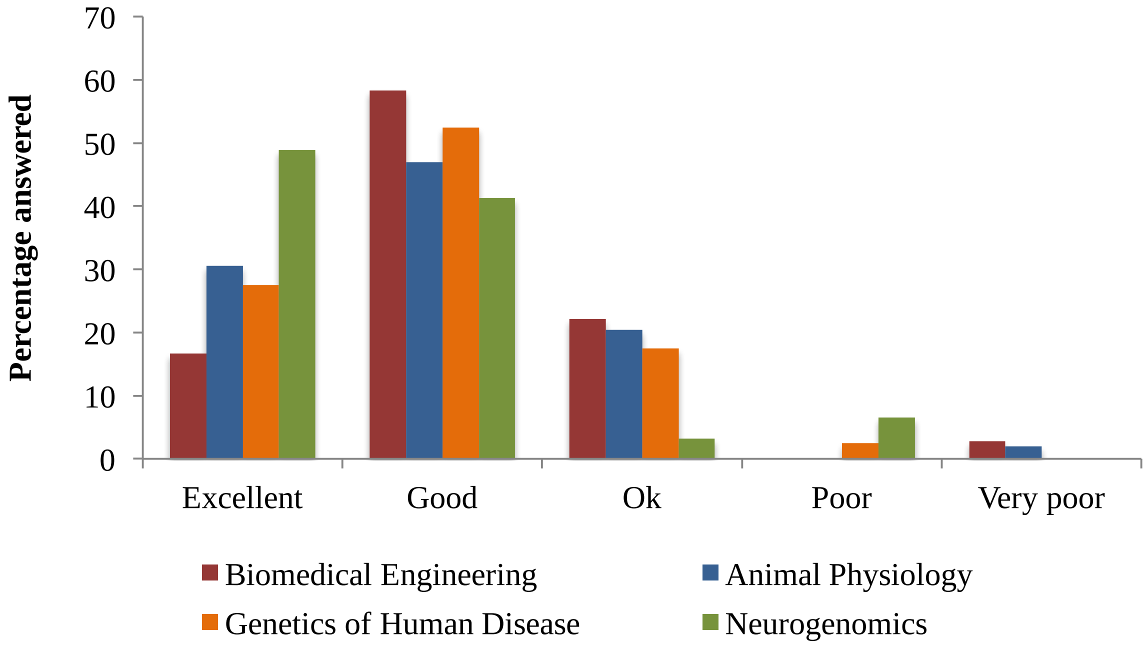
*Effectiveness of the Integrated Theory Pages*




Students also rated their perception of learning from Labster lab simulations. In all four courses, almost 31% and 50% of the responding students chose "Excellent" and "Good", respectively (Figure 5), to express their perception of how useful the simulations had been to their understanding of course concepts. In their open-response comments, students described Labster labs as enjoyable and relevant to the course they were taking. A follow-up survey question in three courses asked students about their overall confidence in the subject matter of the course considering their virtual lab simulation experience. More than 50% of the students in each course rated their confidence in course subject matter as "Good". Two students pointed out that lab animations helped them learn the concepts much more effectively than conventional course material. Other students added that the presentation of material facilitated the review of lab concepts and that it was more convenient to take notes of the process compared to taking notes in an on-site lab.

**Figure 5**

*Effectiveness of Simulations in Understanding of Course Concepts*

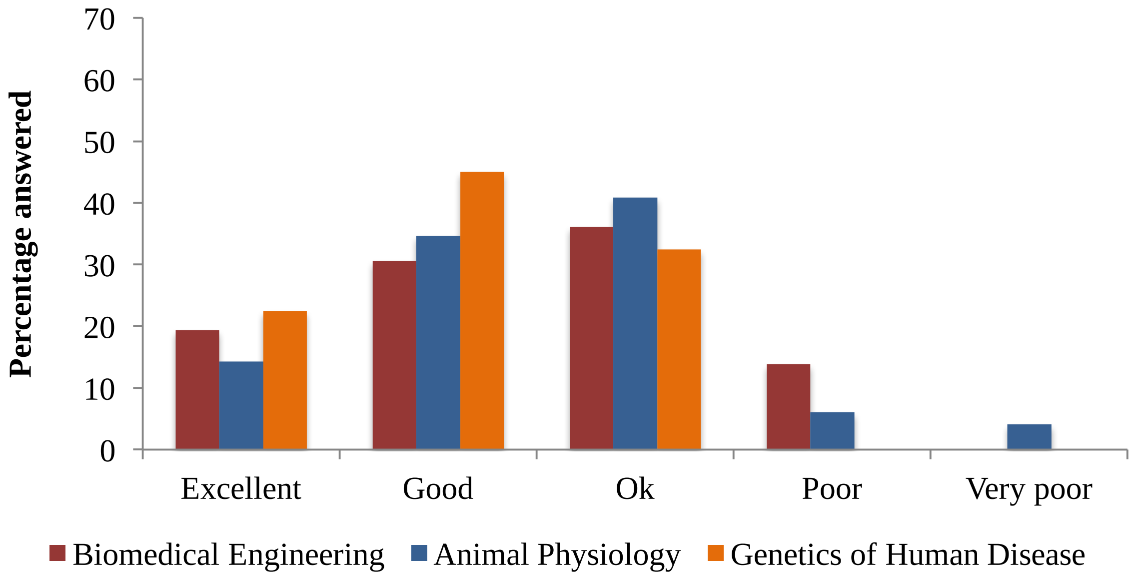



A significant promise of virtual labs is for the students to develop lab skills where on-site labs either do not exist or are logistically difficult to access multiple times during the semester. Thus, the survey asked students about their level of confidence in their lab skills after completing the virtual labs. As Figure 6 shows, close to 37% and 36% of the students in three courses chose “Good” and “Ok”, respectively, to reflect their level of confidence. We compared these results with students’ responses to another question about their perceived confidence in the subject matter of the course after completing the simulations. For this question, almost 52% of the students in all three courses chose “Good” while close to 23% rated their confidence as “Ok”. Survey data suggests that the integrated virtual labs were slightly more effective in reinforcing course concepts. Note that the students in the Neurogenomics course did not receive this question.

In their open-response comments, one student stated that these virtual labs could prepare them for on-site labs. However, another student explained that Labster labs would not replace conducting the same or similar labs on-site, rather suggesting that virtual labs could be used as supplements and not replacements.

**Figure 6**

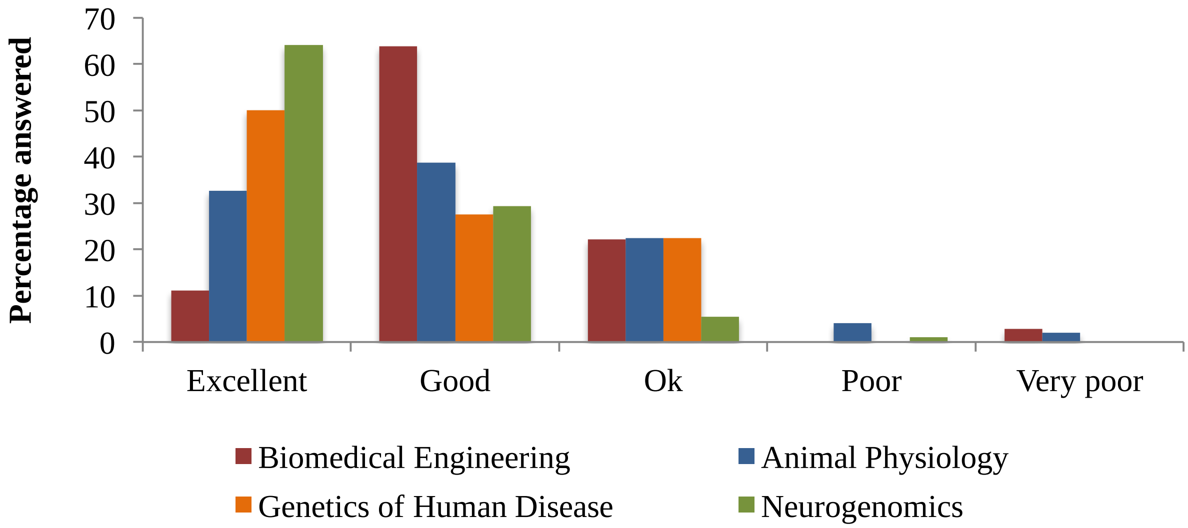
*Level of Confidence in Lab Skills After Completing the Virtual Labs*




Students in all four courses answered a survey question about their perception of how effective virtual labs were as a way of learning. As Figure 7 shows, 39% of all students rated the effectiveness of virtual labs as “Excellent” followed by almost 34% of the students rating the effectiveness as “Good”. The survey in the Biomedical Engineering course included two additional questions on the effectiveness of the labs as a pre-lab activity and lecture substitute. We calculated the average percentage for both questions for each scale. For both questions, on average 39% of the students selected “Excellent” or “Good” while 41% of the students rated the effectiveness of virtual labs as “Ok”.

**Figure 7**

*Labster Simulations as an Effective Way to Learn*

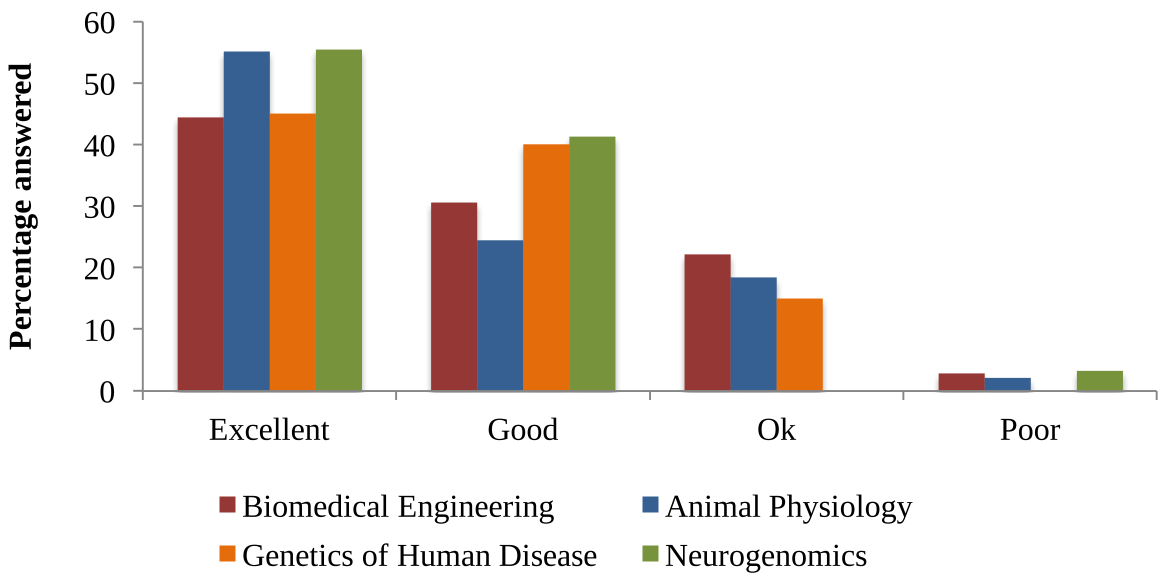



**User Experience**

The virtual labs were developed by the Labster company and, at the time of this study, were offered in a standard format provided through their hosted service. The instructors were interested to discern if the design of the virtual lab simulations impacted students' experience when conducting the selected simulated labs. At least 74% of the students in each course rated their experience navigating the labs as "Excellent" or "Good" (Figure 8).

**Figure 8**

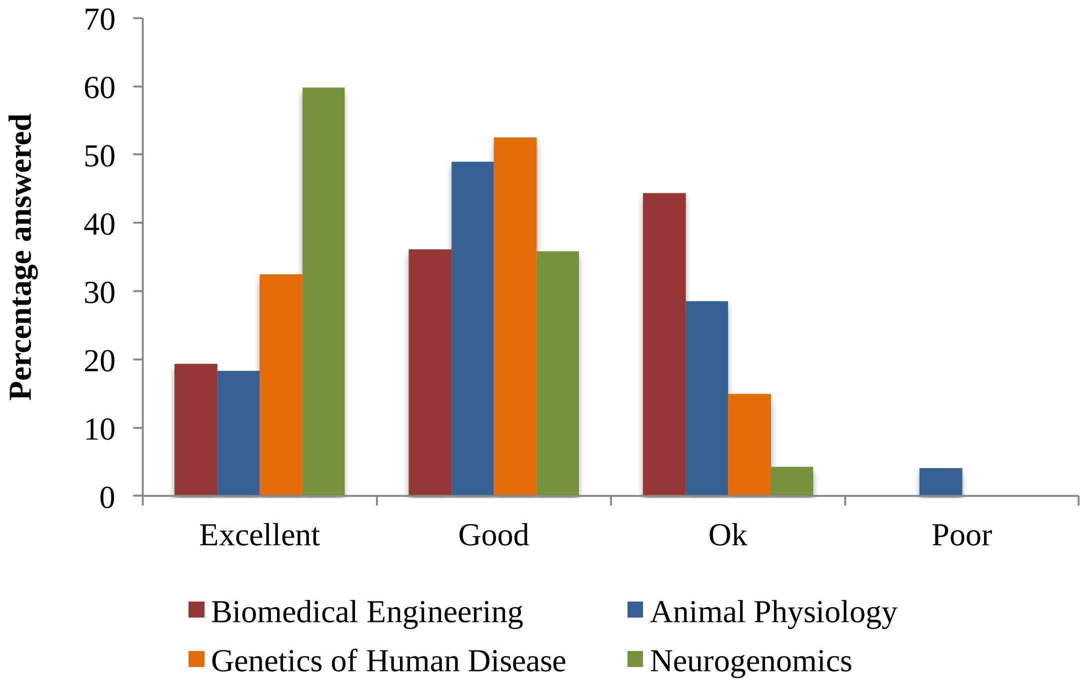
*Ease of Navigating the Virtual Labs*



Students' perceptions of interactivity and their level of engagement with the labs were less favorable, with a larger percentage of students selecting "Good" and "Ok" options. Figure 9 shows that 44% of the students in the Biomedical Engineering course rated their engagement as "Ok". With an engineering background, it is possible that these students identified areas of design improvement in the selected virtual labs. The individual design of each lab could also contribute to students' responses. For example, more than 95% of the students in the Neurogenomics course perceived lab interactivity as "Excellent" or "Good". These students completed two different labs.

**Figure 9**

*Students' Perception of Interactivity and Engagement with the Virtual Labs*




Students' open-ended responses provided additional insight into their experience with Labster labs. Open-response comments indicated that while running the virtual labs, students noticed their device overheated, the Labster application crashed, or that they experienced glitches and lags. A software design-related critique was that to move from one bench to another while completing the labs, students had to leave the lab and then navigate to the new bench. Thus, the students suggested a more seamless transition within the virtual lab environment. Another student noticed that conventional safety protocols were not followed in one of the virtual labs.

## Suggestions for Improvement

In the open-response survey question, the students suggested several ways in which the virtual labs could be improved. Most of the suggestions were geared towards the design of the virtual labs as opposed to the instructors' educative design and integration strategies. For example, the students requested the option to save their work and resume it later. Another student suggested that in-lab quizzes be more closely related to the theory content because the students could guess the correct answer without having to review the theoretical content. As we explained in the instructional design section, lab completion counted towards participation in course grading policy. Pointing out the time it took them to complete the labs, one student suggested that virtual lab completion be assigned more weight towards the final course grade.

## Discussion and Future Work

Simulations and virtual labs can increase students' access to interactive lab experiences where on-site labs are limited, non-existent, or unavailable. Some of the courses in the present study already included on-site labs while two of them had no existing on-site labs. We had contextualized the selected Labster virtual labs in our courses so that the labs connect with learning outcomes, other learning activities, and course assessments. Findings suggest that students generally perceived they benefited from the integrated virtual labs as the labs helped them enhance their knowledge of course concepts and develop their lab skills. Our results are in accordance with previous studies regarding students' attitude towards, and perceived learning value of, virtual labs (Coleman & Smith, 2019; Goulding et al., 2016; Ramos et al., 2016). We posit that aligning the Labster virtual labs with other course components may have contributed to students' positive perceptions. However, we refrain from further comparisons between the findings as curriculum design considerations, learning affordances, and technological specifications of the integrated virtual labs may impact students' experience.

Students in these four courses viewed their experience with virtual labs positively with none of the survey questions receiving a majority negative response. Also, the findings from an additional survey question incorporated by two instructors showed that at least 80% of students in the Animal Physiology course and the Genetics of Human Disease course indicated their willingness to use Labster virtual labs in their future classes (results not shown). Virtual labs can further empower students to become self-directed learners and, as one student pointed out, they enjoyed the flexibility in time that the virtual labs offered. Bortnik et al. (2017) also indicated that learners who used virtual labs to prepare for on-site labs produced higher quality lab reports. Another benefit of virtual labs is that students can repeat the labs as many times as needed. In an experimental study, Makransky et al. (2016) found that the median amount of time the students in the experimental group spent in the virtual lab environment was 56 minutes, whereas the instructor-led tutorials for the control group would not exceed 20 minutes. An implication of the Makransky et al. (2016) study could be that high quality virtual labs can reduce the resources needed for in-person tutorial sessions.

The effectiveness of each integration modality or the impact of course level or course discipline could be investigated in depth, yet was beyond the scope of this pilot study as we only scratched the surface of research addressing learning with virtual labs in undergraduate courses at our institution.

In March 2020, in response to the COVID-19 pandemic, the university where this pilot study was conducted moved the majority of courses from in-person to online delivery mode, resulting in over 1,300 online undergraduate courses being offered in the summer of 2020. In this context, one advantage of virtual lab integration becomes more pronounced: providing access to lab experience where on-site labs are unavailable. Many higher education institutions experienced this shift in delivery mode and the imposed restrictions for students and instructors to be physically present on campus. As reflections on and experiences with integrating virtual labs to provide lab opportunities in the face of COVID-19 restrictions surface in the literature (Callaghan et al., 2020; Mitchell, 2020), we note the importance of alignment between learning objectives and the selected virtual labs.

The main source of data in our study was students' perceptions of their experience. Thus, we could not connect these subjective measures to objective evidence such as responses to lab-related questions on midterm or final exams or pre-lab and post-lab tests in order to measure knowledge and skill gains. We recommend future studies that integrate objective measures of learning to complement students' perceived learning.

## References


Bonwell, C. C., & Eison, J. A. (1991). Active learning: Creating excitement in the classroom. (ED340272). ERIC. https://files.eric.ed.gov/fulltext/ED336049.pdf

Bortnik, B., Stozhko, N., Pervukhina, I., Tchernysheva, A., & Belysheva, G. (2017). Effect of virtual analytical chemistry laboratory on enhancing student research skills and practices. *Research in Learning Technology, 25.* https://doi.org/10.25304/rlt.v25.1968

Callaghan, N. I., Khaira, S., Ouyang, A., Cadavid, J. L., Chang, H. H., Co, I. L., Diep, P., Ivanov, N., Li, G., Tran-Nguyen, N., Smith, C., Davenport Huyer, L & Kilkenny, D. M. (2020). Discovery: Virtual implementation of inquiry-based remote learning for secondary STEM students during the COVID-19 pandemic. *Biomedical Engineering Education, 1*(1), 87-94. https://doi.org/10.1007/s43683-020-00014-z

Coleman, S. K., & Smith, C. L. (2019). Evaluating the benefits of virtual training for bioscience students. *Higher Education Pedagogies, 4*(1), 287-299. https://doi.org/10.1080/23752696.2019.1599689

Dyrberg, N. R., Treusch, A. H., & Wiegand, C. (2016). Virtual laboratories in science education: students' motivation and experiences in two tertiary biology courses. *Journal of Biological Education, 51*(4), 358-374. https://doi.org/10.1080/00219266.2016.1257498

Goulding, H. M., Kay, R. & Li, J. (2016). Assessing the impact of a virtual lab in health care education. In *Proceedings of E-learn: World conference on e-learning* (pp. 923-928). Washington, DC, United States: Association for the Advancement of Computing in Education (AACE). https://www.learntechlib.org/primary/p/174023/

Makransky, G., Thisgaard, M. W., & Gadegaard, H. (2016). Virtual simulations as preparation for lab exercises: Assessing learning of key laboratory skills in microbiology and improvement of essential non-cognitive skills. *PloS One, 11*(6), e0155895. https://doi.org/10.1371/journal.pone.0155895

Mitchell, J. E. (2020). How do we think about labs and practical skills in an online context? In B. Gibbs, & G. C. Wood (Eds.), *Emerging stronger: Lasting impact from crisis innovation* (pp. 35-50). Engineering Professors' Council. http://epc.ac.uk/wp-content/uploads/2020/08/Gibbs-Wood-eds-2020-Emerging-Stronger.pdf

Ramos, S., Pimentel, E. P., Marietto, M. des G. B., & Botelho, W. T. (2016). Hands-on and virtual laboratories to undergraduate chemistry education: Toward a pedagogical integration. 2016 IEEE Frontiers in Education Conference (FIE). https://doi.org/10.1109/fie.2016.7757580

Wiggins, G. P., & McTighe, J. (2005). *Understanding by design.* ASCD.

# Appendix 1: Generic End of Term Survey

1. How would you rate the effectiveness with which course concepts were explained in the Labster simulations?
    a. Excellent
    b. Good
    c. Okay
    d. Poor
    e. Very poor

2. How would you rate the extent to which these online simulations improved your understanding of important course concepts?
    a. Excellent
    b. Good
    c. Okay
    d. Poor
    e. Very poor

3. How would you rate the extent to which these online simulations improved your application of important course concepts to real world cases?
    a. Excellent
    b. Good
    c. Okay
    d. Poor
    e. Very poor

4. How would you rate the ease at which you were able to navigate through these online simulations on your own?
    a. Excellent
    b. Good
    c. Okay
    d. Poor
    e. Very poor

5. How would you rate the interactivity and your level of engagement with the online simulations?
    a. Excellent
    b. Good
    c. Okay
    d. Poor
    e. Very poor

6. How would you rate your confidence in the subjects after completing the online simulations?
    a. Excellent
    b. Good
    c. Okay
    d. Poor
    e. Very poor

7. How would you rate your confidence in your laboratory skills after completing the online simulations?
    a. Excellent
    b. Good
    c. Okay
    d. Poor
    e. Very poor

8. How would you rate your critical thinking and evaluation skills after completing the Labster simulations?
    a. Excellent
    b. Good
    c. Okay
    d. Poor
    e. Very poor

9. How would you rate the contribution of the online simulations to the value of your learning in the course?
    a. Excellent
    b. Good
    c. Okay
    d. Poor
    e. Very poor

10. In general, how would you rate the Labster simulations as an effective way to learn?
    a. Excellent
    b. Good
    c. Okay
    d. Poor
    e. Very poor

11. Do you have any other comments or suggestions about the Labster simulations?

**Authors**

Dr. Maria Papaconstantinou is an Associate Professor, Teaching Stream in the Human Biology Program at the University of Toronto. She teaches courses in a variety of disciplines, including genetics, global health, and translational medicine. Her current research interests lie in the examination of the impact and effectiveness of various pedagogical approaches on undergraduate learning outcomes, including blended learning strategies, genetics animations, and the use of virtual and augmented reality.
Email: m.papaconstantinou@utoronto.ca

Dr. Dawn Kilkenny is an Assistant Professor, Teaching Stream in the Faculty of Applied Science & Engineering at the University of Toronto. She holds a Dean's Emerging Innovation in Teaching Professorship and was the 2016 Sanford Fleming Foundation Wighton Fellow, recognizing excellence in development and teaching of undergraduate laboratory-based courses in Canadian programs.
Email: dawn.kilkenny@utoronto.ca

Dr. Chris Garside is Associate Professor, Teaching Stream in the Department of Cell and Systems Biology at the University of Toronto and teaches courses in animal physiology and cell and molecular biology. His research interests include the exploration of, and investigation into, innovative and evidence-based approaches to improve teaching, learning, and engagement.
Email: chris.garside@utoronto.ca

Dr. William (Bill) Ju M.Sc., Ph.D. is an Associate Professor, Teaching Stream in the Human Biology Program at the University of Toronto. His pedagogical interests include the use of AI to inform teaching and incorporating EDI in courses. Email: wmyh.ju@utoronto.ca

Dr. Hedieh Najafi is a researcher with Online Learning Strategies at the University of Toronto. Her research interests include scaffolding technology supported collaborative learning, pedagogical design for self-directed online learning, and learning in virtual environments including virtual labs.
Email: hedieh.najafi@utoronto.ca

Dr. Laurie Harrison is the Director, Online Learning Strategies at the University of Toronto and provides strategic advice regarding digital learning initiatives, faculty development, and program evaluation. Her Ph.D. at the Ontario Institute for Studies in Education explored e-learning policy and strategy development in Ontario with a focus on response to rapid social change.
Email: laurie.harrison@utoronto.ca