Student use of simulation-based optics lab experiments in introductory physics classes

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Computer simulations are used in introductory physics classes to help students understand abstract concepts through manipulating experimental variables. Learning in both the classroom and the lab requires a social construction of knowledge to develop both content and scientific skill mastery. One challenge, however, is the disconnect that has been seen between students' understanding of abstract concepts taught in the classroom with the real-world experiences in the lab. We report here on the usage of HTML5-based computer simulations in labs on geometric and physical optics in a large, algebra-based, studio physics course for life science students at a private, research-intensive institution. Our research on students' use of optics simulations in place of hands-on equipment demonstrate similar learning outcomes on quizzes and pre/post assessments as with traditional hands-on equipment alone. These results suggest a strategy for providing students multiple modes of dynamic visual representation through the use of simulations.

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I. INTRODUCTION

Laboratory instruction is an integral part of science classes, as it allows students to engage with physical phenomena and deepen their knowledge of course content [1]. Using virtual tools in physics labs may be imperative in online courses, and can encourage content mastery as part of in-person courses [2]. Interactive lab simulations allow students to easily explore physical concepts [3], encourage self-guided exploration [4], and may be more accessible, inexpensive, and less time-consuming during setup and tear-down [5, 6]. Alternatively, hands-on labs provide opportunities for students to interact directly with physical phenomena, learn how to use tools, and collect real data [1, 7], while simulation-based labs may present over-simplified and idealized contexts [8].

Previous studies have largely focused on student performance with simulated labs for topics in mechanics, and have found that simulated labs are at least as effective as hands-on labs in supporting conceptual learning objectives for labs [2, 9–15]. As a continuation of previous studies, we compared student learning outcomes of simulation-based and traditional hands-on equipment-based labs for topics in geometric and physical optics. Transitioning from concrete concepts in mechanics, where students can directly observe interacting and moving objects, to the abstract concepts of optics often requires the use of visualization tools such as graphs and diagrams to fully represent physical phenomena. Therefore, the use of dynamic visual tools may better support student learning [16], such as those provided in simulations.

Here we investigate the research question: Do simulation-based labs or hands-on labs affect student understanding and content knowledge gain? Specifically, this study adds to the literature concerning the impact of simulated geometric and physical optics labs on student performance on standardized and course-specific assessments.

II. METHODS

A. Target Population

We conducted this study through an introductory, algebra-based electricity, magnetism, and optics course at a large, private, research university. This was a studio-style class geared towards life-science majors and ran for 15 weeks in the spring semester. The class initially enrolled a total of 434 students over 5 studio sections, of whom 414 completed the course. Studio classes in the SCALE-UP format combine lecture, discussion, and lab sections, and are designed to encourage collaboration and discussion by seating students at round tables [17]. The class was composed of approximately 63% female students, 26% male students, and 11% who either did not report their gender or chose gender nonconforming, with approximately 16% URM (underrepresented minority).

Each class section had its own teaching staff, composed of one faculty instructor, two graduate student teaching fellows (TAs), and two undergraduate learning assistants (LAs). LAs are undergraduates who have previously taken an introductory physics class and return to the class to assist in instruction [18]. LAs provide feedback and are available to help students understand course topics, in addition to graduate TAs and the faculty instructor. Each member of the teaching staff circulated around the studio classroom.

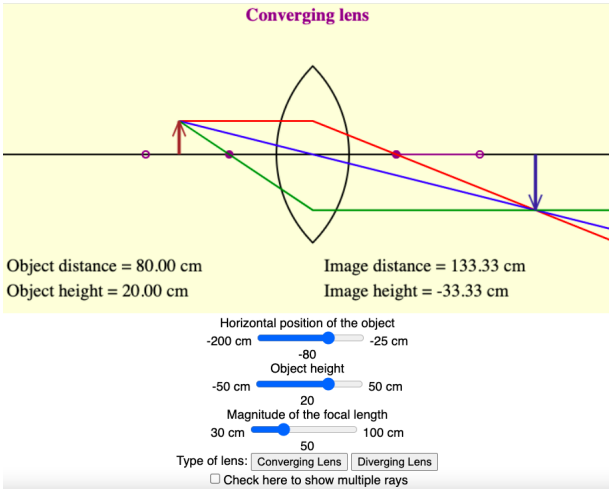


FIG. 1: Screenshot of simulation used in the Lenses lab. Students can manipulate the object position and height, as well as the focal length of a converging or diverging lens.

B. Experimental Design

Students were instructed in geometric optics concepts about lenses and in physical optics concepts about interference and diffraction using 105-minute interactive lectures for each. After instruction, students completed 105-minute lab experiments in each topic, during weeks 12 and 13 respectively (Table I). Lab experiments were therefore an essential part of instruction for both of these topics.

In this study, simulations were used in two labs by the experimental group, replacing the hands-on equipment of a traditional lab. Students in the control group completed an entirely hands-on lab experiment. For the lenses lab (geometric optics), students used an optical lab bench with either convex or concave lenses as well as a light source and screen. For the interference lab (physical optics), students used a red diode laser (650 nm) and a variety of single slits and double slits. Students in the experimental group completed a simulation lab that mirrored these experimental set ups.

The simulations (one on lenses and three different ones on interference and diffraction) were created by one of the authors (AD), and designed to represent common lab scenarios used during instruction. The simulations were written in HTML5 (Javascript). All lab materials, including the simulations, are available on the project website [19]. The lenses

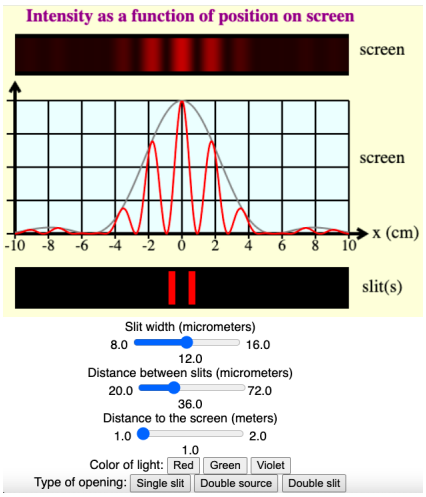


FIG. 2: Screenshot of simulation from the Interference and Diffraction lab. Students can choose from a wide range of wavelengths of laser light not easily done in a hands-on lab.

simulation used for the geometric optics lab featured an interactive animation of an object, a lens (either converging or diverging), and an image. Students could adjust the type of lens, the focal length, and the object distance and height, while the simulation shows a ray diagram along with the resulting image distance and height. A screenshot of the lens simulation is shown in Figure 1.

For the physical optics lab, students used three different interference and diffraction simulations. The first was a single-slit simulation in which the students saw a graph of the diffraction pattern. Students could use light of one of four different wavelengths, and adjust the distance to the screen. Students had to determine the slit width, and then use that information to find an unknown wavelength. The second simulation was similar, but was for a double slit. Students had to determine the slit width, the distance between the slits, and again determine an unknown wavelength. The third simulation was more full featured, with students selecting either a single slit or a double slit. A graph of the resulting pattern is shown, and students can adjust the slit width, distance between the slits, distance to the screen, and choose between three different wavelengths, as shown in Figure 2.

Students were either in the experimental (simulation only lab) or control (hands-on equipment lab) group based on their section in the course. Students flipped between the two groups for each lab, such that each student completed one lab using only a simulation (experimental group), and the other using traditional hands-on equipment (control group). While students could choose their class sections, they did not know which sections were part of the experimental or control group. The time available for every lab was kept the same.

Week	Assessment
1	LOCE Subset Pre-test
12	Lenses Lab
12	Quiz 4
13	Interference and Diffraction Lab
15	LOCE Subset Post-test
15	Quiz 5

TABLE I: Timeline of class assessments used in this study. The class ran for 15 weeks during the spring semester.

C. Assessments

We evaluated student performance using matched-set statistical analysis of topical course assessments on light and optics (Quiz 4 and Quiz 5) as well as a subset of questions from the Light and Optics Concept Evaluation (LOCE), a 50-item, multiple-choice research-based assessment of light and optics topics [20], administered as a pre- and post-test. A course timeline is shown in Table I.

Course Assessments on Optics: In this course, five quizzes were the primary source of assessment; no cumulative midterms or finals were given. Several course assessment problems were written to specifically address the scenarios and concepts covered in the lens and diffraction labs. Quiz 4 primarily focused on geometric optics, and Quiz 5 focused on physical optics.

A problem on Quiz 4 was about image formation through both the combination of a lens and mirror. Students were asked to draw ray diagrams and calculate image distances through both optical objects, as well as predict changes in the resulting images based on adjustments to the theoretical object set up. This problem was closely related to the lens lab, with the image provided in the quiz being similar to that in the simulation, as well as asking about physical adjustments that would be directly made with the hands-on equipment.

Two problems on Quiz 5 asked students about interference and diffraction from two point sources. One of these questions closely resembled the interference and diffraction lab, using an intensity graph like that shown in the simulation or that produced using the hands-on lab equipment. Students were asked to calculate the slit separation and slit width from the pattern shown for a particular given wavelength.

LOCE Subset Pre- and Post-Tests: A 26 question subset of the Light and Optics Concept Evaluation (LOCE) questions relevant to the material covered in the labs being studied in this research was administered to students pre- and post-instruction. The subset only includes lenses, image formation, diffraction and interference, excluding other topics [20].

Students were asked to complete the LOCE question subset as an online survey outside of class time prior to starting the course. Students were then asked to complete the questions a second time at the end of the course in the same online format but during class time, to help improve participation rates.

Assessment	N_1, N_2	$N_1\ \bar{x} \pm \sigma$	$N_2\ \bar{x} \pm \sigma$	Pearson's r	Cohen's d
Quiz 4 Total Score (Out of 20)	130, 113	17.44 ± 2.37	17.61 ± 2.46	0.04 ($p = 0.57$)	–
Quiz 4 Lab Problem (Out of 10)	130, 113	8.13 ± 1.72	8.09 ± 1.69	0.01 ($p = 0.87$)	–
Quiz 5 Total Score (Out of 20)	130, 113	16.21 ± 3.50	16.48 ± 3.48	0.04 ($p = 0.56$)	–
Quiz 5 Lab Problems (Out of 7)	130, 113	4.93 ± 1.85	5.26 ± 1.74	0.09 ($p = 0.15$)	–

TABLE II: Statistical analysis of course assessments on optics. Entries of "–" for Cohen's d indicate that no statistically significant differences between experimental and control groups were found for any of the assessments listed.

D. Data Analysis

We included only students with matched score sets on the LOCE subset as well as those who completed the course. Selection criteria for the LOCE pre- and post-test responses were applied to determine which students would be included in the analysis [21]. We required a minimum length of 5 minutes for survey responses and a 70% or greater completion rate of each survey [22]. Of the 434 students initially enrolled in the course, 243 met the inclusion criteria for analysis (57% included). Of those who met the inclusion criteria, 130 students were in the first experimental group using the simulation for the lenses (geometric optics) lab (N_1 = 130) while the remaining 113 students were in the first control group using hands-on equipment for the same lab (N_2 = 113). For the second lab on interference and diffraction (physical optics lab), the two groups switched, with N_2 acting as the experimental group with the simulation only, and N_1 acting as the control group with the traditional hands-on equipment only.

For all assessments, we calculated two-tailed Pearson's correlation coefficients (r) and Cohen's d effect sizes, along with associated p-values, between the experimental (simulation lab) and control (hands-on lab) groups. Normalized content learning gains were calculated for each group between the pre- and post-test LOCE scores [23].

III. FINDINGS AND DISCUSSION

Course Assessments on Optics: As shown in Table II, students on average scored well on quizzes with optics-specific assessments, but statistical analysis resulted in very small Pearson's r and Cohen's d values, with $p > 0.05$. We therefore found no statistically significant differences in Quiz 4 total scores, Quiz 5 total scores, Quiz 4 lab-specific problem scores, or Quiz 5 lab-specific problem scores between the experimental and control groups.

LOCE Subset Pre- and Post-Test Scores: For the pre-instruction LOCE scores, the p-value shows statistical significance ($p < 0.05$); however, the effect size is small between the two groups (d = 0.293), and the confidence level has a high range between medium and no difference. In addition, the correlation value is small (r = 0.146) [24]. Therefore, we conclude that there is no significant difference between groups on the LOCE pre-test. Furthermore, there was no statistically significant difference between groups on the LOCE post-test (p = 0.155) with a small correlation value (r = 0.091) and small effect size (d = 0.183). This indicates that despite possible differences in understanding these concepts based on past experiences (as measured by the pre-test), students showed similar levels of understanding post-instruction. We conclude there are no significant differences between the experimental groups on either the LOCE pre- or post-test. While overall normalized gains were low (below 0.3) [23], the two groups did show small increases between pre- and post-instruction scores (N_1: g = 0.025, N_2: g = 0.112).

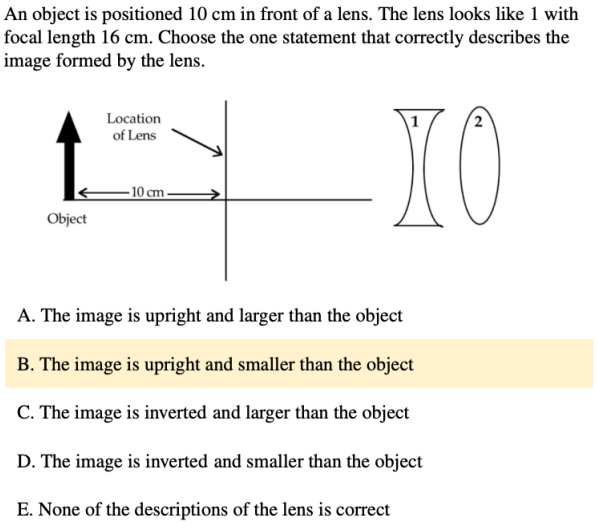
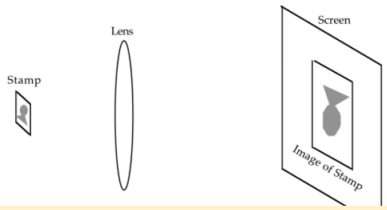


FIG. 3: LOCE assessment item 22 on geometric optics with correct response shown (B). The figure is similar to the ray diagrams in the simulation used by the experimental group.

LOCE Subset Item Responses: There were two items in the LOCE subset that showed statistically significant differences for post-instruction scores between the two groups. The experimental group that used the simulation lens lab (N_1) had more students answer item 22 correctly (as shown in Fig. 3) than the group with the hands-on equipment lens lab (N_2) (r = 0.149, p = 0.020). This question was about the formation of an image through a diverging lens, suggesting that having the visual representation of a virtual image in the simulation, including the principal rays, may have been beneficial for students in their ability to answer this item. Figure 3 shows the

A stamp is placed to the left of the lens, and its image is formed on a screen to the right of the lens. Suppose that the screen is temporarily moved further away with the positions of the stamp and lens unchanged. Which is true?



A. The image will be blurry

B. The image will be sharp but slightly larger

C. The image will be sharp but slightly smaller

D. The image will be unchanged

E. The image will disappear

F. None of these is correct

FIG. 4: LOCE assessment item 27 on geometric optics with the correct response highlighted (A). The figure given is similar to the optical bench setup used by the control group.

specific item, image, and correct answer.

In comparison, the group with the hands-on lens lab (N_2) had more students answer item 27 correctly than the experimental group with the simulation lens lab (N_1) (r = 0.204, p = 0.001). This question, as shown in Figure 4, was about image formation when an experimental system is physically altered, suggesting that having the hands-on experience in the lab may have been beneficial for students in their ability to answer this question. Furthermore, the figures provided in each question differ qualitatively, with the figure in item 22 being similar to an incomplete ray diagram much like shown in the simulation for the lab. For item 27, the figure looks more like the physical lab setup with hands-on equipment.

IV. CONCLUSIONS

We investigated student performance on topical assessments on geometric and physical optics when using either a hands-on or a simulation-based lab. Students were divided into two groups, one who used a traditional hands-on lab setup, the other using a computer simulation designed for the lab. We did not find evidence of improved or diminished student performance between groups.

This result suggests that the mode of presentation for optics labs (hands-on or simulation-based) in these in-person, studio-style introductory second-semester physics classes does not affect student performance or knowledge gain on optics topics. This adds to the current body of knowledge on the effects of simulation, hands-on, or hybrid labs on student understanding and course performance, based on the mixed results of the research literature [2, 9–15, 25]. Because simulation-based and hands-on labs may affect course performance equally, it may be useful to implement simulation-based labs in classes with limited equipment resources or lab space, or classes conducted during semesters with blended online and in-person learning due to external circumstances.

V. LIMITATIONS AND FUTURE WORK

Regarding limitations, this study may not have minimized instructor effects on student performance. There were five different faculty instructors, ten different TAs, and ten different LAs over five class sections, which may have caused differences in student performance due to varying teaching methods and graders. We also acknowledge that students in this physics course are mostly junior and senior life science majors at a large, private university, and our subjects are not necessarily representative of all physics students in the United States in demographics or mathematical preparedness [26].

In addition, this study focused only on students' conceptual understanding of geometric and physical optics, which may limit the generalizability of our results. It is also best practice to administer all the questions in a research-validated assessment like the LOCE, not just a subset. In the future, we intend to conduct similar studies with labs on other concepts, especially more complex topics that are less readily visualized [7]. Moreover, some skills only gained in hands-on labs, such as understanding real data and using instruments and tools, or developing beliefs and expectations about experimental science, are not best measured with the LOCE or other conceptual assessments. These learning gains should not be overlooked, and in the future, it may be useful to include assessments such as the Physics Lab Inventory of Critical Thinking [27] or the Colorado Learning Attitudes about Science Survey for Experimental Physics (E-CLASS) [28].

Finally, the differences in how the two groups answered items 22 and 27 from the LOCE suggests that there may be a connection between the context in which they learned the material (i.e. whether they conducted the simulation or hands-on lab) and the context of an assessment question. Our results suggest that the wording of the question or use of a specific visual in the item may impact students' answers in research-based assessments. More work may be needed to better understand student use of visual tools for learning about optics.

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