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Efficacy of Online Laboratory Exercises in Achieving Undergraduate Learning Outcomes in Introductory Astronomy Classes

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Fully online courses and degree programs are popular with students today. It is important that these courses provide the same rigor and value of a traditional learning experience in a face-to-face classroom in order to ensure mastery of concepts and learning objectives. Online classes typically have suffered due to a lack of hands-on experiences for the students. One remedy to this is to include simulated hands-on work in the course through online laboratory exercises. The belief is that these simulated labs allow students to actively engage in the learning process, thus providing a traditional learning component in the online classroom. This research investigates the effectiveness of online laboratory exercises in enhancing student understanding of core concepts taught in introductory astronomy courses. Identical classes, one with and one without an online laboratory component, were compared using pre- and post-quizzes to compare the percent gain in content mastery between the classes. A Likert-style end survey was used to quantify student perception of the laboratory component. This study showed that students in the classes with online laboratory exercises demonstrated significant gains in scores compared to those without the labs. Further, the study indicated that different styles of online labs vary significantly in effectiveness and that labs with a component of realism result in the highest gains in student learning. Finally, the survey results showed that students believed the labs helped them to learn the course material and that the labs were an effective “hands-on” experience in an online environment.

Even before the COVID-19 global pandemic emerged as a potential watershed moment in higher education, the debate has raged over the effectiveness of online versus face-to-face learning experiences. The literature largely supports similar learning outcome achievements between virtual and traditional classrooms, although student perception of instructors and course quality is often higher for traditional face-to-face classrooms (Johnson, 2000). Similarly, comparisons have shown no statistical difference in the achievement of learning outcomes regardless of face-to-face, hybrid, or fully online delivery (Lovern, 2010). The importance of including hands-on learning experiences in online courses has long been assumed as a means of improving student engagement and content mastery, but few studies assess quantitatively the extent to which online laboratory exercises affect learning outcomes (Waldrop, 2013, Stuckey-Mickell & Stuckey-Danner, 2007); most rely on reports of student perception of learning and student experience. A few specific studies have focused on the learning impacts of virtual versus hands-on laboratory experiences (see (Darrah, 2014), (Corter, 2011), and (Brinson, 2015)); these studies have shown that virtual is as effective as hands-on learning experiences, if not more effective in some situations. However, the results depend on both the discipline and the specific topic studied as well as the style of online laboratory exercise used. In addition, previous studies often examined virtual laboratories conducted in a university laboratory setting with an instructor present; not in a truly remote, fully online learning environment, or as a supplement to traditional labs as opposed to the primary laboratory experience for the course. In addition, many studies assessing the effectiveness of online labs do not include a true control group, which means that the results are observatory and not causal.

The American Public University System (APUS) is a fully online, open-enrollment university offering associate, bachelor’s, and master’s degrees in a wide range of majors. This research focuses on the Introductory Astronomy course in the APUS Space Studies program, which is a survey-style course covering the solar system, stars and galaxies, and cosmology. The APUS Introductory Astronomy course is a required general education course for Natural Science majors, a required core course for Space Studies majors, and a general education elective course for many other majors to meet their natural science credit requirement. Thus, the student population in the course encompasses a wide variety of majors and backgrounds. Because this is a first-year course, no prior knowledge of the topics is assumed. Colloquial evidence from course instructors supports the idea that the students generally enter the class with roughly the same skill level and without extensive knowledge of astronomical concepts.

The purpose of this research is to assess student mastery of learning outcomes in two different versions of the APUS Introductory Astronomy course. This study focuses on the use of online laboratory exercises in a fully remote environment, not as a supplement to a hands-on learning experience. The work described here eliminates many of the biases inherent in previous research by using identical courses and the same student population. In addition, the students in both study groups are fully acclimated to online learning, which eliminates any bias due to the learning environment itself. This research will also assess student perception of the effectiveness of the online lab exercises, providing essential quantitative analysis which has been largely lacking in studies of the effectiveness of online laboratory exercises. It also provides data specific to the astronomy discipline and compares learning gains from the types of labs that are most commonly used in introductory astronomy courses.

Literature Review

Education research clearly establishes that laboratory exercises are beneficial in science learning across a wide range of science disciplines. While there are few direct studies comparing student mastery of learning outcomes in astronomy courses specifically, there is ample evidence supporting this in other science disciplines. Hands-on, interactive components, such as those provided by laboratory exercises, reach a wider range of learning styles and contribute to the depth of understanding of the material for all students (Marino, 2018). Laboratory exercises have also been shown to increase achievement in science classrooms (Marino, 2018, Bandura et al., 1996) and to promote critical thinking and meaningful learning (Jonassen et al., 1999). Labs are also an important means of providing scientific authenticity in the classroom (Alderman 2004); this has been shown to be true in astronomy classrooms in particular (Buckner et. al, 2020).

While laboratory exercises have traditionally involved lab equipment and measurements, virtual laboratory exercises that simulate these components are an increasingly important tool in science classrooms. Virtual labs have many advantages over hands-on labs, including eliminating the need for expensive lab equipment, offering the convenience of completing the labs at any time and in any location, allowing students to work at their own pace and to explore difficult or interesting concepts on their own in more depth, and providing more information and increased safety to students (Bhargava et al., 2006, Lynch & Ghergulescu, 2017, Heradio, et. al, 2016). Virtual labs also allow students to focus on processes and concepts rather than lab techniques (Marino, 2018). They are particularly effective for students with disabilities (Lynch & Ghergulescu, 2017). However, virtual labs also have unique disadvantages compared to traditional, hands-on labs, including the lack of natural variation in data, the challenge of working with poor/unexpected data, and the lack of opportunity to learn to use real equipment (Lynch & Ghergulescu, 2017, Lewis, 2014)).

Most of the research on the effectiveness of laboratory experiences has focused on the use of hands-on laboratory exercises in traditional, face-to-face classrooms. But as online learning becomes more common, an increasing number of studies have examined the benefits of virtual lab exercises, although these studies are still typically performed in traditional classrooms. In their seminal review, Ma and Nickerson (2006) define the different types of lab exercises as virtual, remote, and hands on; they conclude that virtual labs are at least as effective as hands-on or remote lab exercises in furthering student learning but find that more experimental studies are needed to assess the learning effectiveness of virtual and remote labs. This is echoed in a study by Lindsay and Good (2005), who conclude that each lab modality has its strengths and weaknesses and that more data is needed to differentiate their effectiveness in terms of learning outcomes. As might be expected, gains in student learning varied considerably between disciplines, subjects, and lab styles (Brinson, 2015). It should be noted that most of the studies considered used virtual labs as part of a traditional classroom setting or as supplements to hands-on laboratory experiences as opposed to virtual labs that are part of a fully online learning experience.

Orbah (1979) and Grober et al. (2007) examined different types of laboratory exercises in science classrooms and found that different types of labs yield different results. Their studies suggest that realism is a key motivator in lab exercises. There is also evidence that suggests that the design of the lab simulation is closely linked to learning (Russell et al., 2004).

Most of the research investigating the efficacy of virtual labs indicates that virtual labs are at least as effective as, if not more than, hands-on labs; these studies have mainly evaluated the content knowledge learning outcome category. Brinson (2015) compared student experiences with non-traditional labs (e.g., virtual labs) and traditional (hands-on) labs in 50 research studies performed at all levels (elementary through undergraduate) and across all science disciplines. His review found that virtual labs have equal or better achievement of learning objects in all categories, although the large majority of the studies focused on content knowledge only. Based on these studies, Brinson (2015) concluded that virtual labs are an acceptable substitute for hands-on labs in science classes. These studies evaluated lab exercises in a wide range of science and engineering disciplines, mainly in traditional, brick-and-mortar schools and universities.

A few quantitative studies indicate that online lab exercises do contribute to learning outcome mastery, although these studies typically assess the use of online labs in conjunction with traditional instruction. Wolf (2009) presented a quantitative assessment of learning gains in a comparison of face-to-face versus online laboratory experiments in a graduate-level computer network course. This study provides empirical evidence for increased gains using online labs compared to the traditional labs, although all students in the study were part of a face-to-face lecture class that supported the lab.

Similarly, Paxinou et. al (2018) found positive gains for students who used online simulations to prepare for traditional biology laboratory exercises. This study compared distance learning and traditional students and found that online simulations were equally effective in preparing students for the lab exercises. De la Torre et. al (2015) found a positive effect on the end-of-course evaluation when simulated virtual labs are combined with synchronous interaction for engineering students. However, their results were observational only due to the lack of a control. Finally, Finkelstein et. al (2005; 2006) presented results from a controlled study of the use of online labs by traditional students. These studies found the simulations were as productive or more productive than traditional labs and identified key components for improving online laboratory exercises. While by no means a complete listing, these studies illustrate the implied value of online laboratory exercises and highlight the need for studies with standard student populations and causal data. They also indicate the lack of research involving the use of online laboratory exercises in fully online environments.

Perception of learning is an important component in evaluating the effectiveness of laboratory exercises. Koballa and Glyn (2007) found that student disposition toward classroom activities has a powerful influence on student engagement. Corsi (2011) found that student perception is closely linked to the completion of the lab exercises. Morgil et al. (2008) demonstrated that student perception is a strong predictor of performance in the class as well. Crandall et. al (2015) reported positive student feedback for both chemistry students who completed online labs and those who completed traditional labs, with different advantages reported for each modality. No significant difference was found in learning outcomes in this study. Brinson (2015) assessed perception qualitatively and found that it is typically higher for virtual lab experiences. This work discussed the need for a more quantitative evaluation of student perception in order to better characterize the relationship between perception and lab activities, both virtual and traditional.

Research Questions

Including simulated laboratory exercises in online introductory astronomy 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?

Question 2. Are some types of online laboratory exercises more effective at promoting student mastery of core concepts than others?

Question 3. Do online laboratory exercises increase perceived student mastery of core concepts, as reported by the students?

Question 4. Do online laboratory exercises increase student enjoyment of a class?

Method

This research uses students solely from APUS. The university student population is approximately 80% military-affiliated, and the mean student age is 32. The study body is 40.69% minorities. The majority of the students (88%) also work full-time. Students in this study align with these overall demographics.

The focus of the research is the APUS Introductory Astronomy course. This is a 100-level survey course. It covers topics ranging from planetary astronomy to solar system physics to stars and galaxies and even includes a short section on cosmology. The course is meant to provide a broad overview of the topics rather than an in-depth treatment and seeks to draw connections between the concepts in order to leave students with a general understanding of our place in the universe. It also provides a base understanding of the field for incoming space studies majors; subsequent courses in the program build on the foundation provided by the course. No prior knowledge of astronomy is assumed.

The course objectives (CO) that are specifically targeted by the laboratory exercises include mastery of:

- CO1: Recall major advances in astronomical knowledge contributed by such scientists as Copernicus, Galileo, Kepler, and Newton.
- CO3: Interpret the motions of the stars, sun, and moon in the sky and how those motions combine to create seasons, lunar phases, and eclipses.
- CO5: Compare and contrast the surface processes and/or atmospheres of the terrestrial planets in our solar system.
- CO7: Describe the layers of the sun and the role of magnetic fields in shaping solar atmospheric phenomena.
- CO10: Make use of the Hertzsprung-Russell diagram and other methods to classify stars based on their observed properties and determine stellar ages through the comparison of cluster diagrams.
- CO11: Describe the lifecycles of both low-mass and high-mass stars, understand how their properties change during each evolutionary

stage, and how their evolution can be represented on a Hertzsprung-Russell diagram.

This course was originally designed as a four-credit hour lecture plus lab class. In order to meet changing credit hour requirements, a general education version of the class was created; this version is a three-credit-hour lecture-only course. Students in both classes are pulled from the same general demographics presented before. Students are solely responsible for choosing the course and section of enrollment, thereby generating a randomized population in any given course offering. While both courses are general education courses and both are open for enrollment by students in any degree program, the lab class is specifically intended for space studies majors while the non-lab class can fulfill the general natural science requirement for all other majors. In the study, a pre-assessment is performed to determine if the differences in the majors represented in the classes (majors versus non-majors) create a bias in the data (see the following).

Both classes use the same chapters in the same textbook, the same lecture materials, and the same assessments. The classes share 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 both classes are generally successful in meeting the learning objectives of the course.

Evaluation of mastery of the learning objectives was performed using a pre- and post-quizzes, which consisted of fifteen multiple-choice questions. The questions were identical in both the pre-and post-quizzes. 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 the subset of course learning outcomes previously listed. They were carefully crafted to focus on concepts that the lab helped reinforce but that were also taught in the non-lab class. This means that students in both 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 lab class version.

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 student enjoyment of the laboratory exercises and whether the students felt that the labs provided a hands-on learning experience in the virtual classroom.

The sample size for this study was 331 students in total; this number is based on the post-test data. The study evaluated students from 36 sections of the course, with 21 sections of the non-lab class and 15 sections of the lab class. The non-lab class sample size is a total of 186 students, while a total of 145 students make up the lab class sample. The classes were taught by 10 different instructors from the APUS Space Studies faculty pool. The lab classes were taught by seven different instructors during the data collection period, and the non-lab classes were taught by nine different instructors during this period. Of the 10 total instructors involved, six taught both the lab and non-lab classes. All sections of both courses were created from master course shells which ensure that the content and classroom experience is consistent for all sections of the classes, regardless of the instructor. In addition, the results from all sections were averaged together to lessen any effects due to differences in instructors and teaching styles.

Three different styles of laboratory exercises were used in the class. The first type of lab is a fully pre-designed laboratory exercise developed by the Astronomy Education at the University of Nebraska-Lincoln Web Site (http://astro.unl.edu). These labs include student lab manuals with specific instructions that guide students to understand the concepts in the lab through the use of online simulations. The lab manuals provide a step-by-step process that leads students to the correct conclusions. The labs include supplemental and background information on the topics covered; this information is integrated into the beginning sections of the lab in order to give students a foundation for understanding the more complex concepts developed in the lab exercise. The online simulations have preset values that allow students to simulate real astronomical objects and take appropriate measurements. There are also controls that allow for individual exploration of the concepts, but this is not included as part of the student manual. In practice, the majority of the students simply follow the directions in the lab manual. This first lab style is thus a scripted lab experience with no open exploration component. Students follow instructions to set the values for the controls in the simulation, record data, and answer directed questions that lead them to interpret the data and draw connections relating to the 'big picture' astronomical concepts targeted by the lab.

The second type of lab is based on individual online simulations that are freely available on the internet. Labs utilizing these simulations can be designed by an instructor. These labs reflect the options available in the simulations and generally rely on the course textbook and resources to provide background/supplemental information. While these labs can include individual exploration, the specific labs developed for the courses in this study included only specific instructions for the use of the simulation and not an explorative component.

For the courses in this study, the lab was designed by the course master authors and used without modification by all instructors who taught the lab course. In other words, while this type of lab does allow for instructor individualization, in this study there was no individualization between the course offerings. This lab-style is very similar to the pre-designed labs described before in that students follow specific instructions to set controls, record data, and answer directed questions that help them to interpret the data and draw connections. The main difference lies in the lack of accompanying background and supplementary information. While the textbook and class lesson content provide this information, it is not overtly coupled to the lab questions.

The third type of lab is based on databases of astronomical data, typically telescope data that has been made public. These labs are designed by an instructor. They allow students to explore real telescope images and datasets that represent current observations of celestial objects. The lab used in the courses in this study used data from the Helioviewer website (www.helioviewer.org), which includes data from the SOHO, TRACE, SDO, STEREO-A, STEREO-B, Yohkoh, Hinode, MLSO, and PROBA2 missions. Helioviewer was created by NASA. The lab is completely explorative in nature; students used the simulation to explore the solar surface in different wavelengths and examined solar active regions of their own choosing to analyze in their lab report. For the courses in this study, the lab was designed by the same course master authors and used without modification by all instructors who taught the lab course. As previously mentioned, no individualization existed between the different course offerings included in the study dataset. This lab-style is an open exploration and thus differs significantly from the two prescriptive lab styles just described. In this lab style, the students choose which solar active regions they will study and then observe their selected regions at a variety of wavelengths. They use the tools in the simulation to make their own observations and use these to draw conclusions about solar activity. As with the second lab style, no accompanying background or supplementary information is provided outside of the textbook and course lessons.

Results

The data collected represents the average scores on each quiz question for 15 sections of the lab course and 21 sections of the non-lab course. Drawn from courses taught over a period of 10 months, 331 students participated in the quizzes. As noted before, the non-lab sample size is 186 students, while the lab class sample size is 145 students. This participation number is based on the number of students who completed the post-quiz in order to focus only on data from students who completed both quizzes, not from the students who began but did not complete the study.

Average scores for each individual question on the quizzes were collected for each course for both the pre- and post-quizzes. The pre-quiz averages were compared to determine if any initial biases existed in the two student populations (those in the non-lab versus those in the lab sections of the course) due to prior knowledge of the material, major, etc. The results are shown in Figure 1.

The blue bars in the figure represent average scores from students in the lab sections of the class while the red bars represent average scores from students in the non-lab sections. To quantify the gains, the overall average scores were analyzed using a within-subjects design, correlated-groups one-tailed t-test. The non-lab course question averages were taken as the control values and the t-test analysis was performed using the average scores for each of the 15 sections of the lab course in the study in comparison to the non-lab averages. The null hypothesis was that virtual labs have no effect or a negative effect on student mastery of learning outcomes: H_0: $\mu_0 \geq \mu_a$. $T_{obtained}$ (5.44) was well above the critical value for the 99% level (2.624), taken from Table Q.3 in Jackson (2009); the effect size was 1.40 and the confidence interval was [8.42 – 24.10].

Percent gains were calculated by subtracting the pre-test scores from the post-test scores for each question. The results are shown in Figure 2. Again, the blue bars in the figure represent average scores from students in the lab sections of the class while the red bars represent average scores from students in the non-lab sections. A second t-test was then used individually to assess the significance of each question in the pre- and post-quizzes. Individual lab class averages on each question were compared to the corresponding average values of the combined results for the non-lab classes. The null hypothesis in each case was that the virtual labs have no effect or a negative effect on student mastery of the concept addressed by each quiz question: H_0: $\mu_0 \geq \mu_a$. Individual $t_{obtained}$ values for each question were computed and compared to the critical value for the 90%, 95%, and 99% confidence levels. It was found that questions 2 (1.45) and 12 (1.47) demonstrated gains significant at the 90% confidence level (1.35) and questions 3 (2.64), 4 (4.02), 6 (3.69), 7 (3.65), 8 (3.11), 9 (6.56), 11 (3.69), and 13 (2.95) showed significant gains at the 99% (2.16) confidence level (Jackson, 2009).

The data was further analyzed by grouping the quiz questions according to the concepts taught in each lab and comparing the average gains in scores for each question group. This was done to investigate which lab styles (designated as “pre-designed labs,” “online simulations,” and “astronomical databases”) yielded the highest increase in student scores. The results are shown

Figure 1
Comparison of Pre-Test Averages

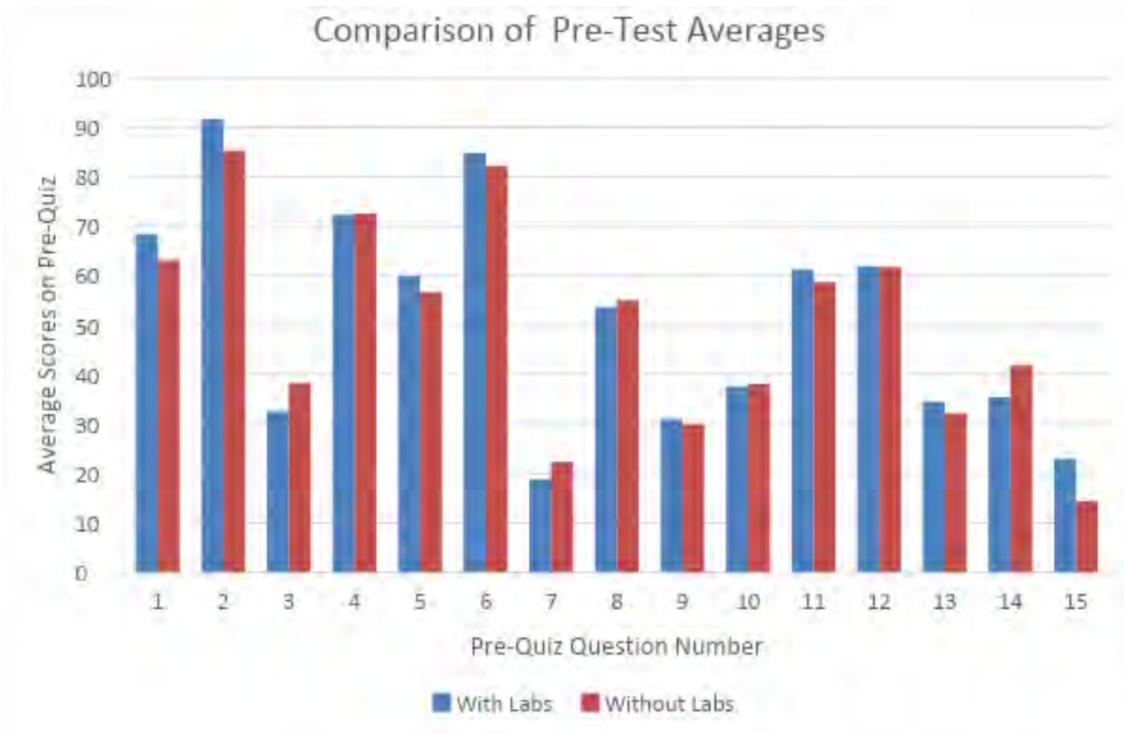
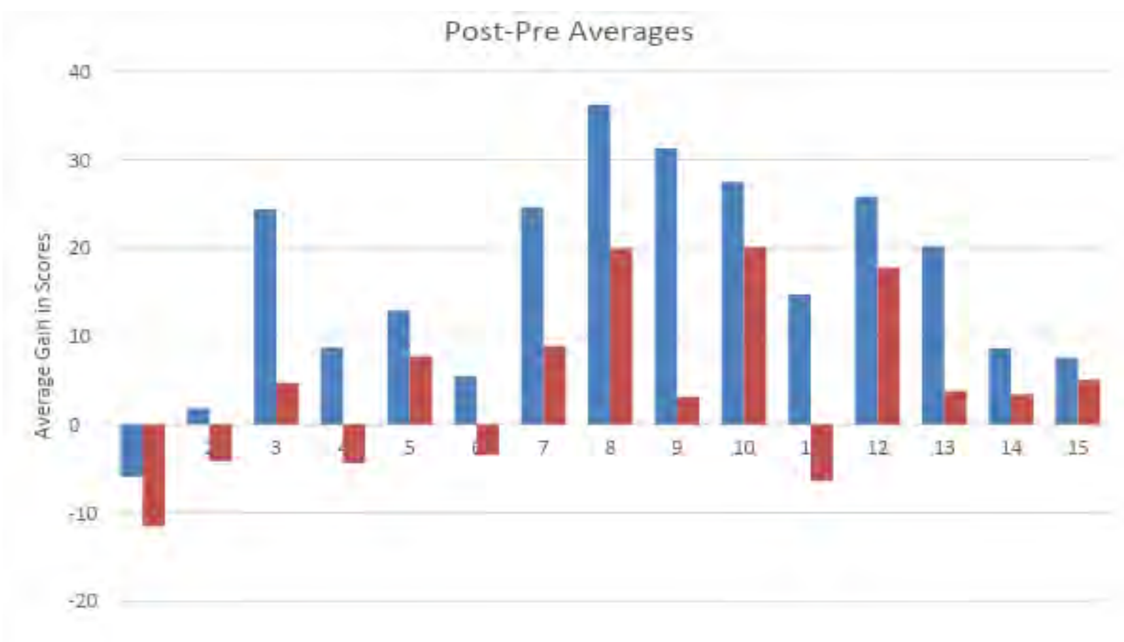


Figure 2
Post-Test Gains per Question



in Figure 3. Figure 3 indicates almost no difference in score gains for questions addressed by the pre-designed labs and labs using the online simulations, suggesting that the inclusion of background/supplementary information does not significantly impact student learning in online labs. Interestingly, open exploration labs using astronomical databases show a twofold increase in score gains compared to other lab styles. This result suggests that labs that present an authentic research experience to the students, allowing them to investigate and explore the data, may yield the biggest gains in student learning. This result is in support of the findings of Orbach (1979) and Grober et al. (2007), which indicated that realism in the lab is a key motivator for students. This also suggests that creativity and individual exploration lead to greater student buy-in to the laboratory experience and result in increased student learning. The difference seen in these results may also be explained by the theory that students learn science best when acting as a scientist rather than performing an academic exercise (Bruner, 1977).

Finally, the results of the Likert-style survey are presented to quantify the students' experiences with the labs. This survey was given only in the classes that included the labs. The survey evaluated student perceptions of the effectiveness of the laboratory exercises in helping them to learn the material as well as student enjoyment of the labs. The survey questions can be grouped into three main categories: 1) student perception of how well the labs helped them to master the material (questions 1–3); 2) ease of use of the lab simulations (questions 4–5); and 3) student enjoyment of the lab experience (questions 6–7). Each response was evaluated on a 5-point scale ranging from "strongly disagree" to "strongly agree." The aggregate responses are shown in Figure 4. While this represents qualitative data, we do feel it imperative to consider the student impression of their experiences in online courses, as discussed next.

Discussion

Figure 1 clearly indicates that the average scores for each course are consistent for all questions. The minor variations for individual questions are not significant. The graph thus strongly suggests that the students in both classes have approximately the same level of understanding of the material upon entering the classes. There is no evidence of a pre-existing or systematic bias of any kind between the two student populations initially. This is strong evidence in support of the fact that the student groups participating in the study were initially identical.

The average scores for each of the post-quiz questions were then compared to the corresponding pre-quiz averages. The percent gain/loss in average scores was calculated and is shown in Figure 2. Again, data from the lab section is represented by the blue bars, and data from the non-lab sections is represented by the red bars. This data differs significantly from the pre-quiz results and indicates an almost universal increase in scores for the lab class compared to the non-lab sections of the course. This strongly suggests that the inclusion of a lab component significantly increases student mastery and retention of the course concepts which are reinforced by the labs; this mastery is lacking in students who did not have the benefit of the lab experiences. It is interesting to note that, for questions 2, 4, 6, and 11, the scores in the non-lab class actually decreased for those topics, while students in the lab class increased in mastery. In question 1, average scores for both student populations decreased, but the decrease was much smaller for students in the lab course. In every case, the data indicates that students in the lab course performed better than their counterparts in the non-lab course.

Finally, the data collected from the Likert-style exit survey was evaluated. The mode and the mean of the response distribution were evaluated for each question. In all cases, the mean and the mode agreed with each other. For questions 1, 2, 3, and 6, the mean and mode fell in the "strongly agree" category. For questions 4, 5, and 7, the mean and mode were in the "agree" category.

Overall, there is a clear, positive response to the lab experience. An overwhelming majority of the students surveyed, approximately 94%, either agreed or strongly agreed that the labs clarified the material and helped them to understand the course materials better. Eighty-three percent of the students perceived the labs as a 'hands-on' experience in a fully remote learning environment. In general, 80% of students reported that the instructions were clear. Evaluation of the ease of use of the lab software shows the greatest variation in response, although the majority, 60%, either agreed or strongly agreed that the lab software worked for them with no problems. Colloquial data gathered from instructor experience in teaching the class indicates that ease of use increased as the course progressed and the students gained expertise and familiarity in working with the labs. It also indicates that some online lab resources are more user-friendly than others, which is an expected conclusion. Ninety percent of the students agreed or strongly agreed that the labs increased their enjoyment of the course, and approximately 75% of the students agreed or strongly agreed with the statement: "The labs were the best part of the class." In general, it can be stated that students felt that the labs clarified the material in the course, increased their individual understanding of the material, provided a hands-on experience in the class, and increased their enjoyment of the course.

Figure 3
Comparison of Gains for Different Lab Styles

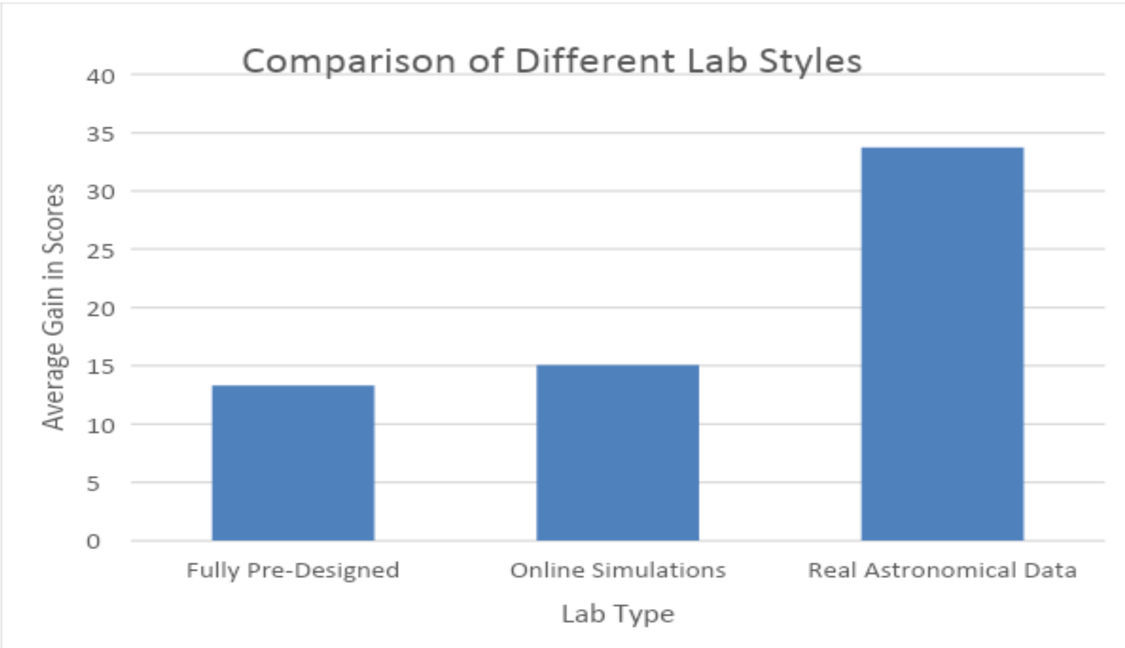
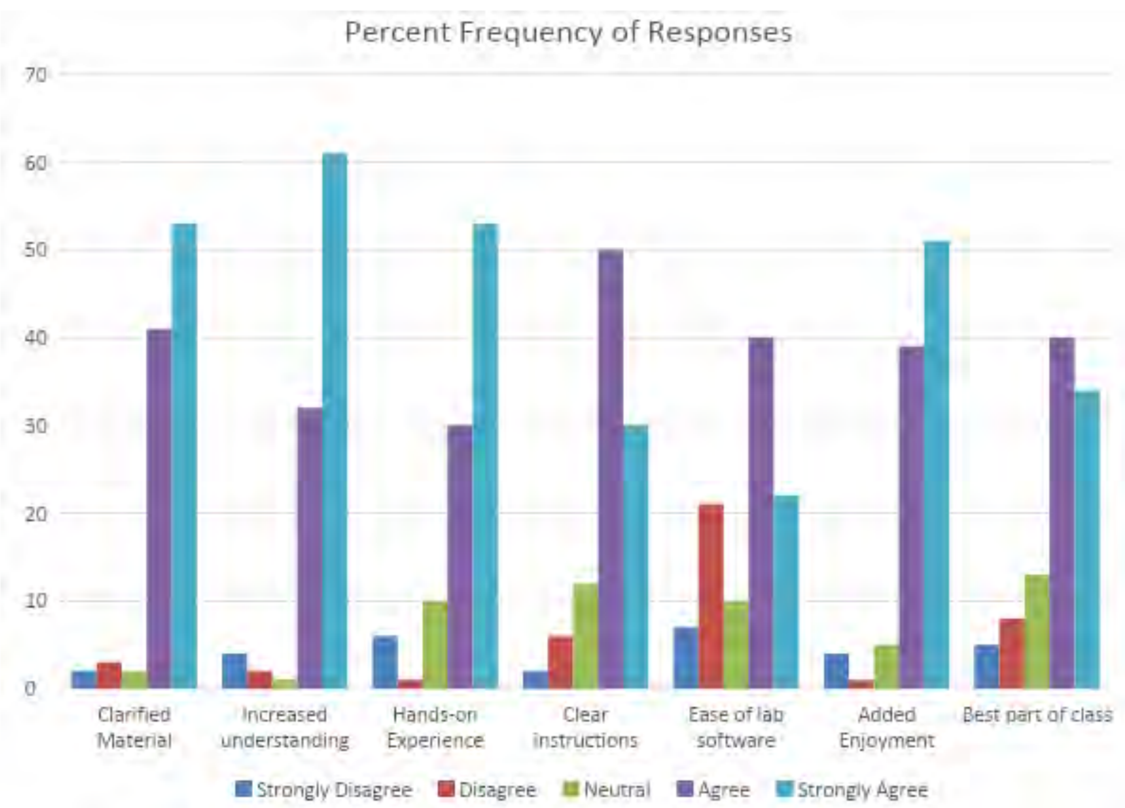


Figure 4
Student Responses to Survey Data



When given the opportunity to provide feedback on the class, students in the lab course frequently mentioned the lab experiences they had. Typical feedback included comments such as (**bolded** emphasis added):

> As for the content, labs were so helpful in putting what we've read to use. Nothing can replace real classroom/lab settings but what we were able to go through were very good alternatives. I am a **visual learner** by way of doing things so being able to adjust settings and levers and **seeing how things interact helps me learn better**. I really wish other courses have similar labs.
>
> I think the labs, with the symposium as a capstone, were my favorite portion of the course. Doing them really helped me grasp the concepts of the readings, which could sometimes be a bit tough to digest. I have a hard time remembering something if it's just conceptual, so the **labs really helped me apply what I was learning**!

It is important to note that comments such as these were unsolicited and unprompted. They are representative of the kinds of comments instructors of the course in this study typically receive. Feedback like the comments included here indicates a strong student belief in the effectiveness of the lab exercises in increasing their learning. Coupled with the results in Figure 2, which show an increase in student scores for the lab sections of the class, these comments provide an additional indication of the effectiveness of the lab exercises in increasing student mastery of learning objectives in the course. It is the coupling of this student impression data with the quantitative data that brings validity to the idea of student satisfaction as an important aspect of internal motivation and focus in online learning environments.

Conclusions

This study shows that online laboratory exercises in a remote learning environment contribute significantly to learning outcome achievements. In addition, the results indicate a strong correlation between the inclusion of online labs in a course and student satisfaction. The data present in this article also suggest that working with real data and having the ability to explore concepts in a less structured lab assignment increases student mastery and retention of learning objectives.

Future Work

Data collection continues in order to increase the sizes of the student populations in the study. Increased participation will increase the accuracy of the statistical analysis performed here. Important avenues for future work also exist, including investigating a wider variety of online lab options to determine the most effective types of labs to use in order to maximize student mastery of core content. Another important area for future study includes expanding the project to include other sciences. Astronomy is an inherently visual science and attracts students who prefer visual learning modalities. It will be important to determine if the gains presented here are also found in other scientific disciplines, each of which has their own style of laboratory exercises. Work is currently underway to investigate the efficacy of online labs in APUS introductory-level physics and biology courses using the same model and method described in this article.

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