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An Equity-Focused Redesign of an Introductory Organismal Biology Lab Course To Develop Foundational Scientific Practices

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Laboratory courses can serve as important avenues to equitably support introductory biology students to develop foundational scientific literacy skills while experiencing the authentic research process. We present a model for an equity-focused redesign of an introductory organismal biology laboratory course at a teaching institution with limited research infrastructure. We incorporated elements of inquiry, structure, and climate into our three redesigned course components: weekly research investigations, skill-building assignments, and student-designed group projects. Students were trained in the research process through weekly experiments using locally relevant model organisms, collecting and analyzing novel data and writing brief results sections in the conventions of a research journal article. Student groups then collaborated to complete a student-designed research project and poster presentation using one of the model organisms. Through weekly inquiry labs and practice in skill-building assignments, most students in the sample mastered skills in analyzing, graphing, and writing about experimental results. Notably, students mastered skills that were practiced more frequently throughout the lab course, demonstrating the value of repeated and scaffolded practice. Students reported significant gains in self-efficacy and science identity, as well as sense of project ownership. Student gains were influenced by instructor but not their major or the semester in which they took the course, and growth occurred across students regardless of their incoming score on the presemester survey. This intentional course design model, combined with consistent expectations for instructors across multiple sections, has the potential to equitably support students with a range of prior knowledge and experiences to make meaningful gains in science literacy skills during an introductory semester.

KEYWORDS course redesign, data analysis, equity, inquiry, introductory biology, organismal biology, project ownership, research skills, self-efficacy

INTRODUCTION

Structural change for STEM equity

Making the introductory undergraduate biology experience more inclusive is critical for supporting the retention and success of all students in science, technology, engineering, and math (STEM), especially first-generation college students and those who are minoritized and excluded from science due to race and ethnicity (1). By employing an equity mindset to frame student performance and success in introductory biology courses, we attribute differential student outcomes to systemic issues and institutional shortcomings, and not to student "deficits" in background preparation or motivation (2). This mindset is empowering for faculty, because we can explore how course design and pedagogical practices can be used to remove barriers and provide supports for student learning, and through these institution-centered approaches we can change STEM culture to support all students interested in pursuing science (1–3).

Scientific literacy is critical for success in undergraduate STEM

Scientific literacy, which involves knowledge of scientific concepts but also an understanding of the nature of science (4, 5), is critical for success in undergraduate STEM fields. Development of scientific literacy is particularly important as many undergraduate biology programs have moved toward adopting the American Association for the Advancement of Science (AAAS) *Vision and Change* recommendations, which emphasize incorporating competencies related to the process of science, science communication, and quantitative and

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data interpretation skills (6). Therefore, introductory undergraduate biology courses serve as a critical context for equitable building of scientific literacy in biology majors through intentional course design and pedagogy. Our introductory organismal biology laboratory course at a 4-year teaching institution with limited research infrastructure serves a diverse student body, including many students who enter a biology major with limited quantitative skills or previous hands-on research experiences. We aimed to redesign our entire introductory lab course using an equity mindset to develop scientific literacy through authentic research and structured skill-building experiences in a supportive learning environment.

Equitable training in foundational scientific skills through course-based research

Engaging in scientific inquiry allows students to develop an understanding of the nature of science, because it involves authentic processes through which scientific knowledge is acquired (4). Research- and inquiry-oriented lab courses equitably provide all enrolled students with opportunities to engage in the "essential components" of mentored research, particularly in instances where students have ownership of projects and work collaboratively (7–11). Engaging students in authentic research practices in coursework can provide students opportunities to use scientific practices and communicate discoveries through authentic assessments, including data reports and scientific posters and presentations (12).

Course-based undergraduate research experiences (CUREs) engage students in a semester-long research project that involves iterative work toward discoveries that are relevant to a broader scientific community (13) and have been shown to have positive effects on undergraduate students' sense of project ownership and intention to pursue science (14, 15). Conversion of courses to a complete research-based CURE model, unfortunately, is often not logistically feasible for many institutions that may not have the research infrastructure, staff, and/or the financial, supply, or space resources required to engage students in these research experiences (16–18). An alternative course design approach is to engage students in short-term weekly or modular inquiry experiences which have positive impacts on student sense of project ownership (19), enhanced student self-efficacy and improved inquiry skills (20), and increased sense of scientific ability (21).

Overlaying attention to course structure and climate in STEM labs

Beyond the inquiry and research activities themselves, lab course redesign for equity should also consider course structure and climate. Students enter STEM courses shaped by their past experiences, and these can influence success and sense of belonging (22). Instructor interventions that communicate a growth mindset, belonging, and high expectations with assurances of capacity for success can help to mitigate stress and underperformance that can accompany past negative experiences in STEM (22). Additionally, increased structure in introductory biology courses for majors can enhance learning gains and sense of belonging, often with disproportionally positive impacts for minoritized students in STEM (23–25). Scaffolding is an instructional approach that provides structured guidance to students throughout the learning process in an efficient and effective way, and it is particularly important during skill-building at the introductory level, where most undergraduates have limited prior experience with the processes of science (26). Students who receive intentional guided instruction in science process skills early in their undergraduate careers demonstrate better content acquisition and interdisciplinary ways of knowing; however, many faculty report not making sufficient time for this skill-building in their course design (27). Course design that scaffolds teaching of scientific skills through inquiry experiences can positively impact experimental design skills and science process skills in introductory biology (21, 28, 29). Intentional instruction during course-based inquiry experiences can also be used to teach quantitative and statistical skills that are critical to research and hypothesis testing in the discipline and often not taught in introductory biology (30–33). Direct instruction in these analytical skills during the introductory course can provide a solid quantitative foundation and has the potential to level the playing field for undergraduates who may not have experienced or mastered them in secondary school, especially during the COVID-19 pandemic (34). Transparent assessment design—which communicates the purpose and the relevance of the assignment, details the specific tasks the student is asked to do, and articulates the criteria by which students will be graded—complements scaffolded instruction and has been shown to be beneficial for first-generation, low-income, and underrepresented minoritized groups (35). Providing frequent opportunities for feedback (36, 37) as well as use of a mastery-based grading system that outlines a clear list of learning targets and allows students multiple opportunities and revisions to demonstrate mastery (38, 39) are supportive ways to cultivate motivation and growth mindset during the learning process. Finally, using all free resources is a course design decision that ensures that students do not withdraw from or fail a course due to inability to afford the course materials (40).

We aimed to incorporate these elements of inquiry, structure, and climate to engage in an equity- and scientific literacy-focused redesign of our introductory organismal biology lab course. Below, we describe our redesign model in detail. We then provide an assessment of the extent to which the redesign model increased student data analysis and writing skills, fostered student dispositions related to persistence in the sciences, and enhanced consistency of student learning gains and course experiences across multiple semesters of a multisection introductory biology lab course.

METHODS

Institutional and course context

This study was conducted at Salem State University, a regional comprehensive public 4-year institution on the north shore of the Boston, MA area. Salem State serves a diverse student body and accepts students with a range of academic preparation (e.g., the academic year 2020 university acceptance rate for the first-year class was 88% and the enrolled first-year class was 40% students of color). The Introduction to Organisms course is one-half of a two-semester sequence for biology or related STEM majors who are typically first-year or early-stage transfer students. The course examines the diversity of life within evolutionary and ecological frameworks and includes a required lecture and corequisite lab enrollment. All lab sections meet in-person for 2 h and 40 min once per week throughout the semester.

Original laboratory format

The original laboratory format involved weekly exercises of mostly nonexperimental observations, basic dissections, and computer simulations that required a paid subscription. The lab lacked opportunities for student experience with nature of science through scientific inquiry, as only 6 of the 12 lab activities involved hypothesis testing and active data collection and analysis. Learning for 11 of the 12 labs was assessed from worksheets in their purchased published lab manual that prompted students to label drawings or write short responses to a list of questions. When data analysis did occur, graphs were printed and attached to the lab manual worksheet to reference when answering question prompts. One instructor-designed experiment was performed by student groups midsemester. A research proposal and complete written lab report of the results were required of all students following this experiment, though limited lab time was used for instruction on the experimental or scientific writing process. Instead, students were referred to a required text about writing in the biological sciences.

In summary, the original lab format provided limited opportunities for students to experience the nature of science and inquiry, or to engage in independent scientific skill development through repeated and supported practice of specific skills during lab activities and on assessments. We observed that students who entered the lab course with prior experience in basic scientific practices (e.g., graphing, statistical analysis, designing experiments with replicate data, etc.) did well, while those with limited experience still lacked proficiency in these fundamental skills at the end of the course. This led us to complete an equity- and scientific literacy-focused redesign of the lab course.

Laboratory redesign process

With support from an institutional grant from the Davis Educational Foundation the authors received stipends to pursue substantial lab course redesign work. Work during Spring 2018 involved articulating objectives for scientific literacy, mapping out authentic experiments, and scaffolding of scientific skills across the redesigned course weeks. The most substantial stipend-supported work took place during Summer 2018. We piloted experiments for the redesigned lab by collaborating with undergraduate research assistants (an approach that has been demonstrated as valuable for biology course redesign [41]), who were supported through their own internal departmental grants for summer undergraduate biology research. During this time, we coordinated with the laboratory technician staff that prepared the labs during the semester, drafted the free biology lab manual website for students (using Google sites) containing protocols and data analysis tutorials, and created course assessments and research instruments. A sample assignment with rubric is provided in the supplemental material, and additional assignments and a link to view the lab manual website are available upon written request to the authors.

Research data collection and analysis

Sample. Data were collected from all sections of the redesigned lab course during three semesters, Fall 2018 (3 sections; $n = 52$ students), Spring 2019 (4 sections; $n = 64$ students), and Fall 2019 (4 sections, $n = 64$ students). All course sections in the study were capped at a maximum of 20 students and were taught by one of three full-time instructors in the Biology Department.

Synthesis assignment to measure skill-building. Following the weekly lab and assignment series (about midsemester), students completed a synthesis assignment consisting of 8 multiple choice items related to experimental design and data analysis, as well as a graphing task to create a well-formatted figure and caption. Students completed the synthesis assignment online in the learning management system and were allowed to use their lab notebooks, previous assignments, and course resources but were required to work independently. Data about semester and lab instructor were recorded for the synthesis assignment data set, but student names were removed for the research data analysis. Data were pooled for all sections ($n = 168$ students; response rate of 93%). Item analysis was performed, and these data were compared to the number of times that the skill was practiced in weekly assignments. Graphing task data were pooled for all sections ($n = 155$ students; response rate of 86%) and scored using a standardized 20-point checklist (see Appendix S3 in the supplemental material). Item analysis for each graphing checklist item was performed, and the percentage of students correctly demonstrating each checklist item was calculated. The influences of semester and instructor on scores were examined using an effect tests in JMP Pro 16.

Skills and attitudes survey. We administered surveys during the first and final weeks for each of the study semesters to capture data about changes in skills and attitudes that occurred after completing the redesigned lab course. The survey included 10 true-false and multiple-choice questions to assess a range of skills related to data analysis and interpretation and experimental design. Three of the skill items were selected from the Test of Science Literacy Skills (TOSLS) (42), and the remainder were created in-house by the study authors. The presemester and postsemester survey also included nine Likert scale attitudes items selected from the published Persistence in the Sciences (PITS) assessment survey (43) that were related to self-efficacy, science identity, and science community values. The selection of PITS survey items was to avoid survey fatigue but still cover a range of attitudes. Students completed a survey coversheet in which they stated their major, their course semester and section, and a personal code to link their presemester and postsemester scores for analysis. Our sample included 146 students who fully completed the skills portion of the survey both pre- and postsemester (response rate = 81%) and 140 students who fully completed the attitudes portion of the survey both pre- and postsemester (response rate = 78%). Changes in skills scores from presemester to postsemester surveys were compared using matched-pairs *t* tests in JMP Pro 16. Changes in attitude scores from presemester to postsemester surveys were compared using matched-pairs Wilcoxon signed rank analysis in JMP Pro 16. We calculated normalized changes in the skills score and attitudes score to capture the ratio of gain to the maximum possible gain, or loss to the maximum possible loss, across the semester (44), and then we used JMP Pro 16 to examine the influence of the fixed effects of major, instructor, and semester on the normalized change scores using parametric effect tests for skills and effect likelihood ratio tests for attitudes. Additionally, we examined the distribution of normalized changes in skills and attitudes scores based on student presemester survey score quartile, and we also examined the correlation between normalized changes in skills and in attitudes for each student for which we had paired data.

Project ownership survey. We selected eight items related to project ownership content from the PITS survey. The project ownership items were listed at the postsemester skills and attitudes survey (described above). Our sample included 149 students who fully completed the project ownership survey (response rate = 83%), and we used JMP Pro 16 to examine the influence of the fixed effects of major, instructor, and semester on the average project ownership scores in the sample by using effect likelihood ratio tests.

RESULTS

Structure of the redesigned laboratory course

In the redesigned laboratory format, we aimed to scaffold research skill-building so that students learned, practiced, and mastered analyzing data and writing results sections during the first half of the course and were equipped to design, carry out, and present their own student-designed research projects during the final weeks of the course. To this end, the redesigned course format had three main features, each carefully planned with equity-based principles in mind; these features are described below (and summarized in a detailed table in Appendix S1).

Weekly research investigations with a diversity of model organisms. To train students in the process of science, the first half of the redesigned laboratory course engaged students in weekly investigations using a new model organism each week (Table 1). Model organisms were intentionally chosen to reflect local habitats and biota, contributing to a sense of place and to tie experiments to ecological and societal issues. Students were trained in how to prepare lab notebooks for research investigations during the first lab of the semester. To prepare students for each inquiry lab, students read background information on the free lab manual website and then wrote overview purpose paragraphs and hypotheses in their lab notebooks. Students also drafted data tables from the lab manual website into their lab notebooks so that they were ready for data collection in lab.

During lab, students received a brief introduction to the model organism and the experimental context, as well as the new equipment and measurement techniques to be used that week. Students then worked in small groups using shared equipment at lab benches to collect data to test their hypotheses. Experimental outcomes were unknown to both students and instructors. The weekly research investigations were collaborative by design, encouraging peer support and relationship-building, yet they also required each individual to be an active participant in experimentation and data collection. Every student was responsible for generating at least one replicate data point for the class data set in each lab, reinforcing that their role was critical to the group. Students who were proficient with the lab skills that week generated additional data points, while students who were developing proficiency during lab worked at their own slower pace with the support of peers and instructors. All data were pooled on a collaborative spreadsheet, and this served as the data set for the skill-building assignment that week.

Skill-building through scaffolded assignments. Following the Snail, Algae, Stomatal Density, *Daphnia*, and Lettuce Seed labs, students engaged in skill-building assignments focused on authentic data analysis, figure preparation, and writing for scientific journals (Table 1). Specifically, we aimed for students to be able to create properly labeled graphs of experimental data and write accompanying figure captions, perform statistical tests and interpret the results, write results text narratives that incorporated statistics and figure references, and interpret data from their experimental results and related published research articles to evaluate hypotheses. After data collection in each weekly investigation, instruction was provided about the new graphing, statistics, or writing skills that were to be practiced that week. The assignment documents provided detailed guidance for the analysis of the collaborative class data set using Microsoft Excel for graphing and free online calculators for statistics. Additionally, the electronic lab manual contained a "Data

TABLE 1
Overview of weekly lab experiments and corresponding assignments

Question and model organism	**How does species richness vary along a habitat gradient in a marine ecosystem?**	**What is the relationship between shell height and movement in the Eastern mud snail *Ilyanassa obsoleta*?**	**How do light exposure and nutrient levels influence population growth in *Tetraselmis* algae?**	**Does CO_2 exposure in the habitat influence the stomatal density of *Rhododendron* plant leaves?**	**How does environmental salt contamination influence mortality of freshwater *Daphnia magna*?**	**How does environmental salt contamination influence germination and growth of *Lactuca sativa* seeds?**	**How does relative heart mass vary across vertebrate animals?**
Relevance	Biodiversity, ecological buffers to climate change	Invasive species	Biofuels, harmful algal blooms	Pollution	Ecotoxicology	Ecotoxicology	Physiological ecology, natural history of vertebrates
Field and laboratory techniques	Quadrat sampling along a transect; species identification using iNaturalist; species richness calculations	Labeling of snail shells; measurement of shell heights using calipers or rulers; quantification of snail movement using observation grids	Hemocytometer counts of algae using compound microscopes; algae population density calculations	Preparation of stomatal peels; stomatal counts using compound microscopes; stomatal density calculations	Preparation of NaCl solution dilution series; mortality observation assay	Preparation of NaCl solution dilution series; measurement of germination and root length	Dissection of various vertebrate specimens; measures of whole body and tissues; calculation of relative heart mass
Assessment	**In-Class Summary**	**Weekly Data Assignment**	**Weekly Data Assignment**	**Weekly Data Assignment**	**Weekly Data Assignment**	**Weekly Data Assignment**	**In-Class Summary**
Scatterplot		Simple			Multiseries		
Calculating means and SD		x	x	x	x	x	x
Column graph	Column graph	Column graph + custom error bars of SD	Column graph + custom error bars of SD	Column graph + custom error bars of SD	Column graph + custom error bars of SD	Column graph + custom error bars of SD	Column graph + custom error bars of SD
Figure captions	x	x	x	x	x	x	x
Connection to published literature		x	x	x	x	x	
Statistical test(s) and results narrative			*t* test	*t* test	ANOVA, Tukey's	ANOVA, Tukey's	Selection of *t* test or ANOVA based on data comparison

Analysis and Writing" navigation tab that directed students to nine separate "skills" pages that provided tutorials for each skill (e.g., mean and standard deviation, *t* tests, reading journal articles, etc.).

Assignments were scaffolded so that new data analysis skills were introduced progressively across the weeks, and they were iterative such that skills that were introduced in previous weeks were repeated in subsequent assignments. Students also analyzed their results in the context of published scientific studies (selected by the instructors) that were relevant to each lab investigation (41). To train students in the skills needed to evaluate and make connections to scientific findings in a discussion section of a paper, figures from the selected studies were provided with accompanying "thought questions" directed at interpreting figures and comparing their findings with those from the literature. Detailed rubrics were prepared to ensure transparency in assignment goals and grading criteria. Students submitted their assignments independently each week, and rubrics were used to provide students with specific feedback. Students were strongly encouraged to use instructor feedback to revise and resubmit their assignments without grading penalties and as many times as needed for mastery to be achieved (see Appendix S2 for a sample assignment and grading rubric).

Student-designed group projects. After building skills through structured lab investigations, students worked in small groups during the final weeks of the course to design and carry out novel research projects using one of the model organisms previously encountered in the structured lab investigations. The research project was scaffolded such that each week students completed a new component of the scientific process. Students first worked together to design their experiments, generate the materials lists required so that the laboratory prep staff could collect necessary supplies and equipment, and prepare data sheets. Student groups then engaged in experimentation the subsequent week, working collaboratively to divide roles and collect reliable experimental data. The following week students conducted data analysis, prepared figures, and reviewed scholarly literature to reference in the discussion of their results. In the final week students collaborated on research poster preparation using a PowerPoint template and then shared their results in an e-poster presentation session in which all the group posters were simultaneously projected onto the whiteboards or bare walls of the lab. Students used collaborative template documents in Google Drive to guide each step of the process (documents are described and provided in reference 45). Students also provided constructive feedback on each other's posters, supplementing instructor feedback with peer feedback and modeling the peer review process. In the final assignment, students used a template to prepare a project summary, allowing them to independently report on the entire research process. The overall goals of the student-designed research projects were to comprehensively assess students' mastery of the targeted skills, while simultaneously reinforcing for students the notion that they are developing scientists—belonging to and practicing the conventions of the scientific community.

Synthesis assignment

Scores on the synthesis assignment multiple choice questions ranged from 12.5% to 100%, and the median score was 75% (first quartile [Q1], 62.5%; Q3, 100%; $n = 168$) (Fig. 1). Synthesis assignment multiple choice scores were not significantly influenced by semester (effect test, $F = 2.26$, $P = 0.108$) or instructor (effect test, $F = 1.97$, $P = 0.143$). Item analysis showed that students were more likely to earn points for multiple choice items related to skills that they practiced frequently in weekly skill-building assignments (Appendix S3). The percentages of correct responses ranged from 78% to 98% for skills that were practiced in all five weekly assignments. The percentages of correct responses ranged from 83% to 85% for skills that were practiced in four of the five weekly assignments. The

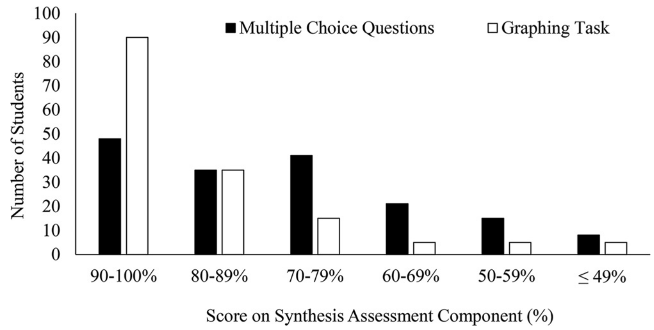

FIG 1. Distribution of synthesis assignment scores on the multiple-choice questions ($n = 168$ students) and graphing task ($n = 155$ students).

percentages of correct responses were lower for skills that were practiced only once or twice in weekly assignments (59% and 64% correct responses, respectively).

Scores on the synthesis assignment graphing task ranged from 10% to 100%, and the median score was 90% (Q1, 80%; Q3, 95%; $n = 155$) (Fig. 1). Synthesis assignment graphing task scores were significantly influenced by instructor (effect test, $F = 31.84$, $P < 0.001$) but not by semester (effect test, $F = 0.793$, $P = 0.454$). Item analysis of graphing checklist data showed general proficiency in creating properly formatted column graphs and figure captions, which was practiced in all five weekly skill-building assignments. Of the 20 items on the graphing checklist, 17 items were correctly addressed in 75% of our sample. Notably, for 11 of those 17 items, over 90% of the sample earned points (Appendix S4). Only 3 of the 20 checklist items were below a level of 75% proficiency by the pooled student sample: no autogenerated title inside the graph (item 5; 65% of sample), error bars correctly formatted (item 8; 69% of sample), caption includes statement that the data displayed are mean and SD (item 19; 55% of sample).

Project ownership content survey

Students generally agreed with the statements about project ownership that were presented on the postsemester survey (Table 2). Students felt responsible for the outcomes of their research and found the research to be interesting and exciting. In conducting research, students mostly agreed that they overcame challenges, sought advice, and felt a sense of personal achievement. Students reported more neutral responses about the research project feeling personal and important to them. Project ownership attitudes were significantly influenced by instructor (effect test, $P < 0.001$) but not by semester (effect test, $P = 0.100$) or major (effect test, $P = 0.280$).

Pre- and postsemester skills and attitudes survey

There was significant improvement in total scores on the 10-point skills survey from presemester (5.7 ± 1.9) to

TABLE 2
Project ownership attitudes from postsemester survey ($n = 149$ students)

Likert-scale project attitudes survey item[a]	Mean ± SD
I was responsible for the outcomes of my research.	4.2 ± 0.8
My research was interesting.	4.1 ± 0.9
My research was exciting.	3.9 ± 1.0
I faced the challenges that I managed to overcome in completing my research project.	3.9 ± 0.9
In conducting my research project, I actively sought advice and assistance.	3.9 ± 0.9
The findings of my research project gave me a sense of personal achievement.	3.9 ± 0.9
I had a personal reason for choosing the research project I worked on.	3.6 ± 1.0
The research question I worked on was important to me.	3.6 ± 0.9
Avg project ownership category score.	3.9 ± 0.7

[a]Likert scale: 1 = strongly disagree, 2 = disagree, 3 = neither agree or disagree, 4 = agree, 5 = strongly agree.

postsemester (6.4 ± 1.9) (matched pairs t test, $t = 4.12$, $n = 146$, $P = < 0.001$) (Fig. 2). Item analysis showed that the most notable growth in scores occurred in items that were practiced repeatedly during the lab course, such as data display in column graphs (items 1.2 and 1.3) and use of statistics (items 1.4 and 3.1). The item related to understanding the null hypothesis (item 3.2), a concept covered in statistical courses but not in our laboratory course, showed negative growth. Additionally, the items that were obtained from the published instrument (items 4, 5, and 6) were less likely to show growth across the semester compared to items written by the authors that were more directly related to lab course learning objectives and content (items 1.1 to 3.1) (Appendix S5).

There was a significant increase in total attitudes scores (out of 45 points maximum) from presemester (35 ± 5.6 [mean ± standard deviation]) to postsemester (37 ± 6.0) (matched pairs Wilcoxon signed rank, $n = 140$, $P < 0.001$) (Fig. 2). There were significant gains in students' average self-efficacy ratings (matched-pairs Wilcoxon signed rank test, $P < 0.0001$) and science identity ratings (matched-pairs Wilcoxon signed rank test, $P = 0.004$), but not in the science community values ratings (matched-pairs Wilcoxon signed rank test, $P = 0.605$) (Appendix 6).

Factors influencing change in skills and attitudes

Normalized change in skills was lowest for the students with the highest presemester skills scores (quartile 4); however, normalized change in skills did not significantly vary across the four quartiles of presemester scores (Welch's analysis of variance [ANOVA], $P = 0.134$) (Fig. 3A). The normalized change in skills was significantly influenced by instructor (effect test, $F = 4.99$, $P = 0.008$) but was not significantly influenced by student major (effect test, $F = 0.454$, $P = 0.715$) or semester (effect test, $F = 0.812$, $P = 0.446$).

Normalized change in attitudes was highest for the students with the highest presemester attitudes scores (quartile 4); however, there were no significant differences in normalized change in attitudes across the four quartiles of presemester scores (Welch's ANOVA, $P = 0.899$) (Fig. 3A). The normalized change in attitudes was significantly influenced by instructor (effect test, $P = 0.006$) but was not significantly influenced by student major (effect test, $P = 0.177$) or semester (effect test, $P = 0.346$). There was no significant correlation between

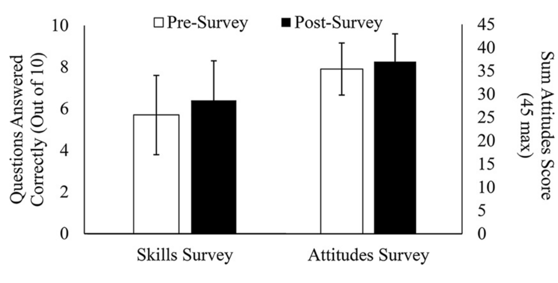

FIG 2. Changes in skills and attitudes (mean ± SD) from presemester to postsemester surveys ($n = 146$).

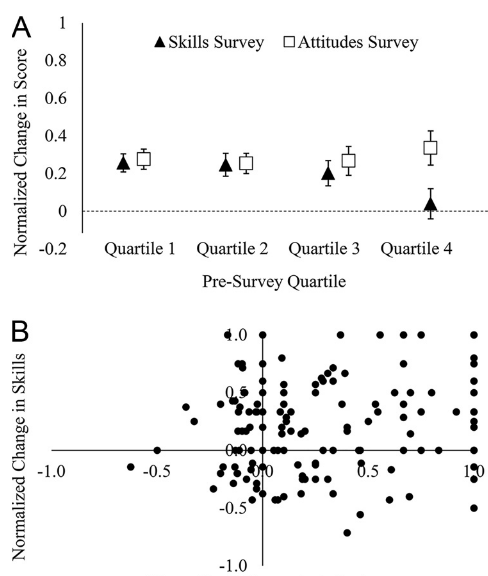

FIG 3. (A) Distribution of normalized change in skills and attitudes scores (mean ± SD) based on presemester survey scores. (B) Relationship between students' normalized change in attitudes and normalized change in skills.

normalized change in skills and normalized change in attitudes across the sample ($n = 135$; $r = 0.116$, $P = 0.1812$) (Fig. 3B).

Ethics statement

Our research protocols were reviewed and deemed exempt by the Salem State University institutional review board. Standard teaching lab safety principles and practices were followed to mitigate any biosafety risks associated with this project.

DISCUSSION

The majority of students built foundational research skills during the redesigned course

Our students, like many lower-division students, enter college with a range of high school preparation and often with limited experiences in using quantitative and statistical analysis skills in biology (30, 31, 46). Indeed, in our survey, the skills items associated with error bars of standard deviation and interpreting *P* values were among the lowest-scoring items for our incoming introductory biology students. Through our redesigned course, most students developed scientific skills related to data analysis and preparing results sections in the conventions of a scientific journal. Using 70% as a lower bound for proficiency (47), we found that three-quarters of the students sampled demonstrated proficiency on the concepts tested in the synthesis assignment multiple choice questions, and over one-third of those proficient students scored 90% or above. Additionally, proficiency in creating a properly formatted graph and caption on the synthesis assignment graphing task was at 90% for our sample. Therefore, we have evidence that through our equity-based redesign of weekly lab investigations and skill-building assignments, most of our students were able to improve skills in analyzing, graphing, and writing about experimental data. This corroborates findings from other studies demonstrating that use of guided-inquiry modules can support positive gains in scientific reasoning and experimental design skills (21, 48, 49) and statistical skills (30, 31).

Student gains in knowledge and skills occurred independently of their declared major or the semester in which they took the course, and growth occurred across students regardless of their incoming score on the presemester survey. This suggests that this intentional course redesign equitably supported introductory students with a range of prior knowledge and experiences to make gains during the course. Notably, students mastered skills that were practiced more frequently throughout the lab course. This demonstrated the value of a course design that included repeated and scaffolded practice for introductory students to build foundational skills and that such a course has the potential to help set up all students for success, regardless of their high school background and experience (46, 48). A limitation of this study is that we were not able to disaggregate data on student outcomes based on student demographics (race, ethnicity, gender, first-generation status, etc.), and this would be an important step to fully assess progress toward equity (2). Another limitation is that we were not able to track students after the semester of introductory organismal biology. Future studies would benefit from increased demographic data collection and disaggregation and continued surveying of the students throughout their undergraduate career to determine the extent to which the skills and knowledge persist and are built upon as students take more advanced biology courses.

The redesigned course led to gains in dispositions associated with persistence in the sciences

Previous studies have shown that scaffolding skill building through inquiry-based learning can increase students' awareness of their own skills and increase their perceptions of their ability to do science (21, 50). During our redesigned course, students reported increased sense of science identity and self-efficacy, dispositions that are positively associated with students' persistence in the sciences (43, 51). An additional factor associated with student retention in the sciences is project ownership, which is a metric that has been used in particular to show the value of course-based research experiences over traditional lab formats. In our course redesign, students completed a short-term group research project that allowed them to take full ownership to design a novel experiment using a model organism and methods practiced in the first half of the semester, and they were responsible for independently completing all aspects of the research process. Students reported a general sense of project ownership in line with scores reported by other students who completed short-term research experiences in the context of a lab course (19). Therefore, course design that sequences a short-term group research project after scaffolded skill-building can enhance student confidence to engage in research at the introductory level (19, 21). We believe that by intentionally building research skills through weekly lab investigations, assignments, and feedback in the beginning of the course, each individual student in our redesigned lab course was better equipped to contribute to the student-designed group project in the latter part of the course. The benefits of this course design model may be appealing as an alternative to semester-long CUREs, which typically lead to higher project ownership scores for students (19) but have multiple perceived and real barriers to implementation, including lack of faculty time, resources, and research infrastructure, particularly at teaching institutions (16, 18).

It is important to note that in our pre- and postsemester survey, students' normalized change in skills did not correlate with normalized change in attitudes, a phenomenon that has been reported in previous studies (52). This supports the value of examining actual learning gains in conjunction with self-reported measures when studying the effectiveness of a course-based learning experience, especially at the introductory level (53, 54). A limitation of our study is that the only method of measuring attitudes was through Likert surveys. Future studies would benefit from supplementation with measures of student dispositions that allow for authentic and candid student feedback. Such surveys might aim to evaluate students' confidence and sense of abilities (21, 55) and how they relate to the scientific skill proficiencies of the student.

Course implementation considerations to enhance equity and consistency of outcomes

Introductory undergraduate biology courses are often relatively large and multisection courses taught by teams of instructors and/or teaching assistants. Through our course redesign, we aimed to create a model that led to learning and affective gains for students that were consistent across multiple sections and semesters. Our analyses showed no significant effect of semester on synthesis assignment scores, on surveyed skills and attitudes, or on project ownership. This consistency of effects indicated that the substantial effort taken during the summer to create structured lab activities, detailed homework assignments, and guided project documents for use in all course sections allowed for a solid course rollout beginning in the first semester of implementation. This finding provides justification for providing adequate time and compensation for faculty to dedicate to this substantial work to redesign for student research and substantial scaffolding in laboratory courses (16, 41).

An important finding was a significant effect of instructor on both student performance and student attitudes, which has been observed with other intentional biology course redesigns (41). While all instructors used the same assignments, the timing of grading assignments, the level of feedback, and flexibility to revise and resubmit assignments for mastery may not have been consistent across instructors. Additionally, while all lab activities were standardized across sections, the instructional delivery, engagement, and interaction between instructor and students likely varied. This could represent a "growing pain" of transitioning to a more authentic research experience in teaching labs, which requires instructors to actively engage more as research mentors and collaborators. This contrasts with a traditional "cookbook" lab, in which an instructor can spend most of the time passively monitoring, rather than engaging with, students (56). Research shows that noncontent "instructor talk" about pedagogical choices and the nature of science and to build rapport and relationships can communicate instructor immediacy and enhance classroom climate and student experience (57). Given that instructor interactive behaviors have positive impacts on student dispositions toward doing science (56), it is important to provide adequate instructor training and resources to ensure equity across instructors in student experiences and learning gains. Some examples include providing supportive instructional materials (e.g., slides for lab introductions, detailed guidelines for equipment demos), clearly outlined grading and feedback protocols to enhance consistency, and informal classroom observation exchanges and feedback on instructional engagement. Depending on departmental budgets or personnel, designating a course coordinator or course mentor to support full-time and contingent faculty who are teaching a newly redesigned course could help enhance equity in course experiences for students.

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

SUPPLEMENTAL FILE 1, PDF file, 0.4 MB.

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