Development of Course-Based Undergraduate Research Experiences Using a Design-Based Approach

By John C. Mordacq, Denise L. Drane, Su L. Swarat, and Stanley M. Lo

In recent years, commissions and reports have called for laboratory courses that engage undergraduates in authentic research experiences. We present an iterative approach for developing course-based undergraduate research experiences (CUREs) that help students learn scientific inquiry skills and foster expert-like perceptions about biology. This study involves the design, implementation, evaluation, and revision of two large introductory biology laboratory courses, where students work collaboratively on research projects developed from faculty laboratories on campus. Quantitative surveys, qualitative focus groups, and student course evaluations are used to evaluate these courses and to provide continuing feedback for improvement over two implementation cycles. Pre- versus postsurvey data indicate that students gain self-efficacy in scientific inquiry skills and develop more expert-like perceptions of biology. These gains are more significant and have larger effect sizes in the second implementation year, a trend also supported by qualitative data. Together, these data indicate a progression of improvement of efficacies of these CUREs.

Laboratory experience is central to undergraduate science education. The President's Council of Advisors on Science and Technology (PCAST) called for the revision of traditional laboratory courses to provide authentic research experiences for all students, especially in the first 2 years of college (PCAST, 2012). Laboratory instructions can be broadly categorized as expository or inquiry (Domin, 1999). Traditional laboratory courses are typically expository, where the procedures are given, and the outcomes are predetermined and known to both students and instructors (Domin, 1999). Authentic research and course-based undergraduate research experiences (CUREs) engage students in scientific inquiry, in which the outcomes are unknown and the procedures are developed on the basis of research questions (Buck, Bretz, & Towns, 2008; Weaver, Russell, & Wink, 2008). Authentic research experiences have been shown to have positive impacts on students, including higher grades and persistence, shorter time to degree, and increased interests in graduate education (PCAST, 2012).

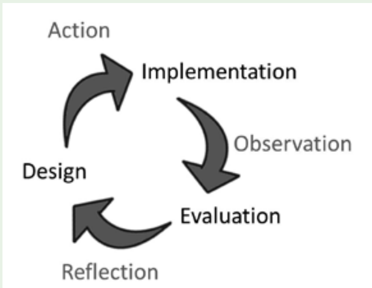
CUREs are defined by four critical components: (a) the use of scientific practices in inquiry, (b) collaboration among students, (c) iteration of experiments, and (d) discovery of novel findings with broader relevance (Brownell & Kloser, 2015). CUREs in existing literature can be further divided into two categories of inquiry: (a) discovery based (inductive: aimed at collecting information and generating hypotheses from observations) and hypothesis driven (deductive: aimed at generating and testing hypotheses; National Academy of Sciences, 1999). Discovery-based examples in the literature include identifying bacteriophages, annotating genome sequences, DNA-barcoding biodiversity, and small-molecule libraries (Butler, Henter, & Mel, 2014; Chen et al., 2005; Hanauer et al., 2006; Newton, Tracy, & Prudenté, 2006). Some hypothesis-driven laboratory courses have examined the ecological relationship between abiotic and biotic factors, investigated acquired resistance to the cancer drug Gleevec, and studied the chemistry of antioxidants in food (Kloser, Brownell, Chiariello, & Fukami, 2011; Kloser, Brownell, Shavelson, & Fukami, 2013; Taylor, Fortune, & Drennan, 2010; Weaver et al., 2006). Because the testable hypothesis is a central yet challenging concept in biology for undergraduates (Taylor & Meyer, 2010), we focus on hypothesis-driven projects in our CUREs. Furthermore, many examples in the literature are designed only for advanced undergraduates (Butler et al., 2014; Caspers & Roberts-Kirchhoff, 2003; Murthy, Thompson, & Hungwe, 2014; Taylor et al., 2010), and some are limited to a small number of students (Kloser et al., 2011; Kloser et al., 2013). The lack of emphasis on all students early in college is disconcerting, as scientific inquiry in an authentic learning environment can highlight the excitement of science and promote students' motivation in pursuing science careers (Corwin, Graham, & Dolan, 2015; Graham, Frederick, Byars-Winston, Hunter, & Handelsman, 2013; PCAST, 2012).

We report innovative laboratory courses that provide authentic research experiences early in students' college careers. Specifically, we describe the design, implementation, evaluation, and redesign of a sequence of two CUREs at the introductory biology level. These courses engage large numbers of students (majors and nonmajors) in hypothesis-driven research projects connected to faculty laboratories on campus.

We do not view our CUREs as final products or interventions that are tested in the general classroom context against a set of predetermined standards. Instead, we use the framework of design-based research (DBR) methodology, which investigates "learning in context through the systematic design and study of instructional strategies and tools" (Design-Based Research Collective, 2003). DBR embraces the interconnections among theory, design, and context of practice (classrooms or laboratories), while fostering collaborations between researchers and practitioners to make changes unique to specific institutional contexts. As such, DBR is characterized by iterative design-implementation-evaluation cycles (Figure 1) aimed at improving both student learning and the educational intervention (Shavelson, Phillips, Town, & Feuer, 2003). Empirical evidence of DBR studies suggests that this methodology is promising in producing effective interventions and, more important, "offer[s] rich clues as to the match between the successful testing of the intervention and the context of practice" (Anderson & Shattuck, 2012, p. 24). Following DBR methodology, we focus our core effect and this article on the ever-evolving design process. We describe the design of our CUREs with supporting theoretical frameworks, share ongoing evaluation results about the efficacies of these courses, and illustrate how research data informed the redesign process. Our DBR approach can offer general insights for practitioners across science disciplines who plan to develop CUREs.

FIGURE 1

Design-based research (DBR) framework with a design-implementation-evaluation cycle. In each step of the cycle, we engage all stakeholders in the process, including the course instructor, teaching assistants, and students. TA = teaching assistant.



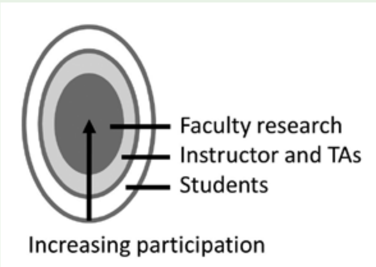
Course design

The *Vision and Change* report in the biological sciences calls for relevant and authentic learning in undergraduate courses (American Association for the Advancement of Science [AAAS], 2011), ideas that are echoed in the PCAST (2012) *Engage to Excel* report for all science, technology, engineering, and mathematics (STEM) disciplines. We define authentic learning as students performing the same tasks as scientists would in the same setting (legitimate), even though students' level of competence may not be as sophisticated (peripheral). This idea of legitimate peripheral participation emerges from the theoretical framework of situated learning, which posits that learning takes place in the same context in which it is applied (Lave & Wenger, 1991). In our courses, students learn scientific inquiry in research projects that can result in novel conclusions with broader relevance, a critical component of CUREs (Brownell & Kloser, 2015). Specifically, students engage in many elements of scientific inquiry originally defined for K–12 science education (National Research Council [NRC], 1996; NRC, 2000b) and subsequently articulated for undergraduate science education (Weaver et al., 2008): asking questions, generating hypotheses, designing experiments, collecting and analyzing data, repeating experiments, and presenting results. These inquiry elements are aligned with core competencies described in *Vision and Change* (AAAS, 2011) and science practices in the *Next Generation Science Standards* (NGSS Lead States, 2013), and they constitute another critical component of CUREs (Brownell & Kloser, 2015).

Situated learning occurs within a community of practice (CoP), defined as a group of people with a common practice (Wenger, 1999). To connect students with the larger scientific community, projects are developed from faculty research

FIGURE 2

Schematic of nested community of practice (CoP). Research projects are developed from faculty laboratories, which represent the core of the CoP. Course instructor and teaching assistants serve as a bridge between faculty laboratories and students, who participate in this CoP by engaging in authentic research.



programs on campus, resulting in a nested CoP (Figure 2). The first course focuses on genetics and studies protein-folding diseases using the transgenic model organism *C. elegans* (Brignull, Moore, Tang, & Morimoto, 2006). The second course deals with cell biology and examines the role of macrophage phagocytosis of apoptotic cells in atherosclerosis (Thorp, Subramanian, & Tabas, 2011).

To create local communities of practice within the laboratory courses, students work collaboratively in small groups of three to four on the research projects. Collaboration is another critical component of CUREs (Brownell & Kloser, 2015), and collaborative learning stems from the educational theory of social constructivism, which posits that individuals learn through social interactions as meaning is co-created and shared (NRC, 2000a). Workshops are designed to engage students within and across groups, as they learn the aforementioned elements of scientific inquiry. Together, these courses are designed to position students in collaborative environments to learn authentic scientific inquiry in the context of relevant research projects.

CUREs described in this article are stand-alone courses not linked to lecture courses, allowing us to pursue research projects without constraints. We acknowledge that a separation between laboratory and lecture courses may have impacts on student learning in the lecture courses. We administered concept inventories in lecture courses to examine such impacts, but the data are beyond the scope of this article. The research projects described here are designed to help students learn biology content material and laboratory techniques while challenging them to design their own experiments, collect and analyze data, and communicate results.

Course implementation

Students are scheduled for one 4-hour laboratory section per week in 9-week quarters. Each laboratory section consists of up to 24 students, working collaboratively in groups of up to four students and guided by one graduate teaching assistant (TA) and one undergraduate TA. The course instructor (first author) is also present and engages up to 72 students at a time in three concurrent and adjacent laboratory sections.

We use a blended learning environment, which includes three elements typically arranged in this order: lectures, laboratory experience, and workshops (Table 1). Lectures are given online by the course instructor and are available on the course website. These lectures (up to 15 minutes) serve as the primary source of information for students, and they introduce biology content material (e.g., signal transduction) and laboratory techniques (e.g., immunofluorescence) before designated laboratory sessions. Student learning from lectures, including biology content material, is assessed by quizzes given in laboratory sections.

Laboratory experience spans the entire quarter and is divided into two major portions. The first part consists of defined experiments with known outcomes, which are used to familiarize students with the research project and laboratory techniques. These experiments are accomplished in the first 2–3 weeks, with detailed protocols and experimental parameters that will serve as controls for subsequent inquiry. Students repeat these experiments to identify problems and learn the laboratory techniques. Subsequently, students ask their own research questions, generate hypotheses, and design experiments to test these hypotheses using sets of available reagents. This second portion of the course spans 4–5 weeks, with time for students to repeat experiments. Iteration of experiments is another critical component of CUREs (Brownell & Kloser, 2015) and allows data collected by students to drive subsequent changes in experimental design.

In the first course, each student group studies the effect of a different gene on protein folding and the proteostasis network. These investigations use RNA interference (RNAi) to knock down each group's gene of choice in a transgenic *C. elegans* model for Huntington's disease. The worms exhibit toxic phenotypes of slow movement and increased numbers of protein aggregates, which can be monitored for changes in RNAi experiments. In the second course, student groups study the effects of various compounds on the efficiency of macrophage phagocytosis. Fluorescent plastic beads, apoptotic cells, and cultured macrophages are used as an in vitro model of phagocytosis and how changes in this process can lead to the disease of atherosclerosis. These disease-related projects are chosen to introduce biology concepts and laboratory techniques in a variety of disciplines (molecular in one quarter and cellular in another quarter), in addition to lending relevance to the courses.

Student learning from the laboratory experience is assessed by a group presentation in the final week and two research proposals due in the middle and at the end of each quarter. The presentation focuses on each group's unique experiment and its connection to the overall research project, results from the initial experiments and student-designed experiments, conclusions, and future directions. Group presentations are graded in individual sections by the instructor and TAs using a rubric that is still undergoing refinements, and thus, qualitative analysis of presentations will not be systematically presented as data in this article. These presentations also provide an opportunity for students to see the diverse possibilities of experiments within one larger research project.

The research proposals are two-page papers with five sections (background and significance, specific aims, experimental design with controls, expected results, and future plans) and are graded by graduate TAs in individual sections using a rubric that is still undergoing refinements. Similar to presentations, qualitative analysis of research proposals will not be systematically presented as data in this article. The first research proposal is based on the initial set of experiments, whereas the second proposal builds on the student-designed experiments and expands to future directions from these experiments. The two iterations of different but similar research proposals provide an opportunity for deliberate practice (Ericsson, 1993), so students can learn and improve from experience.

To support the learning from the laboratory experience, we created a series of workshops (15–20 minutes) to introduce students to experimental design, guide them through the proposal writing process, and provide scaffolding for data analysis and presentation. Undergraduate TAs lead these workshops in laboratory sections, as they are most proximal in expertise and learning to the students (NRC, 2000a), and they have experienced these CUREs as students. Typically, workshops include small-group discussions on worksheets that explicitly address specific scientific inquiry skills (Table 1), followed by a

TABLE 1

Blended course design with lectures, laboratories, and workshops.

Week	Lectures	Laboratories	Workshops
1	Introduction to research project	Introduction to specific experimental methods	—
2	Concepts and techniques specific to experiments	Initial set of experiments	First research proposal and experimental design
3	—	Repeat of initial set of experiments	—
4	Introduction to second set of experiments	Data analysis	Data analysis and data presentation
5	—	Student-designed set of experiments	—
6	Summary of experiments and related concepts	Data analysis	Second research proposal
7	—	Repeat of student-designed set of experiments	—
8	—	Data analysis	Presentation guidelines
9	—	Presentation	—

Note. Research experience in the laboratory is the central focus of the course and spans the entire quarter, with workshops and online lectures included in various weeks as necessary.

sharing of ideas with the entire laboratory section. These workshops are an integral part of the courses, as they are designed to help students learn scientific inquiry skills and promote collaborative learning. The interactive nature of these workshops is modeled after a successful small-group learning program on campus (Drane, Micari, & Light, 2014; Drane, Smith, Light, & Pinto, 2005; Light & Micari, 2013; Micari & Drane, 2007, Swarat, Drane, Smith, Light, & Pinto, 2004). Similar workshops have been successfully implemented in chemistry at the Center for Authentic Science Practice in Education (Weaver et al., 2008).

Course evaluation

DBR advocates for the use of both quantitative and qualitative evaluation methods (Anderson & Shattuck, 2012). As such, our evaluation combines quantitative surveys, qualitative focus groups, and student course evaluations (Table 2) to triangulate findings for subsequent redesign, implementation, and improvement. Wherever applicable, we use data from students in previous traditional expository laboratory courses as historical comparisons.

Study samples

Data from surveys, focus groups, and student course evaluations were collected over three academic years (Table 3). The last year of traditional laboratory courses serves as historical comparison, and the CUREs began in 2012–2013. In the first implementation year, students expressed dissatisfaction with the number of surveys, suggesting respondent fatigue (Ben-Nun, 2008). Therefore, we attempted to achieve a higher response rate and potentially more meaningful responses with the instructor, inviting 60 randomly selected students to participate in our study. Although the response rates increased (Table 3), this approach also resulted in a smaller data set, which reduces statistical power. Focus groups were administered in only three of the laboratory sections at the end of each implementation year due to cost of teaching consultants. Student course evaluations were administered online by our institution.

Quantitative surveys

Quantitative survey instruments include a modified version of the Classroom Undergraduate Research Experience (CURE) Survey (Denofrio, Russell, Lopatto, & Lu, 2007), designed to measure self-efficacy in many elements of scientific inquiry, and the Colorado Learning Attitudes about Science Survey for use in biology (CLASS-Biology; Semsar, Knight, Birol, & Smith, 2011), which probes perceptions about biology (enjoyment, various aspects of problem solving, reasoning, conceptual connections, and real-world connections) on the continuum of experts (PhD-level biologists) to novices (beginning students). The CURE survey includes 14 items, and we modified the administration from the standard 5-point self-rated learning scale postintervention (1 = *no gain*, 5 = *very large gain*) to a 6-point self-efficacy scale (1 = *no skill*, 6 = *very high skill*) pre- and postcourse sequence to capture potentially fluctuating preintervention baseline. A 6-point scale was used to eliminate the ambiguous midpoint option, which could be interpreted as neutral or undecided, two similar but different constructs (Armstrong, 1987; Guy & Norvell, 1977; Komorita, 1963). This modified CURE survey was determined to have high reliability by Cronbach's α (pre = 0.91 and post =

TABLE 2

Logic model for design, implementation, and evaluation.

Goals	Intended outcomes	Activities	Data sources
Engage introductory students in authentic research experiences	Increased self-efficacy in scientific inquiry	Carry out hypothesis-driven, inquiry-based research projects guided by course staff	CURE survey (pre/post)
	More expert-like perceptions of biology		CLASS-Biology survey (pre/post)
Develop our courses in iterative DBR approach	Improved and refined research-based laboratory courses	Make adjustments based on quantitative and qualitative data	SGA, student course evaluations, CURE, and CLASS-Biology surveys

Note. This roadmap describes the alignment among the overall goals, specific intended outcomes, activities in our courses and the design-based research (DBR) process, and associated data sources. Details of the data sources, including Classroom Undergraduate Research Experience (CURE) Survey, Colorado Learning Attitudes about Science Survey for use in biology (CLASS-Biology), small group analysis (SGA), and student course evaluations, are described in the section on course evaluation.

0.92) using JMP Pro (Version 11.0.0). The CLASS-Biology survey consists of 31 items on a standard 5-point Likert scale (1 = *strongly disagree*, 5 = *strongly agree*).

Both surveys were administered at the beginning (pre) and end (post) of the course sequences. Only matched pre/post pairs were included for analysis. Self-efficacy from the CURE survey is reported as changes (post–pre), and statistical significance for within-year changes is calculated using the Wilcoxon signed-ranked test because of the nonparametric nature of the data. Differences in changes across years are tested by analysis of variance (ANOVA) using the Tukey-Kramer method. All statistical analyses were performed in JMP Pro (Version 11.0.0). For the CLASS-Biology data, Likert-scale responses are normalized to a scale of 0%–100% expert-likeness using an algorithm provided by authors of the instrument (Semsar et al., 2011) and reported as changes.

For learning outcomes in scientific inquiry, we found significant positive changes in only three out of 14 items from the CURE survey in 2011–2012 (historical comparison year) but in 11 and 10 items in 2012–2013 and 2013–2014 respectively (Figure 3). In general, 2013–2014 shows the largest positive changes across items, even though statistical power is weaker because of the smaller sample size. In 2013–2014, items with the largest positive changes are: generating research questions or hypothesis, choosing methods of investigation, and analyzing data. Not surprisingly, items with no significant change (e.g., finding literature and working independently) are areas not explicitly focused on in these courses at the moment but could represent potential areas for future improvement. Across years, six items showed significant difference in changes: two that are different between 2011 and 2012, and 2012 and 2013, and four with improvement only in 2013–2014.

From the CLASS-Biology data, students in 2012–2013 developed more expert-like perceptions in only one out of seven categories, but in 2013–2014 gains were observed in five categories: enjoyment, problem-solving difficulty, problem-solving effort, reasoning, and real-world connections (Figure 4). In general, students shift away from expert-like perceptions following introductory courses, whereas students in advanced courses tend to show little to no change (Adams et al., 2006; Adams, Wieman, Perkins, & Barbera, 2008; Semsar et al., 2011). Our data in 2012–2013 show negative trends

TABLE 3

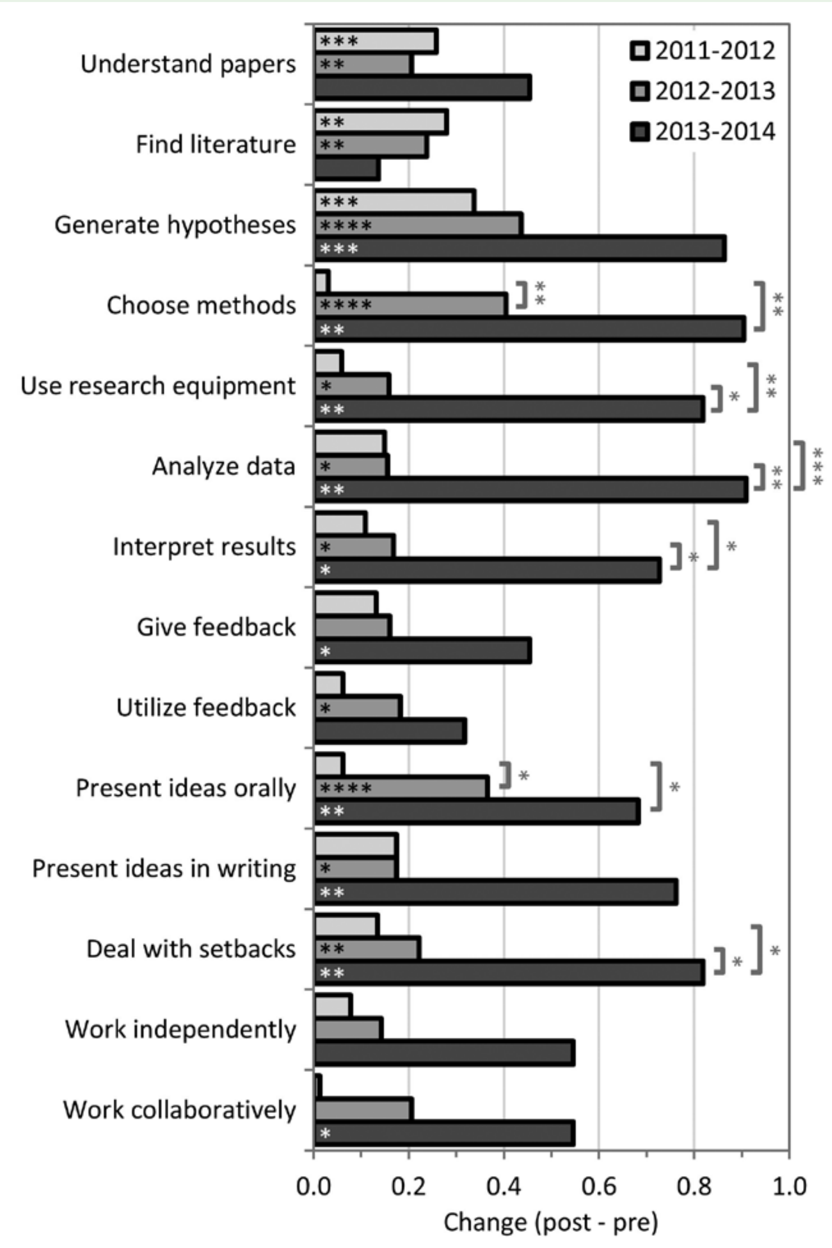
Study samples in historical comparison year (2011–2012) and two implementation years (2012–2013 and 2013–2014).

Academic year	2011–2012	2012–2013	2013–2014
Number of laboratory sections	15	15	15
Number of instructor(s)	3	1	1
Number of graduate TAs	26	16	15
Number of undergraduate TAs	0	51	38
Student enrollment in fall	370	383	302
Academic year	2011–2012	2012–2013	2013–2014
CURE (pre and post)	161/370	126/383	22/60
CLASS-Biology (pre and post)	Not collected	87/383	23/60
SGA focus groups	Not collected	48/72	49/68
Student course evaluations	Not used in study	286/343, 262/323	256/302, 214/279

Note. The top half of the table represents overall numbers of laboratory sections, instructors, teaching assistants (TAs), and students, whereas the bottom half of the table describes response rates of each data source. Classroom Undergraduate Research Experience (CURE) Survey and Colorado Learning Attitudes about Science Survey for use in biology (CLASS-Biology) response rates are presented for matched pre/post pairs. To improve response rates, a randomly selected subset of 60 students was invited to participate in surveys 2013–2014. Small group analysis (SGA) was administered to a randomly select subset of laboratory sections to minimize costs of teaching consultants. Student course evaluations were used in both courses in the sequence in implementation years, and response rates are presented separately for each course. TA = teaching assistant.

FIGURE 3

Cure-Based Undergraduate Research Experience (CURE) Survey results from historical comparison year (2011–2012) and two implementation years (2012–2013 and 2013–2014). Changes within each year (significance indicated at the base of the bars) and differences across years (significance indicated by brackets to the right of the bars) are analyzed by Wilcoxon signed-rank test and analysis of variance with the Tukey-Kramer method, respectively. *$p < .05$. **$p < .01$. ***$p < .001$. ****$p < .0001$.



similar to data from the literature, but in 2013–2014, students developed positive gains, which is rare (Semsar et al., 2011). Collectively, the CURE and CLASS survey data indicate that these courses are more effective in their second year of implementation, possibly due to implementation maturity. Redesign decisions based on these data are discussed in the next section on course revision.

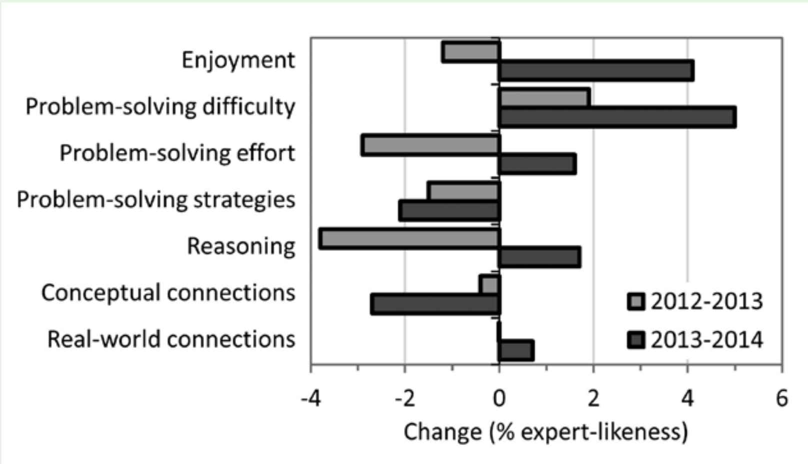
Qualitative focus groups

To solicit feedback from students as participants in this DBR process, we used a qualitative method called small group analysis (SGA; Coffman, 1991, 1998). SGAs are structured focus groups facilitated by trained teaching consultants from the teaching and learning center on campus. Teaching consultants conducted SGAs in laboratory sections for 20–25 minutes, without the instructor or TAs present. We followed the standard SGA implementation protocol (Coffman, 1991, 1998) but modified the three questions to focus on student learning: (a) What aspects of the course enhance your learning, (b) what aspects of the course could be improved to enhance your learning, and (c) what could you, as a student, do to enhance your learning in the course? Students first discuss their responses to these questions in small groups, and the teaching consultants facilitate a full-class discussion that leads to consensus responses built from the initial group responses. Individual students then indicate their agreement with the consensus responses on a 9-point scale. The consensus responses and agreement ratings are reported to the course instructor without identifiers.

Results on the first SGA question ("What aspect of the course enhanced your learning?") from the second course in the sequence are presented (Table 4). In 2012–2013, students focused on the helpfulness of the course instructor and TAs, as well as the class organization and structure. In 2013–2014, students' comments centered more on collaboration and scientific inquiry processes. Results on the second question ("What aspects of the course could be improved to enhance your learning?") were mostly related to the structure of the courses, such as online lectures, format of quizzes, and due dates of assignments. Results on the third question ("What could you, as a student, do to enhance your learning in the course?) included suggestions such as watching online lectures, understanding protocols prior to laboratory sessions, going to office hours, and asking questions. Redesign decisions based on these data are discussed in the next section on course revision.

FIGURE 4

Colorado Learning Attitudes about Science Survey for use in biology (CLASS-Biology) results on students' perceptions about biology in 2012–2013 and 2013–2014. Responses are normalized to percentage of expert-likeness and reported as changes. Data were not collected in the historical comparison year 2011–2012, as the instrument was not yet available.



Student course evaluations

Our institution administers online student course evaluations at the end of each quarter. We focused on the question: "What are the primary weaknesses, if any, of the instruction?" Free responses from students were read informally by the course instructor and curriculum development specialist (first and last authors). A systematic qualitative analysis of these data was not possible given the short time frame for course revisions between the release of course evaluations and the start of subsequent quarters. Findings from these evaluations are discussed in the next section in conjunction with course revision decisions.

Course revision

We used a combination of quantitative and qualitative data to modify our courses on a continuous basis. The CURE survey data from the first implementation year indicate that students gained self-efficacy in generating hypotheses, presenting ideas, and choosing methods but needed more support in analyzing data, interpreting results, receiving feedback, and collaborating with peers. In the second implementation year, we created more online lectures to include topics such as data analysis and refined laboratory protocols to generate more consistent experimental data for statistical analysis. Assignments were redesigned with more defined rubrics, which allowed TAs to give focused feedback to students. We also defined the roles of different student members within each collaborative group.

SGA data from the 2 years are different, and we attribute this to various factors. Responses on the first question ("What aspect of the course enhanced your learning?") shifted from helpfulness of the teaching team to collaboration and scientific inquiry practices. This shift is potentially a result of the course instructor and TAs placing emphasis more on experimental design and less on laboratory techniques. Responses on the second question ("What aspects of the course could be improved to enhance your learning?") indicated specific weaknesses of the course design and led to changes in having more detailed instructions and rubrics provided to students.

On student course evaluations from the first quarter in 2012–2013, many students reported that the format of the course was confusing and disorganized. In the second quarter, we took a more defined approach and implemented workshops that provide students with scaffolds to learn experimental design, data analysis,

TABLE 4

Formative feedback from students collected by small group analysis (SGA) in 2012–2013 and 2013–2014.

Winter 2013, lab section 1 (*n* = 22)	**% agree**	**% neutral**	**% disagree**
Instructor and TAs are accessible and responsive	96	4	0
Online lectures clarify goals of the course	82	9	9
Workshops reinforce course concepts	64	23	14
Winter 2013, lab section 2 (*n* = 15)	**% agree**	**% neutral**	**% disagree**
Instructor and TAs are approachable	100	0	0
The course has clear expectations for students	93	7	0
Online lectures are useful	87	13	0
Winter 2013, lab section 3 (*n* = 11)	**% agree**	**% neutral**	**% disagree**
Workshops are useful	100	0	0
Trial-and-error format is more like research	91	9	0
Choosing our own groups creates accountability	73	18	9
Winter 2014, lab section 1 (*n* = 21)	**% agree**	**% neutral**	**% disagree**
Collaborative environment is helpful	95	5	0
Designing our own experiments helps learning	90	10	0
Experiments build on one another	86	9	5
Winter 2014, lab section 2 (*n*=17)	**% agree**	**% neutral**	**% disagree**
Online lectures help understand concepts	88	12	0
Doing experiments twice helps learning	71	29	0
Proposals and presentation mimics real science	53	41	0
Winter 2014, lab section 3 (*n* = 11)	**% agree**	**% neutral**	**% disagree**
Final experiment helps tie information together	100	0	0
Online lectures give background information	82	18	0
Writing proposals help understand experiments	73	27	0

Note. Representative results on the first question ("What aspects of the course enhance your learning?") are reported. Consensus ratings are provided by individual students at the end of the focus groups on a 1–9 scale: 7–9 agree, 4–6 neutral, and 1–3 disagree. TA = teaching assistant.

proposal writing, and presentation. We also streamlined experiments and protocols to make time for these workshops in laboratory sections.

The composition of the teaching team has changed based on feedback from student course evaluations. In 2012–2013, undergraduate TAs were the primary lead in the laboratory, with graduate TAs being responsible for grading. Since 2013–2014, both graduate and undergraduate TAs have been actively involved in the laboratory, and they play complementary roles. Graduate TAs provide a level of maturity and knowledge based on their own research experience, but for many of them, these courses are their first engagement with CUREs. On the other hand, undergraduate TAs have already taken these courses, are typically more in tune with the learning objectives, and are more likely to understand how students are struggling.

Additional refinements were made based on informal reflections on graded student assignments, ongoing feedback from TAs, and the course instructor's observations on a daily basis. The number of repeated experiments has decreased over time to allow for more interactions among students, TAs, and the course instructor on data analysis, presentation, and proposal writing, thus providing a balance between laboratory techniques and the overall process of scientific inquiry.

Conclusion

In this article, we discuss our iterative DBR approach to design and refine CUREs for large numbers of introductory biology students. Quantitative survey data indicate that students gain self-efficacy in scientific inquiry skills and develop more expert-like perceptions of biology. These gains are more significant in the second implementation year, a trend also supported by qualitative SGA data, which suggest a collaborative learning environment focused on scientific inquiry in 2013–2014. Together, these data indicate a progression of improvement of the effectiveness of these laboratory courses over two cycles of design, implementation, and evaluation. We also documented students' learning gains through course assignments and concept inventories, which will be reported in a separate paper.

Our DBR approach potentially provides valuable suggestions for other practitioners across science disciplines who plan to design and implement CUREs. Improvements in student outcomes may not be immediately apparent in the first year of implementation. As such, reflections based on evaluation and feedback from all individuals involved in the instruction, as well as continuing refinement, are critical to the success of developing CUREs. Feedback can come in many forms, both formally and informally, including focus groups, student course evaluations, responses on surveys, and day-to-day observations and conversations. Others who have developed CUREs have published suggestions focused on the nature of scientific inquiry and the logistics of designing research projects suitable for students (Kloser et al., 2011; Weaver, Russell, & Wink, 2008), whereas our DBR approach emphasizes the importance of iterative and continuous evaluation, feedback, and refinement that respond to the uniqueness of local contexts. ■

Note. These authors contributed equally to this work: John C. Mordacq and Stanley M. Lo.

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