PRACTICE

Developing Prerequisite Skills in a CURE through Competency-Based Assignments

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Abstract

Course-based undergraduate research experiences (CUREs) are increasingly popular, but less often implemented in core laboratory courses due to the strict learning objectives necessary for follow-on courses. A curricular core intermediate-level experimental biosciences laboratory course was implemented, which paired competency-based assignments with client-serving research projects to develop the prerequisite skills for upper-level courses in the context of authentic research. This CURE led to more favorable student outcomes and more positive perceptions than the previous course design. This approach was piloted at a private, research-intensive university in fall 2015 and scaled to full implementation the following year. Several considerations and the necessary resources for such a scaling are discussed.

Keywords: *Abiosciences, laboratory courses, undergraduate research*

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Given the recognition of undergraduate research as a high-impact practice, course-based undergraduate research experiences (CUREs) are increasingly used as a strategy to make research experiences accessible (Bangera and Brownell 2014). The scale and development process for CUREs is varied; CUREs have been developed at the national level with shared research goals or techniques, at the local level with replication or expansion of these models, and by individual faculty to advance their research (Dolan 2016). CURE implementation has often focused on first-year experiences and upper-level laboratory courses (Shelby 2019). Incorporating CUREs in core laboratory courses often faces the challenge of defined learning objectives, because core courses serve as prerequisites for advanced courses. This article describes an intermediate-level experimental biosciences laboratory course that pairs competency-based assignments with client-serving research projects to develop the prerequisite skills for upper-level courses in the context of authentic research. The design develops student skills in a broad range of standard laboratory techniques, models the structure and hierarchy common in biological research laboratories, and integrates faculty research into the curriculum with low burden on faculty time. This CURE has led to more favorable student outcomes and more positive perceptions than the previous course design, and benefited from human capital and other resources that facilitated implementation.

Skills Competency

Prior to piloting CURE sections, the unmodified course included a defined set of skills practiced through close-ended inquiry-based experiments. Interviews with upper-level laboratory instructors revealed that all but one of the laboratory techniques used were indeed referenced in subsequent courses and used as the foundation for continued learning. In addition, a survey of research faculty identified skills that were most desired in students entering mentored research projects. These prerequisite and desired skills were established as the areas for competency assignments (Table 1).

Each of the competency assignments consists of text or video instructional materials about a technique and

TABLE 1. Competency Assignments

Laboratory techniques
Aseptic technique
Research microscopy
Solutions, dilutions, and the pH meter
Pipette training
Electrophoresis/SDS-PAGE
Creating a standard curve
Using controls
Communication skills
Laboratory notebooks
Displaying data
Scientific writing

questions or activities to test understanding. Assignments also often have a hands-on laboratory component to practice skills, with questions that allow students to self-evaluate their proficiency. Having a defined set of competency assignments that students complete regardless of their assigned research project allows the course to continue to serve as a prerequisite that meets the needs of upper-level classes. In addition, development of the CURE allowed better alignment with skills that faculty desire in novice undergraduate researchers taking part in mentored research.

Competency assignments are paired with a research project to constitute the laboratory work for the course. Ideal projects have the following features: (a) are small in scope so that students can make reasonable progress with just a few hours of laboratory work per week over a 14-week semester; (b) align with some (but not necessarily all) of the competency assignments; (c) align with the equipment availability and safety level of the teaching laboratory space; (d) utilize supplies covered by the course budget; (e) utilize techniques familiar to instructional faculty (or have training provided by faculty clients); and (f) involve exploratory or preliminary work, because there is no guarantee of publishable results. Additional faculty clients have been added each year and the variety of projects has expanded with equipment and supply purchases to support them. Projects have included optimization of protein expression, cloning and directed mutagenesis, development of PCR-based assays, forward-genetic mutant screens, and identification and characterization of microbial species. Because projects may align with different competency skills, the due dates for competency assignments are ordered differently for each research project so that students receive training in the skills that are explicitly used in their projects earlier in the semester. Typically, one research project is selected per course section, allowing instructors to coordinate due dates and grading across all students in a section.

Course Design

The CURE experience should represent the essence of a mentored research experience; therefore the course design sought to expose students not only to engagement in a research project, but also to mentorship structures and physical spaces for research. These goals are tightly linked to the elements of a CURE: scientific practices, discovery, relevance, collaboration, and iteration (Auchincloss et al. 2014). Although students principally experience these elements through participation in the research project and skills training, mentorship and the physical research environment also contribute to the enculturation of students in a scientific community.

Students experience elements of scientific practices in Experimental Biosciences CURE research projects by using literature and the research context to guide the decision-making process during their discoveries. The authority students have to make choices varies with the research topics; however, students gain experience in specifying the scope of their investigation, selecting and justifying their approach, collecting and evaluating data, and developing strategies for sharing results. Instructors define the research area and orient the students to the subject by providing introductory materials and scientific literature. Students frame a research question and select an approach that they describe in a project proposal. This proposal defines the student's initial approach and their plan for evaluating data. Students present their results to each other and to a professional audience that includes faculty clients. This provides the opportunity for students to place the relevance of their discoveries in the context of the field and of the goals and needs of the research faculty client. Students in this way act as research collaborators for the faculty clients with the goal of providing research products or data to the clients. In addition, students work as collaborators with peers in research teams. Students divide work on the research project among their team members and document their contributions in laboratory notes and an effort reporting system. As teams begin to get results, they may decide to examine reproducibility or modify their approach to pursue improved outcomes. Course instructor negotiation with research faculty clients is paramount for selecting projects with sufficiently small scope and a time frame that gives students the opportunity for iteration or modification.

The graded components of the course provide support and structure as students gain skills and experience elements of mentored research in the CURE. The competency assignments support students as they develop the basic laboratory skills to complete their research by requiring training and assessment in a defined set of common laboratory techniques. By checking research progress weekly during team meetings and drop-ins, faculty and laboratory teaching assistants serve as mentors, personalizing extension of skill sets for individuals and teams when appropriate. Competency assignments also support development of scientific communication skills, which are assessed in assignments that adhere to guidelines for the scientific communication genre (including project proposals, laboratory records, poster presentations, and progress reports). These communication assignments occur at different points in the semester and allow students to articulate the relevance of their work, describe their approach at different stages, and share their discoveries with different audiences. As part of a scientific community, students also have responsibilities as laboratory citizens. A portion of the course grade reflects their safe and responsible use of the laboratory space and shared equipment, ethical research conduct, dependability, and commitment to making progress. These qualities are observed by teaching assistants and instructors in the laboratory and self-reported by students in reflections and weekly progress surveys. What is not graded is the success or failure of any experiment; students are provided a safe place to fail scientifically without worry about an academic impact. Using this model, the course emphasizes the process of hypothesis-driven research rather than the outcome of a given experiment.

The Experimental Biosciences CURE mentorship structure familiarizes students with the hierarchical mentorship model common to many bioscience research labs. The key mentoring personnel are instructional faculty, undergraduate teaching assistants, and faculty clients. Instructional faculty work with faculty clients prior to the start of class to identify appropriate projects. Student registration in sections (of 18 students) allows teams (of 3 students) to meet weekly with instructional faculty, who monitor research progress and provide mentorship as students reach different stages of the research process. Instructional faculty and undergraduate teaching assistants routinely check in with students in the laboratory to provide guidance as students complete competency assignments and tasks for their research project. In cases where teaching assistants are unfamiliar with the techniques used by students, they model how to approach learning new methods through a series of steps: searching course material and the Internet, asking other students who are working on the same project, asking other teaching assistants who may have different knowledge and training, and, finally, asking instructional faculty.

Students plan a schedule for completion of their laboratory work, practicing the time management skills necessary for mentored research. In addition to research tasks, hands-on training for competency assignments and team meetings contribute to laboratory time. Because students may not be experienced in the time it takes to learn new techniques, instructors use team meetings to help students create a research plan. Students on the same team have mutual availability during their registered section time, but may have different schedules otherwise. Students can select to complete all laboratory work during the time of their scheduled section, or at self-scheduled times during laboratory open hours, when both instructional faculty and teaching assistants are present. Team members are not required to complete all steps of the research project and can assign tasks to different team members based on availability. Students use weekly progress surveys and a shared laboratory notebook to document their work so that instructors and team members have a record of activities completed by the team.

Availability of equipment should be considered when selecting projects so that students can complete their research tasks in teaching laboratory spaces. Unlike traditional labs where an entire class of students is expected to need the same equipment simultaneously, the flexibility to schedule competency assignments differently for each section results in students needing equipment at different times. Therefore, class sets of some equipment are no longer needed; equipment purchases and maintenance can follow demand. In addition, the variety of research projects can be managed so that different types of equipment will be used. Laboratory equipment is not staged for weekly assigned activities; instead, it maintains a consistent location in the laboratory throughout the semester. Operation manuals are included in digital course materials. Because equipment is not staged and step-by-step protocols are not available, students must become more familiar with equipment and procedural choices as they would in a research laboratory. Consistency of equipment location in the teaching laboratory not only mimics research lab environments, but also reduces instructor and staff time for weekly laboratory set-up.

Students participating in the CURE become part of the departmental research community, contributing to projects for faculty clients. This structure links teaching and research within the department with minimal time required from research faculty. Although research faculty may have additional roles if desired, the minimal commitment includes meeting with instructional faculty to establish the project and attending presentations of the students' work. The course design does not require a commitment of physical space from research faculty.

Methods

Experimental Biosciences was piloted as a CURE in fall 2014 (one section) and spring 2015 (two sections) at a

TABLE 2. Effect of CURE Participation on Graduation Outcomes

Dependent variable	Unmodified section cohort mean	CURE section cohort mean	Regression coefficient	Coefficien *t p* value
GPA at graduation	3.59	3.64	0.05	0.53
STEM major retention	53%	81%	0.81	0.02
Research participation	34%	53%	0.72	0.10

Note: GPA at graduation, retention in a STEM major, and participation in mentored research courses were assessed for CURE pilot students and an unmodified section (a comparison based on matched pairs). The regression coefficient is the effect of a binary treatment variable; the treatment is participation in a CURE section.

private, research-intensive university. Beginning in fall 2015, all sections of the course (six to ten per semester) utilized the CURE plus competency assignment format. Because the Experimental Biosciences course serves as a prerequisite for upper-level labs, outcomes for students who participated in pilot sections were evaluated. In total, 163 students enrolled during the initial pilot year, with 36 in the pilot sections and 127 in the unmodified sections. The approach of Ho and colleagues (2007) was used for matching to create better balance of possible confounding covariates. In particular, pairs were matched exactly on ethnicity, gender, and the entering school (natural sciences, engineering, social sciences, or humanities), then nearest neighbor matching was used for advanced placement scores. These matches were obtained using the R package MatchIt (Ho et al. 2011). A set of matched peers resulted in 32 cases (32 pilot section students) and 32 controls from the unmodified sections. Regression was used to estimate the causal effect of taking the pilot section on the three outcomes of interest, including the matching variables as covariates in an effort to make the analysis doubly robust. Linear regression was used for grade point average (GPA) and logistic regression was used for binary outcomes. Deidentified course evaluation responses were obtained from the registrar for each section. Evaluation responses were reverse coded to simplify data visualization, and differences in ratings were evaluated using the Mann-Whitney U test.

For those enrolled during the 2018–2019 school year, the Laboratory Course Assessment Survey (LCAS) instrument (Corwin et al. 2015) was used to assess students' experience with scientific practices. The LCAS includes five items related to opportunities for relevant discovery, six items regarding iteration, and six items to assess frequency of collaboration. Relevant discovery and iteration items are both evaluated using a six-point scale ranging from strongly disagree to strongly agree, whereas collaboration items are assessed with a four-point frequency scale (never, one or two times, monthly, or weekly). Responses for all LCAS items are reported as summed scales, as described in Goodwin et al (2021).

Results

The coexistence of traditional and pilot sections during the initial year allowed for direct comparison of student outcomes and perceptions between the two groups. Once the new course design was expanded to all sections, there were more data to ascertain whether the elements of CUREs were truly reflected in the full-scale implementation.

Pilot Year

To quantify the impact this course had on students, the effect of CURE section enrollment was estimated for several outcomes of interest: cumulative GPA at graduation, future undergraduate research involvement, and whether the student majored in a STEM field. Table 2 shows the effect size from the regression models for each outcome of interest, along with the *p* value for that coefficient effect. The raw regression coefficient for the GPA linear model and the inverse logit of the logistic regression coefficients are included, as are the means of each variable for the CURE section and the unmodified section. For all three outcomes, students who participated in the pilot had better results than those in the traditional unmodified sections for the GPA and research involvement, although these effects were not statistically significant at the $p = 0.05$ level. There was a statistically significant effect for graduating with a STEM major ($p = 0.02$). In this analysis, conclusions are limited by the small sample size of the pilot and the fact that students were aware of section identities during registration. Still, the positive differences across all three outcomes were encouraging.

Further evidence demonstrating the effectiveness of the pilot sections over the traditional ones was found by analyzing student course evaluations. Students rated the CURE higher in overall quality, alignment of assignments with learning, and the "challenge to extend capabilities or develop new ones" (Figure 1). Interestingly, the organization of the CURE also was rated higher, despite having less structure for daily activities related to research project tasks than the laboratory activities for unmodified laboratory experiments. Written comments in course evaluations also illustrated different perceptions of course value. A student enrolled in the unmodified section wrote,

> The experiments drag on and are fairly useless. . . . Also, this class is supposed to prepare us for working in a real laboratory setting, but it seems to attempt to instead distance itself as far as possible from any semblance of a real research lab.

One student taking the CURE course commented,

> The alternate section made me feel as if I was actually doing something useful with lab time for a change. Don't get me wrong, other [university] labs are helpful but when you are given an actual project to work on and minimal instruction and can make your own schedule you get a better feel for what the actual field of science is like. On top of that you get to contribute something actually useful and valuable to the school if your project is successful and walk away feeling much more accomplished than with just a normal lab. Great option over the normal [course].

As course instructors, the authors note that their engagement with mentoring students in their research projects is more rewarding than the instructional roles required in the unmodified sections; similar experiences are reported by other CURE instructors (Shortlidge, Bangera, and Brownell 2016). Although it can be somewhat disconcerting to guide students in a teaching laboratory environment when the experimental outcome is unknown, it also is inspiring to serve as their mentors and to experience the enjoyment of discovery alongside them.

Full-Scale Implementation

Once the new Experimental Biosciences course had been fully implemented for several years, the translation of CURE elements to implementation at scale with multiple instructors was evaluated. Student perceptions of relevant discovery, iteration, and collaboration were all high, as indicated by LCAS item sums in the upper 10 to 20 percent of the scale range (Figure 2). The majority of students agreed that they were expected to generate results that would be of interest to the broader scientific community and that they were expected to explain their contribution to scientific knowledge (Figure 3). A smaller percentage of students felt that they were expected to participate in the framing of a question or hypothesis, which reflects that some of the projects selected for the course were more defined than others, and offered fewer opportunities for students to direct the line of questioning. Students recognized opportunities to repeat and revise their investigations, with the lowest rated item in the iteration section being to "collect and analyze additional data to address new questions or further test hypotheses that arose during the investigation." The collaboration item sum was closest to the maximum of the range (Figure 2). The two highest rated items involved discussing the investigation, sharing problems, and seeking input (Figure 3). The collaboration scale was based on perceived frequency. Weekly team meetings with the instructor likely influenced these ratings, because these meetings provided structured opportunities for students to share ideas with peers and get feedback from instructors. The lowest rated item in this category was "I was encouraged to provide constructive criticism to classmates and challenge each other's [sic] interpretations." Many students rated this item as occurring monthly even though a poster presentation was the only class activity organized with peer feedback as an explicit goal.

Discussion

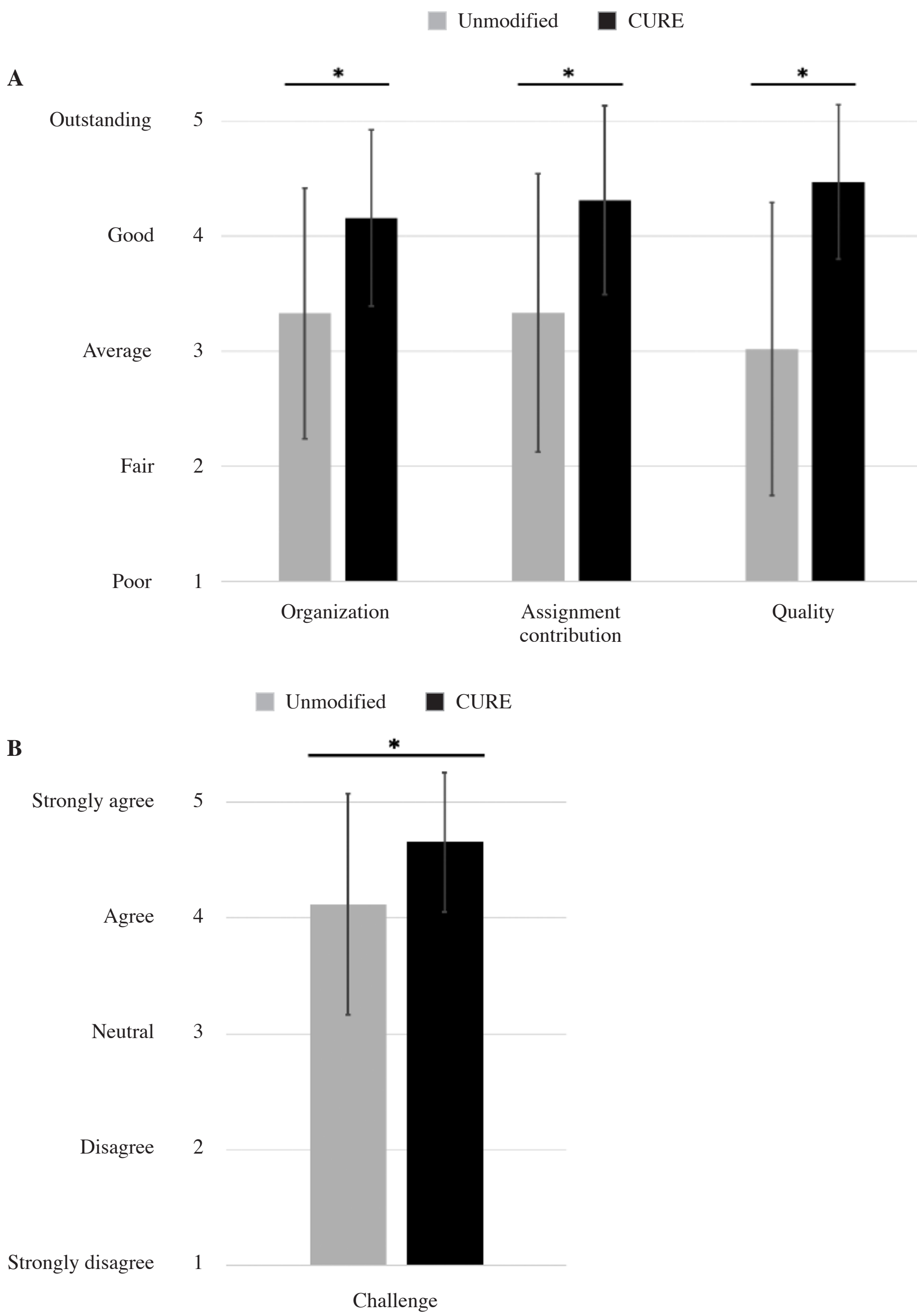
Student enthusiasm for the CURE and instructor satisfaction with student engagement and learning were important drivers in garnering support for scaling to all class sections within a year of the pilot program. An additional instructional faculty member was hired; instructors typically teach two or three sections per semester. Although this method of instruction worked well within the university structure, there is opportunity for the instructor role to be filled by postdoctoral researchers or graduate teaching assistants who bring their own research into the project, as has been done by the Freshman Research Initiative (Rodenbusch et al. 2016). The scale-up aligned with university initiatives for inquiry-based learning and small grants to scaffold research in the biosciences curriculum. Funding from these allowed purchase of equipment and supplies that resulted in a more rapid expansion of research project diversity than would have been possible using budgeted course funds alone.

The scale-up also coincided with investment of university resources to update the teaching laboratory space, creating an opportunity to design a space that better reflected a research environment. Instructor preparatory space was omitted because students are responsible for preparing common reagents. When instructors and teaching assistants do preparatory work, it happens in full view of students. The lack of an instructor demonstration bench reframed instructor and student as parts of a team. Ample student bench space was included to provide each team a drawer, shelf, and cold storage for the duration of the semester. This infrastructure emphasizes that student work and products are important to keep rather than being used for a single experiment and discarded. Indeed, the products and progress of teams during the previous semester become starting points for new teams to begin their research.

Conclusion

The main goal of this design was to integrate into the curriculum an intermediate-level CURE that developed

FIGURE 1. Student Ratings: CURE Sections and Traditional Unmodified Sections



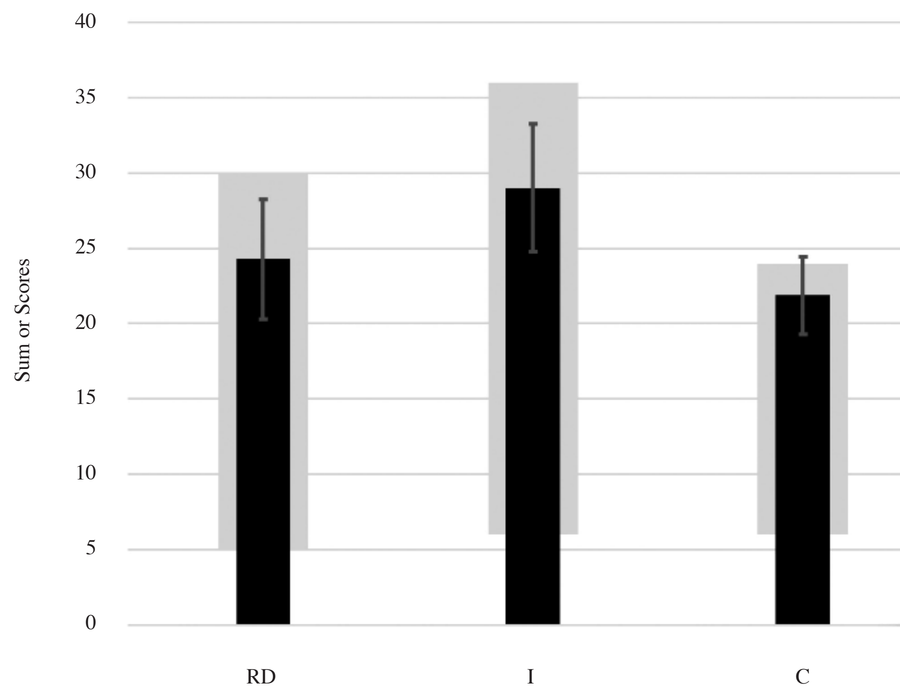
Note: Responses are shown as mean +/– SD (*$p < 0.01$, Mann-Whitney U test). Response rate was 84 percent for unmodified sections and 89 percent for CURE sections.

skills needed for future coursework and allowed students to experience the culture of mentored research. Competency assignments paired with a research project provide a model for implementing CUREs as a core part of the curriculum, helping students develop a defined set of laboratory techniques and skills while also allowing flexibility in the types of research projects that can be incorporated. Key components of the course design are competency assignments that ensure instruction in a standardized set of skills, exposure to mentorship, project management practice, and connection to the research community.

Data Availability Statement

The data underlying this study are not publicly available

FIGURE 2. CURE Characteristics after Scaling, Fall 2018–Spring 2019 Academic Year, *N* = 136–147



due to FERPA considerations. The deidentified survey data are available from the corresponding author upon reasonable request.

IRB Statement

Approval of the study design and protection of human subjects was obtained through Rice University Institutional Review Board: IRB-FY2016-205 for comparison of outcomes for matched pairs, IRB-FY2017-294 for student survey data using the LCAS instrument (Corwin et al. 2015), and IRB-FY2022-11 for data from course evaluations.

COI Statement

Daniel J. Catanese Jr. teaches the intermediate CURE that was created and initially taught by Elizabeth Eich.

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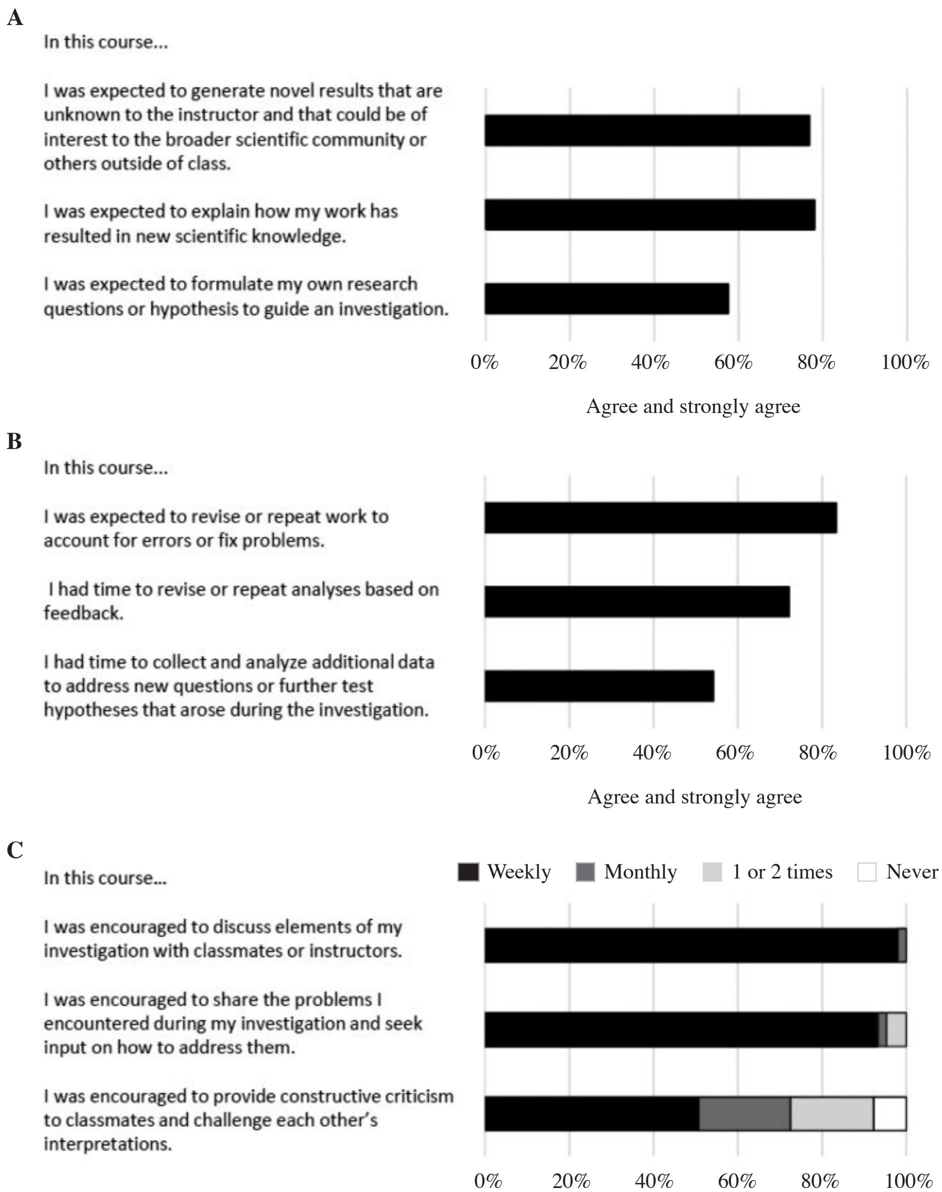
FIGURE 3. Student Responses to Laboratory Course Assessment Survey, *N* = 142–151



Note: A, relevant discovery items; B, iteration items; C, collaboration items.

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