

Impact of Laboratory Exercises on Undergraduate Learning Outcomes in Online STEM General Education Courses Among Working Adult and Returning Students

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Abstract

Fully online courses and degree programs are popular with students. These courses should provide the rigor and value of traditional learning in a face-to-face classroom to ensure mastery of concepts and learning objectives. This research expands previous work to investigate the effectiveness of online laboratory exercises in enhancing student understanding of core concepts taught in fully online introductory astronomy, physics, and biology courses. Identical classes, with or without an online laboratory, were compared to determine gains in content mastery. A Likert-style survey was also used to quantify student perception of the laboratory component for those courses and measure overall student satisfaction. Results indicated astronomy and physics students in online laboratory courses showed significant gains in mastery of learning outcomes, thereby demonstrating effectiveness; biology students in online courses showed more mixed results. Further, surveys indicated student perceptions strongly support the belief that the labs helped to learn the course material and labs were an effective “hands-on” experience, directly contributing to student satisfaction in all disciplines studied. As such, this study represents an assessment of the effectiveness of different online course designs in achieving student mastery and satisfaction.

Keywords: Online laboratory, student satisfaction, student mastery of learning outcomes, STEM education, online learning

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Online options in higher education are becoming more common and increasing in market share, with 61% of undergraduate students taking at least one distance education course as of fall 2021 (U.S. NCES, 2023). Online learning options offer flexibility for adult and returning learners and opportunities for advancement for working professionals and active-duty military service members. Online learning also attracts technology savvy younger generation students who are more comfortable using virtual learning methods. Online courses and degree programs are an integral part of educational systems today and are considerably more prevalent following the COVID-19 pandemic.

Prior Work Review

The effectiveness of online learning experiences compared to face-to-face experiences has been studied for years, with results helping to inform curriculum development, guide teaching strategies, and improve experiences for instructors and students. Several studies have compared online and face-to-face learning environments with consistent conclusions. Johnson identified that students achieved learning outcomes at similar levels, although online learners reported different perceptions of instructor and course quality (Johnson, 2000). Lovern demonstrated that assessment of student achievement of learning outcomes could not be distinguished between online, hybrid and face-to-face learning environments (Lovern, 2011). Some studies have extended this research to laboratory experiments, concluding that online laboratory experiments were as effective and, in some cases, more effective than hands-on laboratory experiments, with results varying depending on the specifics of the laboratory exercises and their role within the course (Darrah et al., 2014; Corter et al., 2011; Brinson, 2015). Implementation of laboratory experiments in introductory science courses presents unique challenges. Course designers and instructors must decide between which lab content to use and how to employ it; some research indicates that laboratory assignments focused on teaching experimental techniques are more valuable than those reinforcing classroom instructions (Holmes and Wieman, 2018.)

As online options increase in scope as well as student numbers, it is vital to ensure the quality of education is comparable to that provided by traditional learning experiences. This study focuses on Science, Technology, Engineering, and Mathematics (STEM) learning in the online environment and evaluates the efficacy of online laboratory exercises as a means of augmenting student mastery of core concepts in fully online, introductory STEM classes.

Phase 1 of this research focused on the use of fully online laboratory exercises in virtual introductory astronomy classrooms (see Miller & Carter, 2023). The astronomy classes targeted in Phase 1 were 100-level survey-style general education courses. The textbook, lecture materials, assessments, teaching pool, and student population were identical for the classes; the only difference was whether the classes included online laboratory exercises. Phase 1 evaluated student quiz results from the first (pre-quiz) and last (post-quiz) weeks of class, comparing learning gains between classes that did/did not include laboratory exercises. The quiz questions were identical in both sets of classes and in both the pre- and post- quizzes; they were designed to evaluate core topics covered by the lecture and readings in both classes but emphasized by the labs. All students were expected to master these core topics, which were directly linked to course learning outcomes, but students in the lab sections received supplemental exposure to the topics through completing the labs. The goal of Phase 1 was to determine whether online laboratory exercises were an effective means of increasing student learning gains in a virtual classroom

setting in the introductory astronomy courses. Student enjoyment and perception were also assessed through a Likert-style survey.

A total of 331 students participated in Phase 1 of this study, with 186 from the non-lab classes and 145 from the lab classes. The results from Phase 1 demonstrated significant gains in assessment scores for students who participated in the classes, which included the labs compared to their peers in the classes without labs, suggesting that the online lab exercises effectively increased content mastery. Student reception to the labs was evaluated and showed a strong perception of both the effectiveness of the online labs as a learning tool as well as increased enjoyment of the online class experience when labs were included. These perceptions were universal and not directly linked to measured student performance; in other words, students enjoyed the labs and believed that they increased understanding of the material regardless of individual student learning gains in the course.

The labs in Phase 1 represented three different styles. The first lab style were fully pre-designed simulation-based laboratory exercises, available on the Astronomy Education at the University of Nebraska-Lincoln website (<http://astro.unl.edu>) through the Nebraska Astronomy Applet (NAAP). These labs include detailed instructions and supplemental/background reading material to help students better understand the labs and concepts. The second style were exercises created by the course designer centered around web-based astronomy simulations. These included instructions but no background/supplemental information. The third style were exercises created by the course designer using open-access astronomical databases. These labs included only basic instructions, allowing students freedom to investigate correlations within the data. Phase 1 results indicated that the style of online lab was a key factor in the efficacy of the laboratory experience, and that labs with a component of realism, e.g., those that allowed the students to use astronomical datasets as opposed to simulated data from virtual lab exercises, resulted in the highest gains in student learning (see Miller & Carter, 2023 for further details on Phase 1).

The current phase of this research study, reported here, focuses on STEM learning in the online environment and evaluates the efficacy of online laboratory exercises as a means of augmenting student mastery of core concepts in fully online, introductory STEM classes across three different disciplines. The current work expands upon the results presented in Phase 1 by evaluating the impact of adjunct virtual lab exercises on the students' ability to meet learning outcomes in online introductory biology and physics courses. New results for the introductory astronomy courses are also discussed.

Literature Review

Overview

Laboratory exercises provide significant value as part of a science curriculum. Phase 1 of this work discussed above explored the integration of online laboratory exercises in fully online introductory astronomy courses, comparing classes with and without virtual labs, finding that simulated hands-on experiences are effective supplements to traditional learning components in online education (Miller & Carter, 2023). Phase 1 of this study confirmed previous work indicating that laboratory exercises increase student performance in science courses (Marino, 2018, Bandura et al., 1996). Additionally, laboratory exercises offer the students who benefit

from different instructional approaches options to learn material in a way that's best suited for them (Marino, 2018).

Laboratory experiments are not limited to the use of hands-on materials—virtual laboratory experiments can be performed using software simulation as explored by Cancilla and Albon, who addressed the transition of science labs from traditional to online, reviewing the various challenges and noting the growing interest in online labs across many disciplines (Cancilla & Albon, 2008). These virtual laboratory experiments have advantages and disadvantages when compared with the traditional hands-on laboratory experiments. Virtual laboratory experiments are less expensive and more convenient to perform (Bhargava et al., 2006; Lynch & Ghergulescu, 2017; Heradio et al., 2016). Virtual laboratory experiments also provide accessibility options; they are particularly effective for students with disabilities (Lynch & Ghergulescu, 2017). Despite these advantages, virtual labs do not expose students to the use of laboratory equipment, experiment set up and the challenges of dealing with real world data (Lynch & Ghergulescu, 2017; Lewis, 2014).

Online Laboratory Exercises in Astronomy Courses

Research on the use of virtual laboratory exercises in astronomy courses is consistent with the general findings discussed above. Beznosko et al. (2021) documented high student satisfaction when transitioning their introductory astronomy courses to virtual laboratory exercises as part of an initiative to reduce student financial burden and increase collaboration. Similarly, Vogt et al. (2013) found that students using online astronomy labs that included image and spectra analysis performed at least as well as their on-campus counterparts. Khorolskyi (2023) also showed that the improved student perception of the course due to the interactive aspect of virtual laboratory exercises was a major factor in students' improved performance. Together, these studies support the conclusion that the use of virtual laboratory exercises in astronomy courses contributes positively to students' achievement of learning outcomes. However, confidence in the conclusions drawn from these studies could be strengthened with larger samples and the use of quantitative measurements of achievement instead or in addition to qualitative assessments such as student satisfaction.

Online Laboratory Exercises in Physics Courses

Similar data exists for the use of virtual laboratory exercises in physics courses. Darrah et al. (2014) studied the use of physics laboratory exercises to reinforce concepts presented in classroom lecture-based instruction confirms that the use of virtual labs can be at least as effective as hands-on labs. Taghavi and Colen (2009) found that the computer simulation exercises resulted in students learning more when used with traditional course material. Sokoloff et al. studies the use of Real Time Physics, a virtual laboratory tool that improved students understanding of introductory physics concepts (Sokoloff et al., 2007). Campbell et al. (2004) examined the performance of groups of students who were assigned to either physical labs or a combined virtual/physical lab, finding that students in the virtual/physical lab group performed as well as their counterparts. These studies confirm the effectiveness of virtual laboratory exercises and provide quantitative data regarding how students performed with meaningful sample sizes. However, there are some gaps in these studies that provide opportunities for future research. These studies are limited in their scope to classes during a short duration, potentially exposing results to variations that may occur over a longer time period. Also, it is unclear if the

population of students participating in these studies consists of adult or traditional learners and how the conclusion may be affected by differences between those groups.

Online Laboratory Exercises in Biology Courses

The use of virtual laboratory exercises in biology courses has also been researched, and conclusions support the idea that virtual laboratory exercises are effective when compared with a face-to-face approach. One study assessed student perceptions of the effectiveness of virtual exercises alongside other students who performed similar exercises in person and identified that most students found the virtual content to be effective (Stuckey-Mickell and Stuckey-Danner, 2007). Additionally, Delgado et al. (2021) confirmed that virtual laboratory experiments allow more focus on concepts and reduce inefficiencies related to lab set (Delgado et al., 2021). Renna and Kumbaraci (2022) also investigated the effectiveness of virtual biology laboratory experiments and concluded that online laboratory experiments were effective in improving student performance. Finally, Son et al. (2016) compared the use of virtual labs and traditional labs in an undergraduate biology course, finding that the use of virtual labs resulted in higher grades and improved students' perception of the course overall. Together, these studies provide a strong basis for the validity of virtual laboratory exercises in biology courses. Similarly to the other areas reviewed, research to date indicates a need for more quantitative analysis with representative sample sizes, a deeper dive into the differences in responses based on the type of learners using the virtual laboratory exercises and increased focus on the type of virtual laboratory exercises used.

Literature Review Conclusion

In conclusion, research on the use of virtual laboratory exercises confirms the benefits of integrating these exercises into science curricula by showing the improved student performance, an opportunity for increased flexibility and access, and an increase in positive student perception of the course. These exercises provide students with an instructional approach that can be central to a curriculum or complement non-laboratory classroom material. Conclusions from these studies can be strengthened by increased emphasis on quantitative over qualitative assessments. For instance, Son et al.'s (2016) biology study used 748 students, while Taghavi and Colen (2009) explored physics education with a small group of 22 participants. In some cases, studies did not explicitly identify the number of participants or data points analyzed. These ranges highlight the need for expanded sample sizes in future studies that explore the use of virtual laboratory exercises in science courses.

Additionally, the reviewed studies show a mix of quantitative and qualitative approaches to draw conclusions. Quantitative methods were seen in studies from Darrah et al. (2014), Sokoloff et al. (2007), Taghavi and Colen (2009), and Vogt et al. (2013), with those studies focusing on statistical analysis of exam scores. Qualitative methods were seen in studies by Son et al. (2016), Renna and Kumbaraci (2022), Stuckey-Mickell and Stuckey-Danner (2007), Beznosko et al. (2021), Khorolskyi (2023) and Delgado et al. (2021). These studies explored student perceptions, providing descriptive reviews of students' perceptions about online laboratory exercises in science courses. While both approaches contribute valuable perspectives, future studies focusing on quantitative data can provide relationships between student outcomes and more detailed factors such as laboratory exercise types and relationship with specific course content.

Additional opportunities exist for research where student populations are more diverse, particularly in the type of learners (adult or traditional). Some of the reviewed studies addressed traditional and non-traditional learners, such as Vogt et al. (2013) who compared outcomes between online learners (considered non-traditional, typically older) and traditional learners (typically younger) in astronomy education. Other studies, such as Darrah et al. (2014), Sokoloff et al. (2007), Taghavi and Colen (2009), and Renna and Kumbaraci (2022), did not explicitly specify student demographics beyond their quantitative analyses. Future studies are needed to identify opportunities for implementation of virtual laboratory exercises depending on the type of student.

Materials and Methods

Research Questions

Research questions for this study mirror those from Phase 1, focusing on the core idea that including simulated laboratory exercises in online introductory STEM classes increases student mastery of core concepts taught in the class, thus enhancing the learning experience.

Question 1. Does the inclusion of online laboratory exercises significantly increase student mastery of core concepts in biology, physics, and astronomy courses?

Question 2. Are online laboratory exercises which include aspects of realism more effective at promoting student mastery of core concepts than simulation-based labs?

Question 3. Do online laboratory exercises increase perceived student mastery of core concepts, as reported by the students, and how does this vary by discipline?

Question 4. Do online laboratory exercises increase student enjoyment of a class in different STEM disciplines?

Experimental Setup

The research reported in this paper and in Phase 1 was reviewed and approved by the APUS IRRB committee under approval ID 2019-205-APUS. All participants in this study were students enrolled in undergraduate classes at the American Public University System (APUS). APUS is a fully online, open-enrollment university offering associate's, bachelor's, and masters' degrees in a wide range of majors. The student body at APUS is older than the national average by about four years (Reyes, 2023) and is mainly composed of returning students and/or working adults (91%; average age 31). Sixty-six percent of students are serving active duty in the military while enrolled, with an additional 23% veterans or otherwise military-affiliated students (APUS, 2023).

The courses in this study comprise three sets of paired, introductory (100-level) classes: one pair of astronomy classes, one pair of physics classes, and one pair of biology classes. As in Phase 1, the pairs of classes were designed to be nearly identical internally, the only substantial difference being the inclusion or exclusion of laboratory exercises.

Paired classes use the same chapters in the same textbook, the same lecture materials, and the same assessments. Each pair shares a common set of learning objectives, all of which are

well covered by the lecture and readings. These learning objectives are assessed by the same weekly quizzes in the courses, as well as through exams that pull questions from the same question pool. Students in each pair of classes are generally successful in meeting learning objectives for the course.

Evaluation of mastery of the learning objectives was performed using pre- and post-quizzes, which consisted of fifteen multiple choice questions in astronomy and biology and twelve questions in physics. The questions were identical in both the pre- and post-quizzes and for both lab and non-lab sections of the classes. Completion of the pre- and post-quizzes was completely voluntary, and the scores on the quizzes did not affect student grades in any way. The questions were designed to directly address a subset of course learning outcomes. They were carefully crafted to focus on concepts that the lab helped reinforce but that were also taught in the non-lab classes. This means that students in both the lab and non-lab classes were expected to learn these concepts based on the primary material in the course textbook. However, the laboratory exercises specifically reinforced these concepts for the students in the classes which included lab exercises.

In addition to the pre- and post-quizzes, a Likert-style survey was given to the students in the lab class at the end of the course. This survey assessed student perceptions of the labs and whether they believed that the labs helped them to master the concepts taught in the course. The surveys also gauged ease of use for the labs, student enjoyment of the laboratory exercises, and whether the students felt that the labs provided a hands-on learning experience in the virtual classroom (see Results for a description of which quiz questions assessed these perceptions). See Appendix A for the survey questionnaire used: all laboratory students in all disciplines received the same questionnaire. This qualitative assessment is an important aspect to consider, as evidence shows that student satisfaction directly relates to retention and persistence (Schreiner and Nelson, 2013; Eather et al., 2022). Studies to date, however, have focused on initiatives for student support and satisfaction at an institutional level rather than the impact of individual course content or design.

All of the courses in this study were part of the general education core required by APUS, and all content and assignments in the courses were delivered asynchronously. In each pair of classes, the course with lab is generally intended for students majoring in the course, or closely related, topic or for programs with higher natural science credit requirements while the course without the lab is intended for non-majors. The general education requirement applies to all APUS students, not just students in the School of STEM; thus, both versions of the courses typically include students from a range of schools, including business and humanities. None of the courses in this study had a pre-requisite requirement; most were taken during the Freshman or Sophomore year of coursework. Data collection occurred during a two-year period comprising 2022 and 2023. The courses were developed, and exclusively taught, by faculty from the School of STEM at APUS. Each of the courses was taught by faculty members with credentials specific to the course content; all faculty were qualified to teach both the lab and non-lab courses during the period of this research.

During this research study, the astronomy courses were taught by 18 different instructors, including three full-time faculty members. Ten instructors taught the lab version of the course for a total of 16 sections. Seven instructors taught the non-lab version of the course for a total of 19

sections. Four of the instructors, two full-time and two part-time taught both lab and non-lab courses. A total of 558 students participated in the study, with 353 from the non-lab course and 205 from the lab course.

The physics courses in this study were taught by 13 different instructors, all but one of whom were part-time faculty members. Six instructors taught the lab version of the course for a total of 21 sections. Nine instructors taught the non-lab version of the course for a total of 19 sections. Two instructors (one of whom was a full-time faculty member) taught both lab and non-lab courses. A total of 587 students participated in the study, with 272 from the non-lab course and 315 from the lab course.

During the study, the biology courses were taught by 12 different instructors, including two full-time faculty members. Nine different instructors taught the non-lab version of the course for a total of 16 different sections; three instructors taught the lab version of the course for a total of six sections. During the length of the study, there was no overlap in the instructor pool for the two biology courses, though this does occur regularly within the teaching cohort. An equal number of sections of the two courses were taught by full-time faculty; more part-time faculty taught the non-laboratory version during this period. A total of 477 students participated in the study, with 331 from the non-lab course and 146 from the lab course.

For the astronomy courses, the lab exercises covered six topics, including planetary orbits, phases of the Moon, the greenhouse effect, the Sun, the HR diagram, and circumstellar habitable zones. As in Phase 1, three different styles of labs were used: instructor-generated labs using web-based simulations created by the University of Colorado Boulder (2024) as part of their PhET Interactive Simulations (the lab content and questions were the same for all sections of the study and the same for both phases), fully developed laboratory exercises using the NAAP laboratory exercises (University of Nebraska-Lincoln, n.d.), and exploratory lab exercises using publicly available astronomical datasets (Helioplayer, n.d.).

For the physics courses, four topics were covered by the lab exercises, which included density (SimPop, n.d.), momentum (Fendt, n.d.), specific heat capacity (Pearson Education, n.d.), and reflection/refraction of light (The Physics Classroom, n.d.). The physics labs were all instructor-generated labs using web-based simulations; these did not vary by section (all instructors used one common set of labs).

For the biology classes, six topics were covered by lab exercises; these were the scientific method (SM), evolution & common descent, evolution & evolutionary pressures, virus characteristics, general evolution, and biotechnology, centering on forensic investigations. The biology laboratories were based on publicly available simulations of experiments and data provided by the Howard Hughes Medical Institute (HHMI) Bioactives (HHMI, n.d.). Students used the simulations developed by HHMI but completed exercises and analyzed their results using worksheets contained within the virtual classroom. Worksheets were not submitted; students were assessed on their understanding and completion of the exercise as part of the course's weekly quizzes. As such, the weekly quiz assessments in the laboratory and non-laboratory course versions differed slightly in the biology pairing, but only in the presence or absence of lab-specific questions. The weekly quizzes carried the same weight in the overall

course grades. However, as noted above, the pre- and post-quizzes used for this study were identical.

Study Limitations and Bias

The unique nature of the parallel course design between laboratory and non-laboratory versions of the same course is a key strength of this study. The use of general education courses, all of which follow an overall uniform design approach, allowed for randomized enrollments within the student cohorts, as discussed above. However, as the results are based on voluntary student participation, it is important to acknowledge the potentially limited nature of the sample pool. Throughout the study, we attempted to address this by conducting the data collection over multiple sections with a diverse instructor cohort and across multiple course starts. An additional limitation is our inability to assess lab impact on persistence and retention. The presentation of the satisfaction survey and post-quiz assessment in the final week of the courses removes the possibility of assessing laboratory impact on persistence: only those students that persist for the entire course would complete the study activities. Similarly, as this study is restricted to a final anonymized pool, we have no way of following students to assess the impact on retention.

In addition to the limitations noted above, the data reported in this study is based on average results and is not correlated by individual student responses. Thus, it is limited in that the learning gains are per class rather than per student. Response rates for all classes were high, ranging from 67% to 81% for the post-quizzes and from 84 to 89% for the pre-quizzes; thus, the averages well represent the class as a whole. The high response rates, coupled with the large number of classes and the fairly consistent number of participants between lab and non-lab classes across each discipline included in the study, make it unlikely that the reported averages might be dominated by an unrepresentative sample of the student population. Finally, the APUS student population differs from the average college freshman class in that the students are mostly working adults and returning students; this represents a bias in the reported results.

Data Description

In this study, “content mastery” is evaluated based on the quiz questions. The pre-quiz question averages indicate the students’ baseline understanding of the topics at the start of the class (pre-instruction). Learning gains are defined by the difference between the post- and pre-quiz performance. Student satisfaction in this study is based on student enjoyment of the labs [survey questions (6) and (7)] and is discussed separately from student experience using the labs [survey questions (4) and (5)]. Student perception of content mastery is based on survey questions (1), (2), and (3); this is different from learning gains, or actual content mastery, as indicated by quantitative performance on the quizzes.

New Astronomy Results

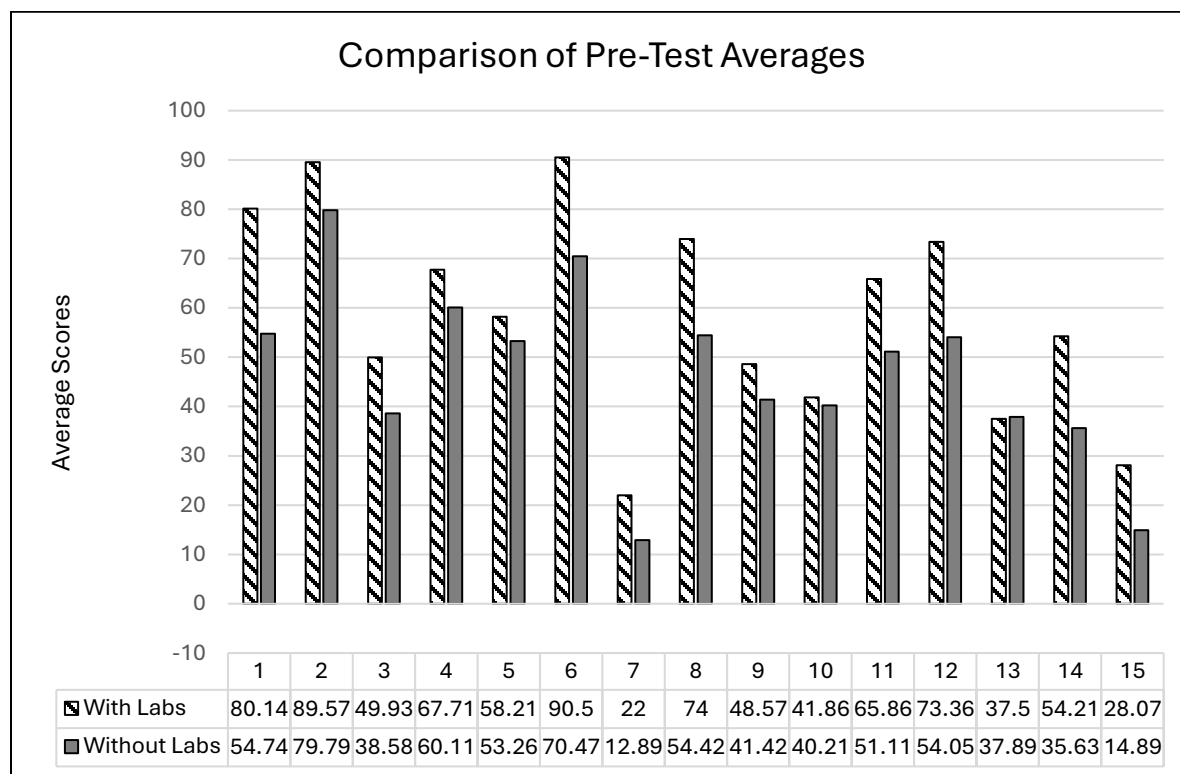
The pre-quiz averages for Phase 2 of the study are shown in Figure 1. The averages are shown for each question on the quiz without weighting. About 90% of students enrolled in the courses completed the pre-quiz (91% for the lab course and 88% for the non-lab course). Averages for the classes with labs are shown with striped bars, while the averages for the classes without labs are shown in solid grey. The students in the lab class outperformed those in the non-lab sections on every question. The largest differences are seen for questions 1, 6, 8, 12, and 14; these correspond with planetary orbits, the greenhouse effect, the Sun, the HR diagram, and

circumstellar habitable zones. The pre-quiz averages indicate that students taking the lab section of the course had a foundational knowledge which was not limited to a specific area but instead covered a of a broad range of core topics.

Levene's test for equality of variance was performed to validate the assumption of homogeneity of variance ($p = 0.55$), and then an independent two-sample, one-tailed t-test was performed to compare the lab ($M = 0.59$, $SD = 0.04$) and non-lab ($M = 0.47$, $SD = 0.03$) student populations to determine the degree of significance in these results. The test met the criterion for significance at the 90% confidence level ($t(28) = 1.69$, $p = 0.05$, $d = 3.13$). This confirms an overall moderate difference between the populations in the study.

Figure 1

Pre-test Score Averages by Question

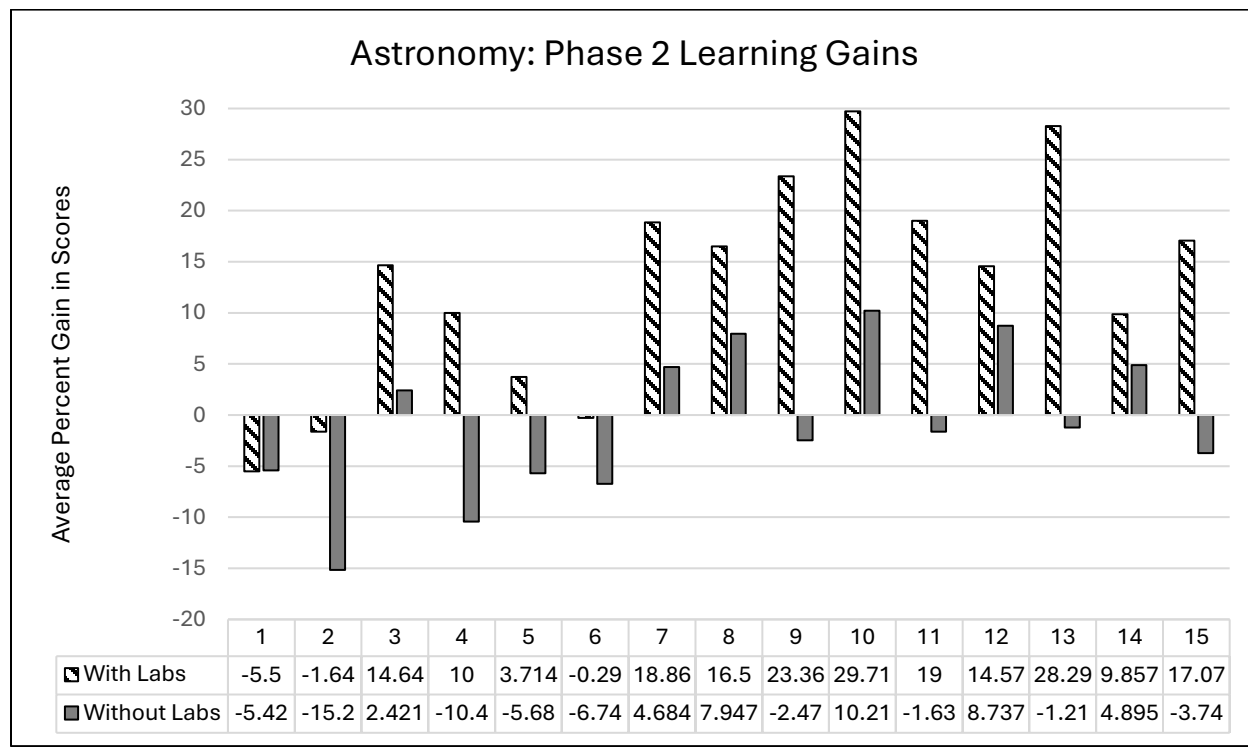


Note. This graph shows the pre-test average scores for both the courses with and without labs in Phase 2.

Figure 2 presents the average learning gains per question; learning gains were calculated by comparing the pre-quiz and post-quiz averages in each case. The average gains per question are shown beneath the graph. Approximately 81% of the students completed the post-quiz in each class (87% for the lab class and 76% for the non-lab class), corresponding to $N = 558$ for the astronomy classes. For all questions except the first, the students in the lab class scored higher than those in the non-lab sections. Students in the non-lab sections frequently showed negative learning gains, meaning that they performed worse at the end of the course than at the beginning.

Figure 2

Phase 2 Learning Gains for Astronomy Courses

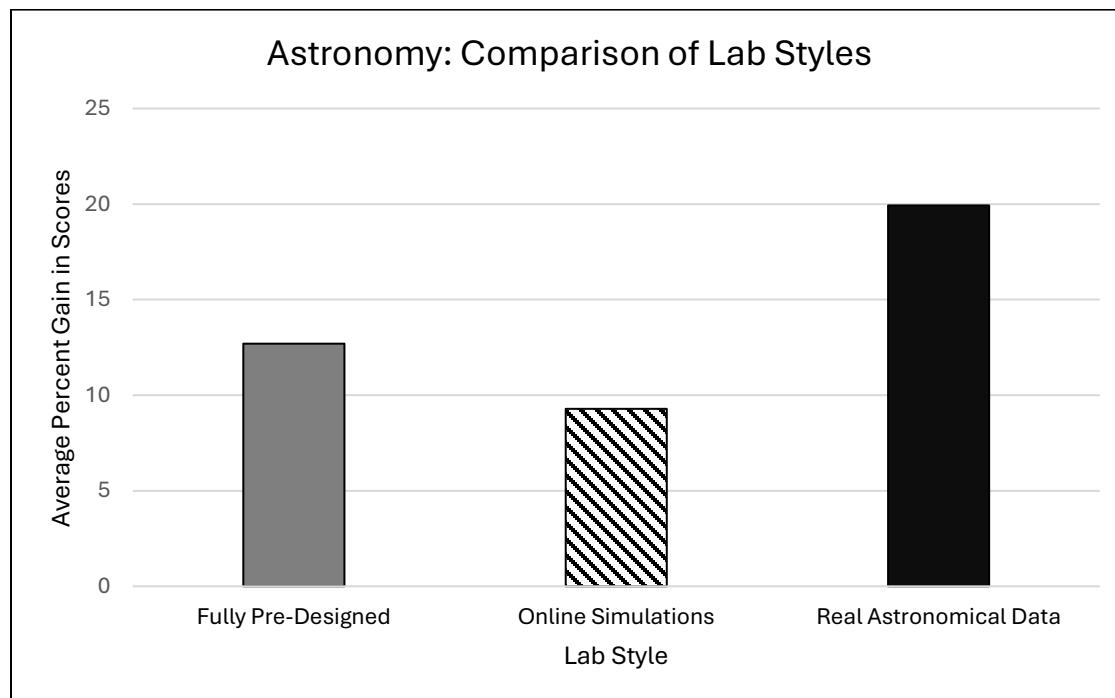


Note. This figure shows the average percentage gain in scores per question for the astronomy courses in Phase 2 of the study.

Figure 3 shows an analysis of the learning gains as a function of lab style. The averages were performed over the subset of questions on the pre/post quizzes which were directly related to the topics of the laboratory exercises in each category. The data show that labs which allow students to interact with astronomical datasets are associated with the highest learning gains, followed by fully pre-designed labs which use simulated data and labs based on independent online simulations.

Figure 3

Average Learning Gains as a Function of Lab Style

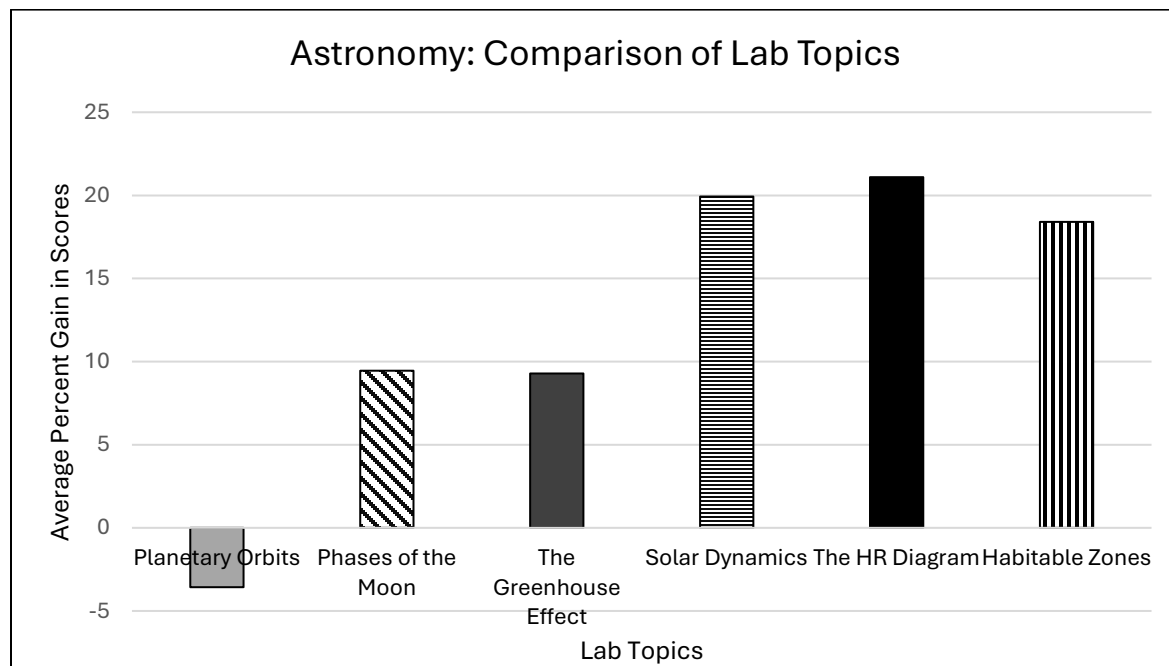


Note. This figure shows the average learning gains for each type of laboratory exercise for the astronomy courses.

Figure 4 shows the learning gains as a function of topic; these are shown in the order in which they occur during the class. The Planetary Orbits lab is an outlier, demonstrating negative learning gains, which indicates that the students actually performed better on the quiz questions relating to this lab at the beginning of the course than after completing the lab. As the first lab in the course, familiarity with the lab software could play a role here. This lab is also the most heavily math-based lab, which might be a confounding factor. Another possibility is retention: because the post quiz is given at the end of the course, students may have forgotten the concepts learned in this lab more than in subsequent labs. Higher gains were seen in the labs completed during the second half of the course in general. However, it is important to remember that the learning gains shown here represent the difference in the students' knowledge at the end of the course compared to the beginning, so a negative learning gain does not simply equate to a lack of retention but is instead an indicator of regression of understanding. No dependence on the style of the lab is seen in this data as labs of the same style were taught at different times throughout the class.

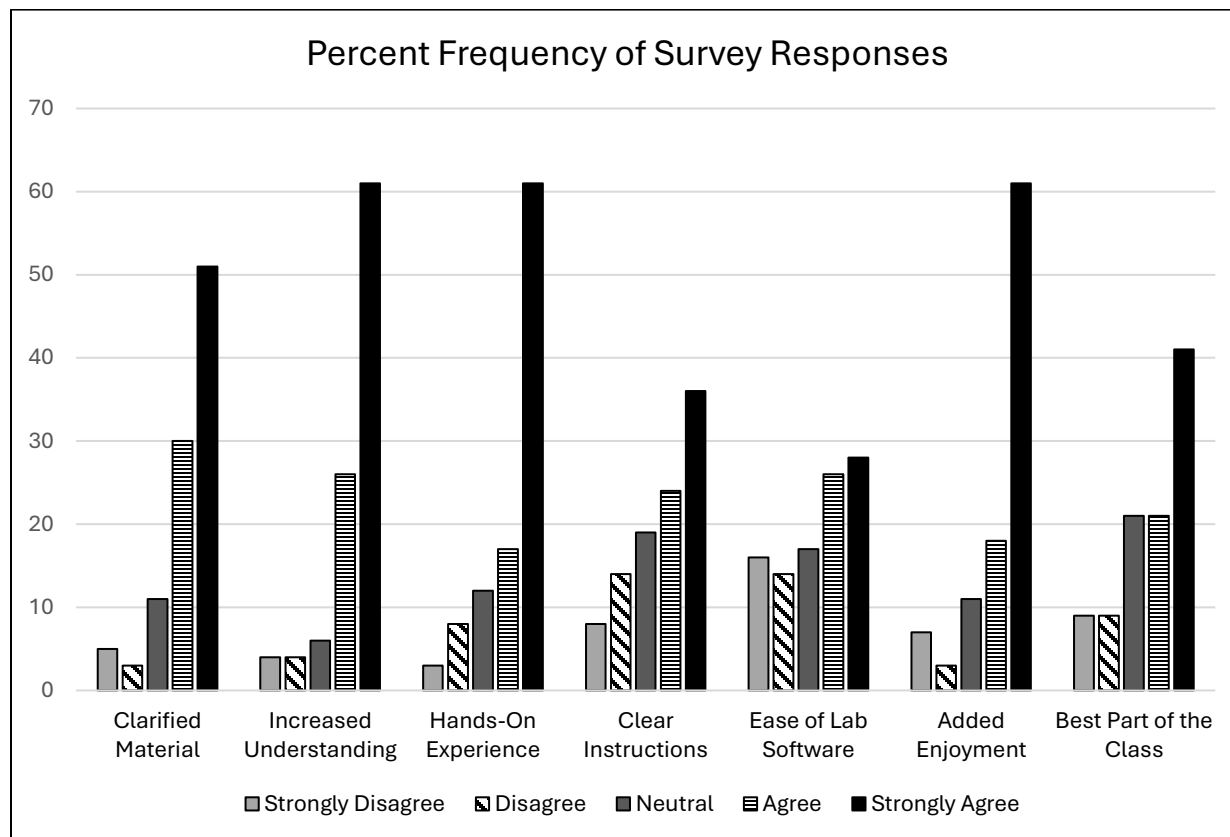
Figure 4

Average Learning Gains as a Function of Lab Topic



Note. This figure shows the average learning gains for each of the different topics covered by the laboratory exercises in the astronomy courses.

Figure 5 presents the results of the Likert survey that was administered to the lab classes. The survey questions can be grouped as evaluating student perception of the following areas: (1) how well the labs helped the students to understand the core topics (questions 1 and 2); (2) whether the labs added a “hands-on” component to the class (question 3); (3) how easy it was to complete the labs (questions 4 and 5); and (4) how enjoyable it was to do the labs (questions 6 and 7). The data was weighted by the number of responses and averaged over all respondents.

Figure 5*Survey Responses for the Astronomy Courses*

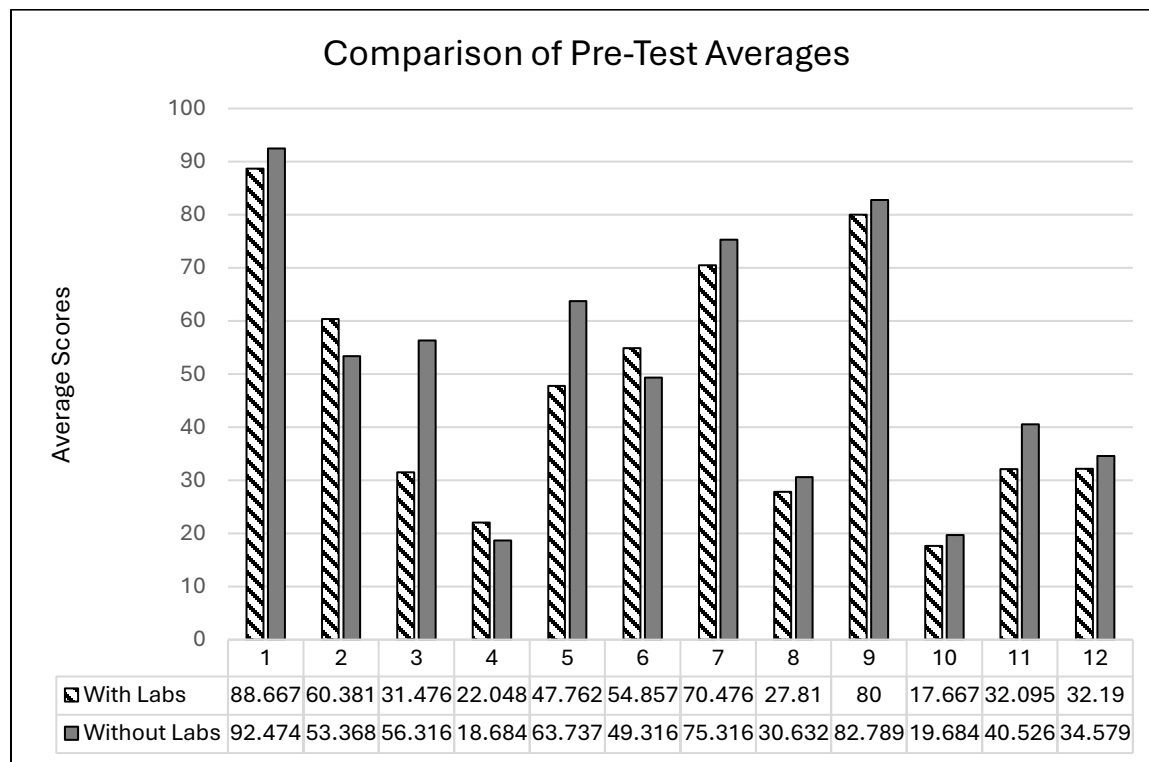
Note. This figure shows the rankings reported by the astronomy courses with labs.

Physics Results

The pre-quiz results for the physics courses are shown in Figure 6 and the average learning gains per question are shown in Figure 7. The physics quizzes consisted of 12 questions. Roughly 86% of students enrolled in the course completed the pre-quiz (84% for the lab class and 88% for the non-lab class), and 68% completed the post-quiz (63% for the lab class and 73% for the non-lab class), corresponding to $N = 587$ for the physics classes. Except for question 3, none of the pre-quiz results show any significant difference between the two classes. The non-lab course students scored higher than the lab course students on question 3, which is unexpected given that the lab classes tend to attract students with a stronger interest/inclination in STEM. Question 3 evaluates understanding of Archimedes' principle.

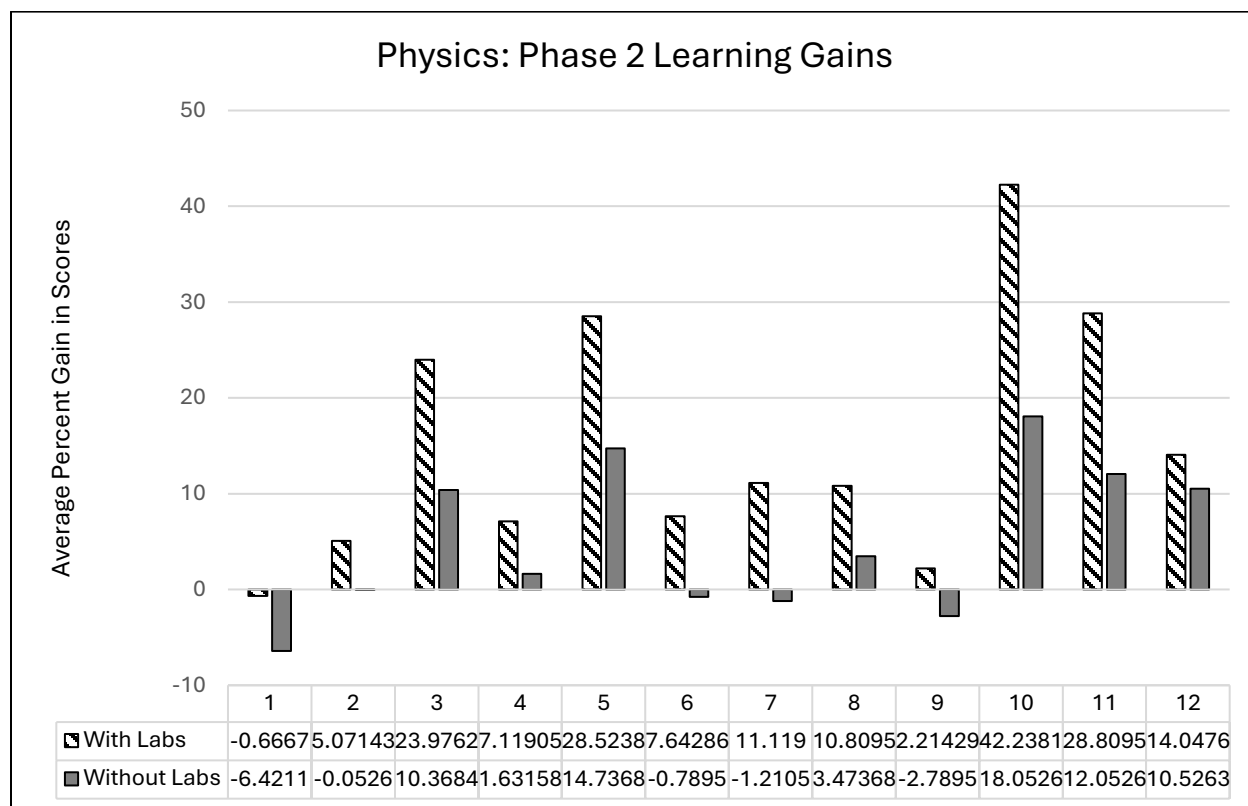
Figure 6

Pre-Test Average Scores for Physics Classes



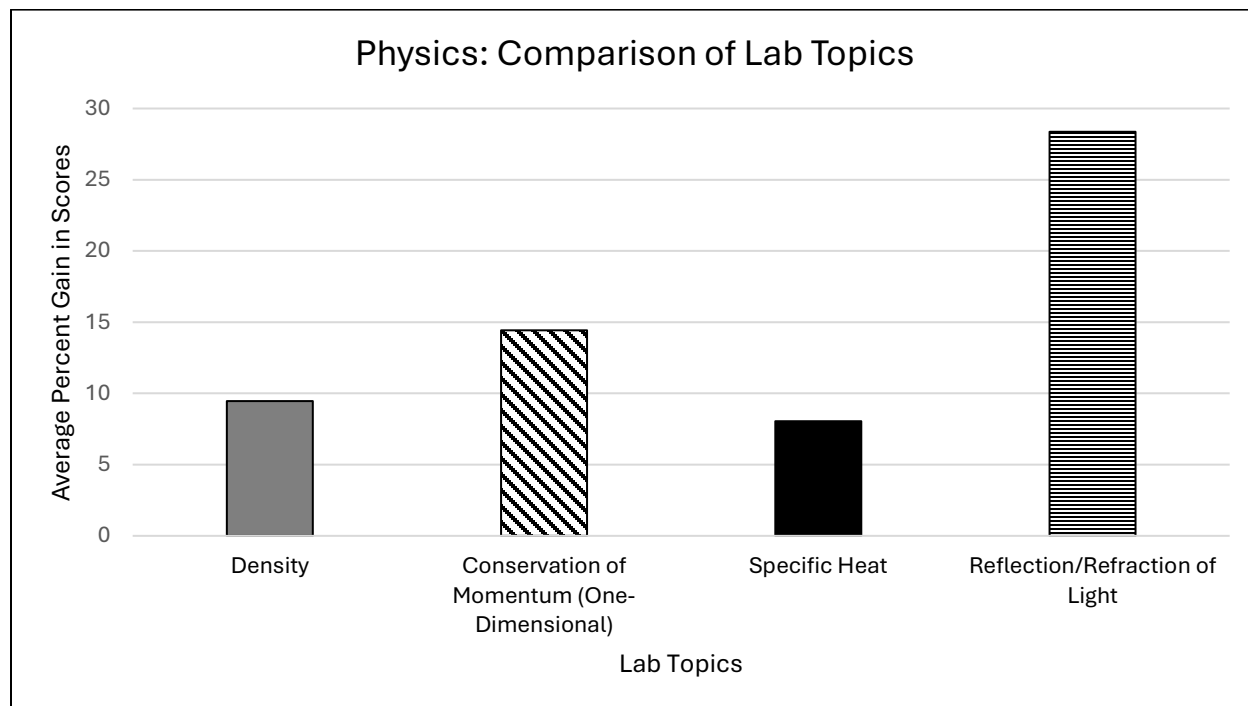
Note. This figure shows the average pre-test scores per question for both the physics lab and non-lab courses.

The learning gains shown in Figure 7 are based on the differences between the pre- and post-quiz scores. In each case, the students enrolled in the lab sections of the course outperformed students in the non-lab sections. The non-lab sections of the classes resulted in negative learning gains for one-third of the quiz questions; the topics addressed by these questions include density, elastic collisions, and thermodynamics, including heat transfer and specific heat capacity.

Figure 7*Phase 2 Learning Gains for Physics Courses*

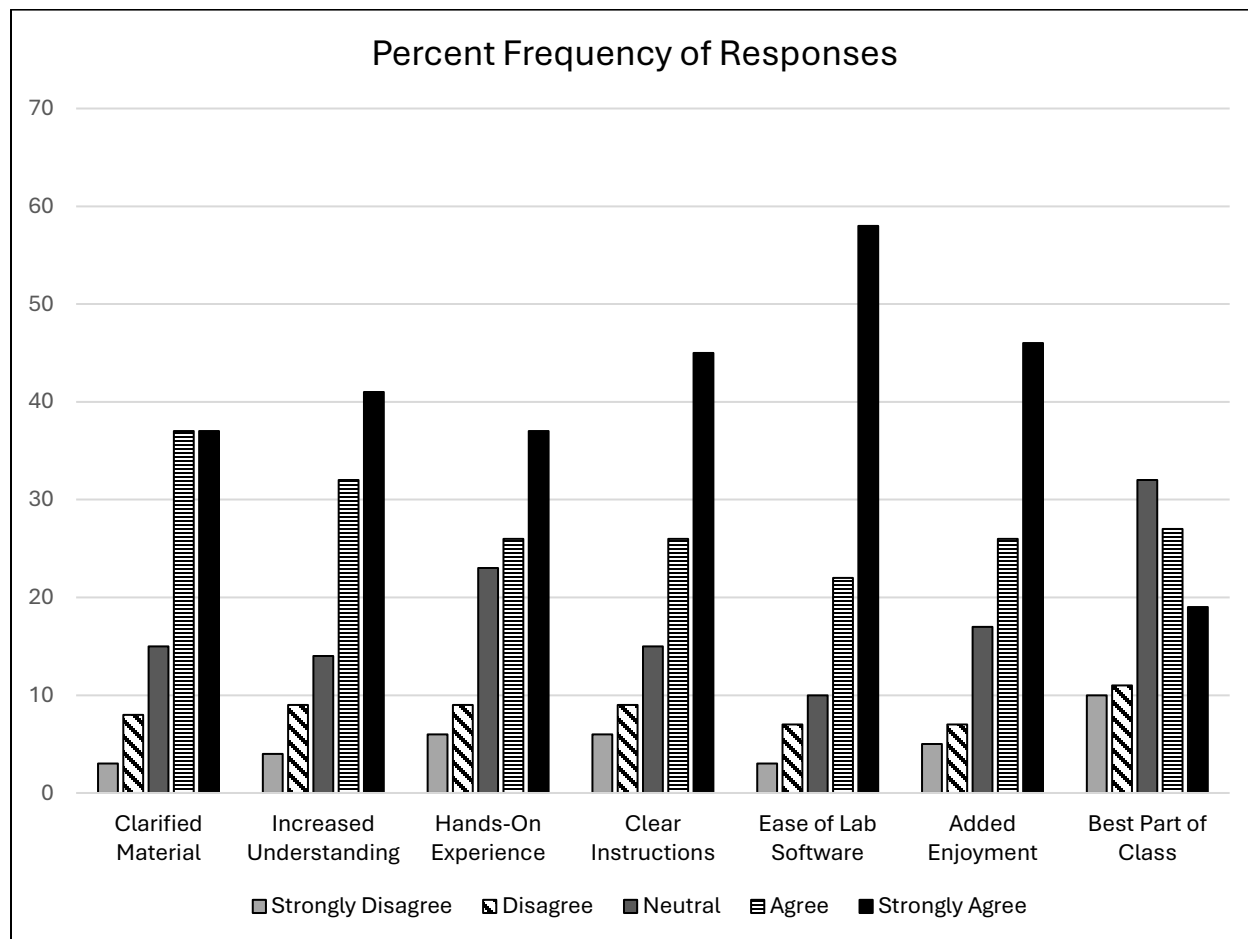
Note. This figure shows the average percentage gain in scores per question for the physics courses with and without labs.

The average learning gains by topic are shown in Figure 8. The lab topics are shown in the same order in which the labs are completed in the course, e.g., density is the first lab and light is the last. There is no significant difference in learning gains for the first three lab topics, which are density, conservation of momentum, and specific heat capacity. The learning gains from the lab exercise investigating the wave-like nature of light are twice that of the other labs; this lab was completed at the end of the class, spanning the same time period during which the post-quiz was offered.

Figure 8*Average Scores by Topic*

Note. This figure shows the average gain in scores per topic covered by the laboratory exercises in the physics courses.

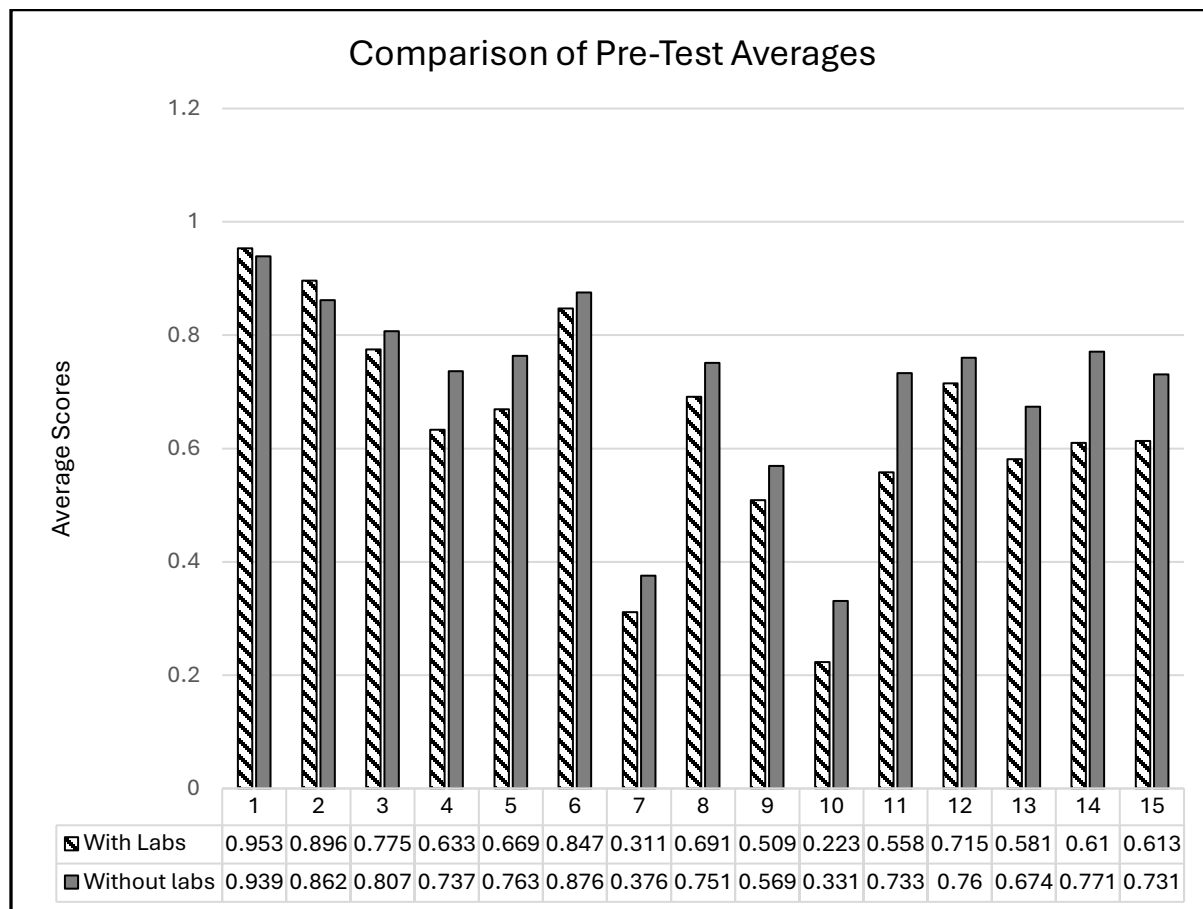
Figure 9 presents the student survey results from the physics classes. Student perception of the value of the labs as a learning tool (questions 1 through 3) and enjoyment of the labs (question 6) are both positive overall, with the majority of the responses in the “agree” and “strongly agree” categories. In general, the students found the labs clear and easy to use (questions 4 and 5). The results regarding whether the labs were considered the best part of the class were neutral to moderately positive.

Figure 9*Survey Responses for the Physics Courses*

Note. This figure shows the student survey responses which evaluated the laboratory exercises in the physics courses.

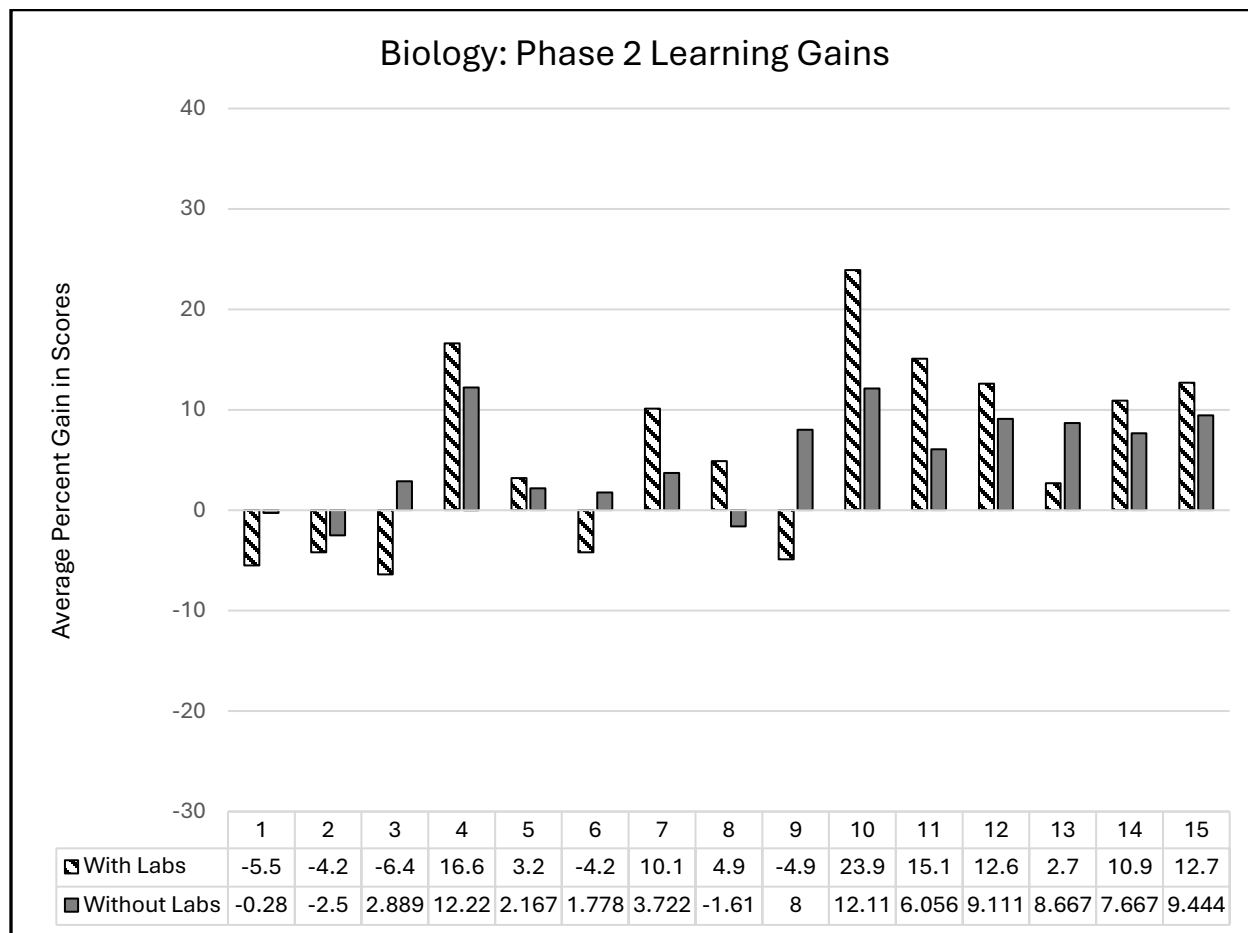
Biology Results

Figure 10 presents the pre-quiz results for the biology classes. Roughly 85% of students enrolled in the course completed the pre-quiz, with 82% for the lab classes and 86% for the non-lab classes. No significant difference is seen in any of the 15 questions evaluated in the pre-quiz.

Figure 10*Pre-Test Average Scores for Biology Classes*

Note. This figure shows the average pre-test scores per question for both the biology lab and non-lab courses.

Figure 11 shows the learning gains calculated by percentage increase in average scores on the pre- vs. post- quizzes. Roughly 73% of students enrolled in the course completed the post-quiz, corresponding to $N = 477$, with 68% for the lab class and 76% for the non-lab class. Learning gains for students in the lab classes were significantly higher compared to the non-lab classes for 3 questions (questions 8, 10, and 11); these questions correspond to the patterns of inheritance and biotech topics. One-third of the quiz questions (questions 1, 3, 6, 9, and 13) show significantly lower learning gains for the lab classes compared to the non-lab classes. The topics covered by these questions are evolution, patterns of inheritance, molecular biology, and diversity of plants. Students in the lab version of the course had negative learning gains for five of the quiz questions (questions 1, 2, 3, 6, and 9), which address evolution, patterns of inheritance, and molecular biology. For 60% of these questions, the non-lab students showed positive learning gains. The reverse situation (negative learning gains for the non-lab students and positive learning gains for the lab students) occurred on only one question (question 8), which related to patterns of inheritance.

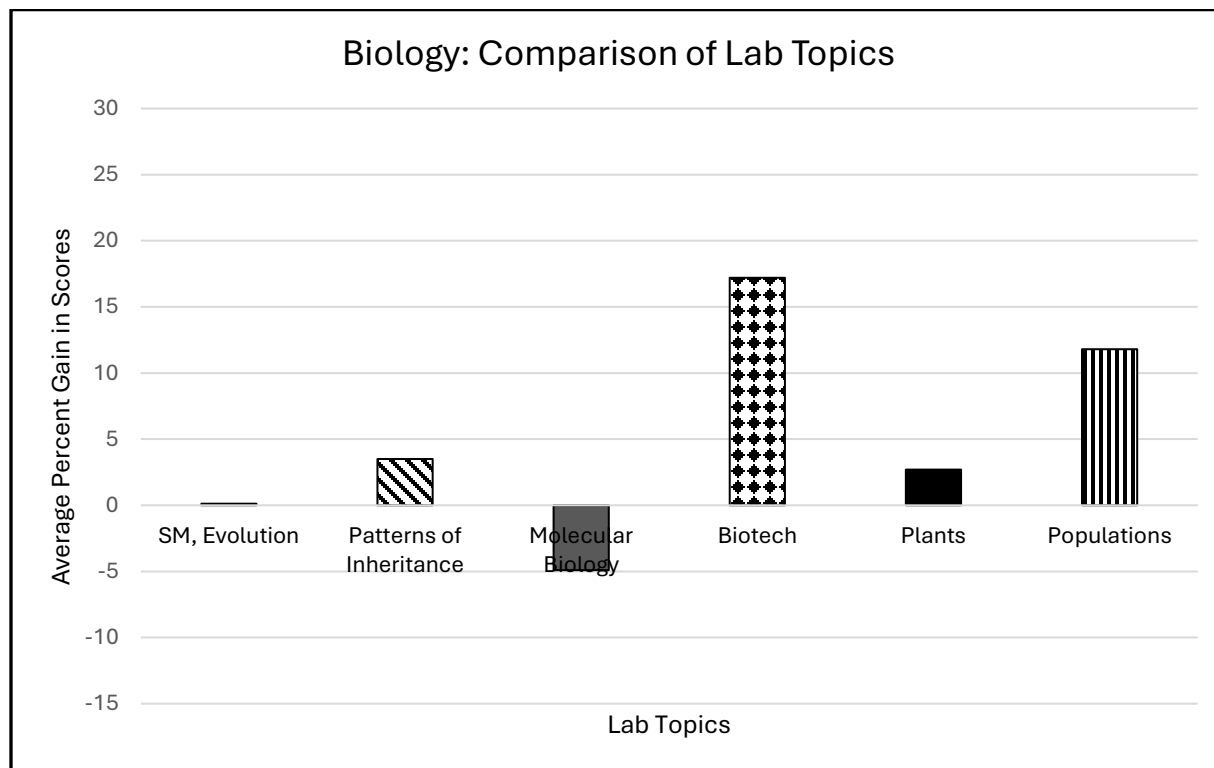
Figure 11*Phase 2 Learning Gains for Biology Courses*

Note. This figure shows the average percentage gain in scores per question for the physics courses with and without labs.

Figure 12 presents the average learning gains as a function of topic. Two topics, biotech and populations, show large learning gains. The evolution topic shows essentially no gains at all, and the molecular biology topic shows negative learning gains, which suggests that this lab confused the students rather than clarifying the concepts. The labs are shown in consecutive order; no overall increase in learning gains is shown over time.

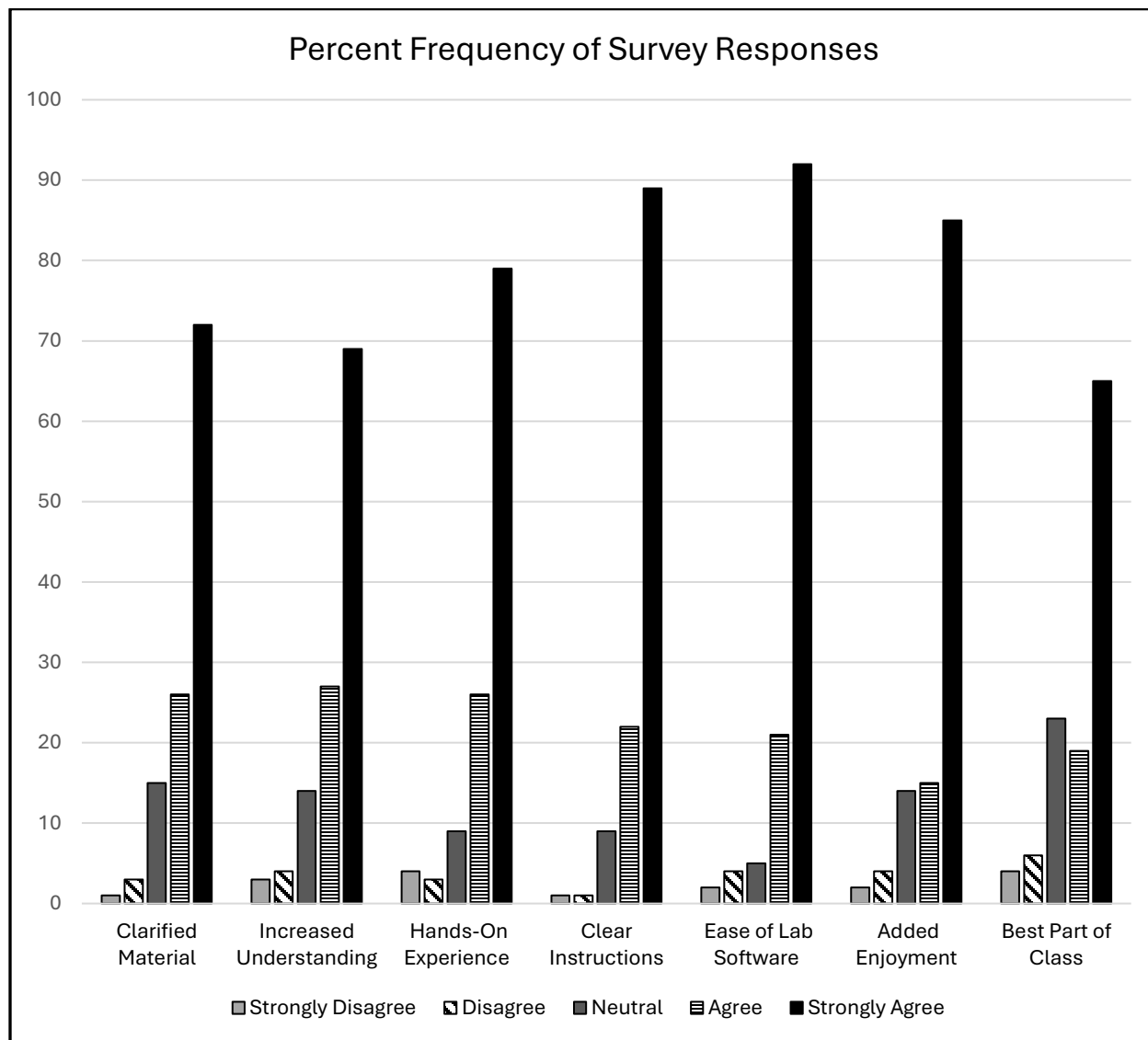
Figure 12

Average Scores by Topic



Note. This figure shows the average gain in scores per topic covered by the laboratory exercises in the biology courses.

Figure 13 shows the survey results from the biology classes. The survey results from the biology classes are overwhelmingly positive across all categories. The students strongly believed that the labs helped them to learn and that the labs were clear and easy to work with. They also strongly supported the idea that the labs were enjoyable and provide a hands-on laboratory experience.

Figure 13*Survey Responses for the Biology Courses*

Note. This figure shows the student survey responses that evaluated the laboratory exercises in the biology courses.

Discussion

New Astronomy Results

The pre-quiz results from Phase 1 of this study showed no indication of difference in the sample populations for the astronomy courses included in the data collection. Although the lab version of the course was intended for majors only, the development of the non-lab course option occurred at the beginning of the study, and a large share of the students in the course were grandfathered into the course progression, resulting in essentially no distinction in the student populations. The current research shows a systematic difference in the pre-quiz scores (see Figure 1); this is likely because now mainly students majoring in space studies are enrolled in this course while the non-lab class includes students from majors across all disciplines. As space studies/astronomy majors, these students are more likely to have an initial understanding of basic astronomical concepts prior to the start of the course.

Analysis was then performed to evaluate the efficacy of the lab exercises in the mastery of course learning objectives for these more knowledgeable students. As in Phase 1, the students in the courses with labs achieved higher learning gains based on a comparison of the pre- and post-quiz scores (see Figure 2). The data in Phase 2 showed much stronger gains for the lab courses compared to the gains reported in Phase 1. In this study, all but three questions on the test showed significant gains at the 0.05 level, with all but one question demonstrating gains at the 0.10 level. Fifty-three percent of the questions overall had significant gains at the 99% confidence level and, of the questions for which significant learning gains were shown, 57% were significant at the 99% level. In the previous study, fewer questions showed significant gain in learning, with 47% at the 99% confidence level and 13% at the 90% confidence level. Table 1 summarizes the statistical analysis for both phases. It confirms that more questions showed significant learning gains in Phase 2 compared with Phase 1 and that, of the questions that were significant in both phases, the gains were either comparable or larger in Phase 2. The increase in gains during Phase 2 of the study suggests that the virtual laboratory exercises benefit all students but are more effective for those with a baseline knowledge of astronomical concepts. This implies that the students who come into the class with prior knowledge are able to better use the lab exercises to increase their learning gains.

Table 1

Statistical Results Per Question

Phase 2	T Statistic	Phase 1	T Statistic
Q2	$t(15) = 4.55, p < 0.001$	Q2	$t(13) = 1.45, p = 0.084$
Q3	$t(15) = 2.38, p = 0.016$	Q3	$t(13) = 2.64, p = 0.010$
Q4	$t(15) = 3.69, p < 0.011$	Q4	$t(13) = 4.02, p < 0.001$

Q5	$t(15) = 2.42, p = 0.014$		<i>(not significant)</i>
Q6	$t(15) = 2.28, p = 0.019$	Q6	$t(13) = 3.69, p = 0.0012$
Q7	$t(15) = 3.02, p = 0.0043$	Q7	$t(13) = 3.65, p = 0.0013$
Q8	$t(15) = 1.64, p = 0.061$	Q8	$t(13) = 3.11, p = 0.0038$
Q9	$t(15) = 7.29, p < 0.001$	Q9	$t(13) = 6.56, p < 0.001$
Q10	$t(15) = 4.14, p < 0.001$		<i>(not significant)</i>
Q11	$t(15) = 5.33, p < 0.001$	Q11	$t(13) = 3.69, p = 0.0012$
Q12	$t(15) = 1.55, p = 0.071$	Q12	$t(13) = 1.47, p = 0.082$
Q13	$t(15) = 2.97, p = 0.0048$	Q13	$t(13) = 2.95, p = 0.0053$
Q14	$T(15) = 1.51, p = 0.076$		<i>(not significant)</i>
Q15	$t(15) = 6.44, p < 0.001$		<i>(not significant)</i>

Note. These results show the statistical significance of the learning gains per question for the astronomy lab courses during both phases of the study.

Learning gains as a function of lab style were analyzed to determine if the style of lab influenced student performance on the pre/post quizzes (see Figure 3). As in Phase 1, the highest gains were achieved for the exploratory style labs that used astronomical datasets; average gains were nearly twice those of the other lab styles. However, there was a small increase in gains for labs using fully pre-designed simulations compared to Phase 1.

Finally, the data was analyzed to determine if there was any correlation between learning gains and course topic; this is shown in Figure 4. In general, the labs on solar dynamics, the HR diagram, and habitable zones show twice the gains of the labs on the phases of the moon or the greenhouse effect, with no clear distinction between lab style indicated. In Phase 1, the gains for the HR diagram and the habitable zones labs showed smaller gains; this may be because these more complicated topics were more difficult overall for the students, who were not able to benefit as much from the lab exercises as a result. The planetary orbits lab shows a small increase in gain compared to the non-lab course, instead of the decrease in learning gain noted in Phase 1.

The survey results, shown in Figure 5, show a strong indication of student satisfaction with the labs, similar to Phase 1. The data reveal that the majority of students believe the labs increase their learning and add an authentic hands-on experience in the virtual classroom. Eighty to ninety percent of the students believe that the labs increase learning, clarify the course material, and increase enjoyment of the course. Sixty percent of students agree or strongly agree that the labs are the best part of the class, although the results are evenly divided in terms of the ease of use of the software. Difficulties using the simulations and software in the labs could contribute to the lower learning gains seen in the lab exercises that depend on simulations rather than astronomical datasets, as shown in Figure 3.

Key Points

Overall, the larger (compared to Phase 1) increases in learning gains on the post-quiz indicate that inclusion of online laboratory exercises is beneficial to learning mastery of astronomical concepts for both majors and non-majors, but that the labs are even more effective for students with a prior understanding of astronomical concepts. The improvement in learning gains over Phase 1 may be due to increased student interest in material that is more directly relevant to their educational plans, prompting greater diligence and care in working on the laboratory exercises, or it could be simply due to the benefits of prior knowledge gained from interest in the field. Regardless, the results of this study suggest that student populations that enter the course with a foundational understanding of astronomical concepts are better able to use online laboratory exercises to augment learning mastery of course topics.

Physics Results

Figure 6 clearly confirms there is no significant difference in student populations at the beginning of each class. APUS currently offers no physics degrees, and the electrical engineering program uses a different set of physics courses for its students. As such, any student enrolled in either physics course included in the study is completing general education requirements. The post-quiz results show strong learning gains across the board, with every question demonstrating a clear increase in performance (see Figure 7). Sixty-six percent of the questions show gains that are significant at the 95% level, and 58% of the questions indicate gains significant at the 99% level, as shown in Table 2. Comparing just the questions with significant learning gains, 64% are significant at the 99% level. These results are stronger than those reported above for the astronomy classes and those reported in Phase 1 of the study, suggesting that hands-on laboratory exercises are especially beneficial in physics classes.

Table 2

Statistical Results Per Question

Physics	T Statistic
Q1	$t(20) = 3.29, p = 0.0018$
Q2	$t(20) = 1.45, p=0.08$
Q3	$t(20) = 2.72, p < 0.0066$

Q4	$t(20) = 1.54, p = 0.070$
Q5	$t(20) = 3.54, p = 0.0010$
Q6	$t(20) = 2.76, p = 0.0060$
Q7	$t(20) = 3.18, p < 0.0024$
Q8	$t(20) = 1.98, p = 0.031$
Q9	$t(20) = 1.41, p = 0.087$
Q10	$t(20) = 6.11, p < 0.001$
Q11	$t(20) = 2.81, p = 0.0054$

Note. These results show the statistical significance of the learning gains per question for the physics lab courses.

Data for five of the post-quiz questions (41%) show a decrease in learning for the classes which did not include the laboratory exercises, indicating that the non-lab students performed worse at the end of the course than at the beginning. For all of these questions, the classes in which students completed the labs performed better. On one question, the lab classes show a significantly smaller decrease, while on the other four, the lab classes show strong positive learning gains. This reinforces the importance of the lab exercises in student retention of learning concepts as well as mastery.

The dependence of learning gains on topic, shown in Figure 8, shows a strong increase for the laboratory exercise exploring the nature of light, specifically concentrating on reflection and refraction. The learning gains on questions reinforced by this lab are two to three times larger than those for any other topic. This lab is offered near the end of the course, just before the post-quiz is administered. It is possible that the strong learning gains for this lab reflect retention over time: students may perform better on questions relating to concepts taught later in the course simply because that material is fresh in their minds, although, as discussed above, the learning gains are a comparison with baseline knowledge at the beginning of the class not simply a reflection of retention of new knowledge gained. Familiarization with the lab software is a possible compounding variable in the study as it could also lead to an increase in post-quiz scores for later labs compared with those completed early on. However, no overall time dependence for the learning gains is noted in the results shown in Figure 8. This suggests that the learning gains are not influenced by the students becoming more familiar with the lab software over time, strengthening the conclusion that the gains shown here represent student mastery of learning objectives.

The physics lab survey results, shown in Figure 9, are generally positive, indicating that the students enjoy the labs and believe that completing them increases their ability to master core concepts in the course. The results are not as strongly positive as those for Astronomy and Biology, however. Approximately 70% of students in the physics classes believe that the labs helped to clarify the course materials and that completing the labs increased their understanding of the topics; they also indicated that the labs increased their enjoyment of the course. Roughly

60% believed that the labs provided a hands-on experience in the course. These percentages are 10 to 20% lower than the results from the astronomy and biology classes. Only 48% percent listed the labs as the best part of the course, compared with 60% for astronomy and 80% for biology. However, the survey questions relating to the use of the software itself elicited very strong positive results. Eighty percent of the students indicated that the lab software was easy to use, and 70% agreed that the instructions for the labs were clear. This is 20 to 30% higher than the responses in the astronomy classes. These responses are comparable to those in the biology classes (~90%) and may reflect the fact that only one style of lab exercise was used in the physics and biology courses compared with three different lab styles in astronomy. For the physics students, perceived ease of use did not correlate with increased perception of learning or increased enjoyment of the lab exercises.

Key Results

The physics results confirm those of the astronomy courses in both Phase 1 and Phase 2 that the inclusion of virtual laboratory exercises in online science courses strongly supports student mastery of learning outcomes. Retention of information may play a role in the strength of the learning gains from the lab exercises, but the current research does not support a correlation between familiarity with the lab software and improvement in student understanding. While the students do not seem to enjoy these particular physics labs as much as the labs in other APUS STEM courses, as seen by comparing Figures 5, 9, and 13, the physics labs clearly help to increase student mastery of course learning outcomes, nonetheless. The anti-correlation between learning gains and student-reported evaluation of learning and satisfaction suggests that student perception may not be an accurate assessment of the effectiveness of classroom learning activities.

Biology Results

Pre-quiz average scores for the biology classes show no significant difference in biology knowledge upon entry to the course, as shown in Figure 10. This is to be expected as the students entering these courses are a diverse cross-section of university majors. While some majors, such as health science-related degrees, tend to take the laboratory versions, there are students representing a wide range of majors who complete the lab version to meet their program's natural science credit requirements. As with physics, APUS currently does not offer a biology degree, though a closely related natural science degree does exist.

The post-quiz average scores for biology show the most mixed results of this study, with five questions showing a reduction in learning gains for the laboratory classes (see Figure 11). Only 20% of the questions show positive learning gains that are significant, as shown in Table 3. As such, the biological science results may indicate that virtual laboratories have the least impact on student learning gains of the three disciplines studied in this research.

Table 3*Statistical Results Per Question with Learning Gain*

Phase 2	T Statistic
Q8	$t(9) = 1.78, p = 0.055$
Q10	$t(9) = 2.55, p = 0.016$
Q11	$t(9) = 2.73, p = 0.012$

Note. These results show the statistical significance of the learning gains per question for the biology lab courses.

Table 4*Statistical Results Per Question with Learning Loss*

Phase 2	T Statistic
Q1	$t(9) = -1.76, p = 0.056$
Q3	$t(9) = -2.06, p = 0.035$
Q6	$t(9) = -1.56, p = 0.077$
Q9	$t(9) = -3.06, p = 0.0068$
Q13	$t(9) = -1.47, p = 0.088$

Note. These results show the statistical significance of the learning loss per question for the biology lab courses.

Notably, five of the post-quiz questions (33%) show a statistically significant decrease in learning for the classes which include the laboratory exercises, as shown in Table 4. This indicates that the lab students performed worse at the end of the course on these questions than on the pre-quiz. Questions 1 and 3 relate to topics covered in Week 1. As such, the decrease may be attributable to uncertainty with the laboratory exercises or a mismatch between the timing of the laboratory exercises in relation to the period when those topics were covered in the main coursework. For example, Question 6 corresponds to a laboratory exercise that is two weeks after the main course content, indicating the possibility that students are not accurately synthesizing or retaining information. Question 9 and Question 13 offer no clear explanation for the decrease in quiz scores, other than the focus as discussed below. It is important to note that all topics were covered in both courses and during the same time in each course. The only functional difference is that concepts being reinforced in the laboratory exercises may have been presented several weeks after students were first exposed to the main content. As noted, this mismatch could indicate a lack of information retention or it could indicate student focus had shifted to novel concepts as emphasized in the main course materials.

The learning gains for each topic, shown in Figure 12, indicate a strong increase for the laboratory exercises exploring patterns of inheritance, biotechnology, and populations and community ecology. A minor gain is shown for the plant focused lab exercise. Only the molecular biology related lab exercises show a marked reduction in percentage gain in score. This does correspond to the question that shows the greatest loss in student learning achievements (Question 9), which may indicate a larger mismatch in the laboratory activities compared to how those topics were discussed as part of the main learning content in the course. Question 13 is focused on plant biology, which corresponds to a lab topic showing a small overall gain in student learning achievement. The laboratories focused on evolution and the scientific method show no significant impact on learning gains; these labs match Questions 1 and 3 discussed above. This may indicate that these laboratories do not enhance, nor detract from, the main course content. Overall, the most reasonable explanation for the decreases shown in student mastery of learning objectives at the question level is likely due to an insufficient alignment in the timing of the laboratory exercises and main course content. As such, future efforts may entail investigating the impact of different laboratory simulations on these topics or a better alignment between presentation of topics and their re-enforcement with laboratory exercises.

Despite the mixed results as quantified by the post-quiz data, students in the biology laboratory version overwhelmingly felt the laboratory experience contributed to their learning environment, as shown in Figure 13. Across all questions surveyed, students in the biology lab course rated the labs and their impact on mastery and enjoyment higher than did students in either astronomy or physics. Nearly 90% of students in the biology classes believe that the labs helped to clarify the course materials and that completing the labs increased their understanding of the topics. A similar number of students also indicated that the labs increased their enjoyment of the course. Nearly 85% stated the labs added sufficient enjoyment to be the best part of the course. Interestingly almost 90% assessed the virtual labs as being a ‘hands-on experience’, though from the practice of biological sciences, it in fact is not. Laboratory exercises that contributed to the highest percent gains by students are focused on topics where practitioners do spend less time manipulating biological materials and more time analyzing with modern computing programs. This is illustrated in Figure 12 in the results indicating high gains in Biotech and Populations. These topics include evolution related topics such as evolutionary relationships and population growth and regulation, or biotechnology where data are frequently analyzed via visual examination of images. As such, these online learning labs may better mimic a working laboratory environment in this subdiscipline of biology.

Key Points

Overall, the biology results indicate only a mild correlation between the inclusion of online laboratory exercises and increases in student mastery of learning outcomes. The results reported here suggest that the timing of labs (in relation to when concepts are taught in the course) is a significant factor in the benefits students gain from completing the lab exercises and that discrepancies in this timing can lead to negative learning and lack of retention compared with non-lab classes. Online laboratory exercises meant to simulate hands-on practices such as manipulation of materials are less effective than those which correspond with subjects that are traditionally based on computer manipulation of data, which is not surprising. This research shows an exceptionally strong anti-correspondence between both student perception of learning and student enjoyment with actual learning outcomes for online biology students.

Conclusion

The research presented here reinforces the conclusion from Phase 1 that online laboratory exercises in a remote learning environment contribute significantly to learning outcome achievements. In addition, these results indicate a strong correlation between the inclusion of online labs in a course and student satisfaction. As such, this study and Phase 1 both support the conclusion that fully virtual laboratory exercises contribute to both mastery of learning objectives and a sense of student satisfaction, although the gains are not equal for all STEM disciplines. Future work in this area could include a more detailed look at the impact of type of online laboratories, with an emphasis on realism in the field/discipline, as well as examining the impact of online laboratories on student retention rather than simple course level satisfaction. The retention question may be particularly important when considering major-focused courses in online education rather than only general education offerings.

Declarations

The authors report there are no competing interests to declare.

The research reported in this paper and in Phase 1 was reviewed and approved by the APUS IRB committee under approval ID 2021-002-APUS and by the APUS IRRB committee under approval ID 2019-205-APUS.

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Appendix A

Likert Survey Questions

All student satisfaction and perception surveys used the same Likert-style questionnaire, shown below.

Please rank each statement on a scale of 1–5, with 5 being “strongly agree,” 4 being “agree,” 3 being “neutral,” 2 being “disagree,” and 1 being “strongly disagree.”

1. The labs clarified material in the text and lessons.
2. The labs helped me to understand the material better.
3. The labs provided a “hands-on” learning experience.
4. The lab instructions were clear.
5. I was able to get the lab software to work without problems.
6. I enjoyed doing the labs in this class.
7. The labs were the best part of the class.

