Integrative and Comparative Biology

*Integrative and Comparative Biology*, pp. 1–11
doi:10.1093/icb/icab006

*Society for Integrative and Comparative Biology*

SYMPOSIUM ARTICLE

# Addressing the Unique Qualities of Upper-Level Biology Course-based Undergraduate Research Experiences through the Integration of Skill-Building

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From the symposium “SICB-Wide Symposium: Biology beyond the Classroom: Experiential Learning through Authentic Research, Design, and Community Engagement” presented at the virtual annual meeting of the Society for Integrative and Comparative Biology, January 3–7, 2020.



**Synopsis** Early exposure to course-based undergraduate research experiences (CUREs) in introductory biology courses can promote positive student outcomes such as increased confidence, critical thinking, and views of applicability in lower-level courses, but it is unknown if these same impacts are achieved by upper-level courses. Upper-level courses differ from introductory courses in several ways, and one difference that could impact these positive student outcomes is the importance of balancing structure with independence in upper-level CUREs where students typically have more autonomy and greater complexity in their research projects. Here we compare and discuss two formats of upper-level biology CUREs (Guided and Autonomous) that vary along a continuum between structure and independence. We share our experiences teaching an upper-level CURE in two different formats and contrast those formats through student reported perceptions of confidence, professional applicability, and CURE format. Results indicate that the Guided Format (i.e., a more even balance between structure and independence) led to more positive impacts on student outcomes than the Autonomous Format (less structure and increased independence). We review the benefits and drawbacks of each approach while considering the unique elements of upper-level courses relative to lower-level courses. We conclude with a discussion of how implementing structured skill-building can assist instructors in adapting CUREs to their courses.

## Introduction

Efforts to engage students in meaningful research experiences early in their undergraduate education have demonstrated a number of positive impacts for students majoring in science fields. One approach to student engagement in research, known broadly as Course-based Undergraduate Research Experiences (CUREs), includes the integration of *authentic* research experiences into the lecture/laboratory component of a course (Auchincloss et al. 2014; Brownell and Kloser 2015). In this case, we use the term “authentic” to describe a CURE curriculum in which students address novel, applicable, and relevant research questions, benefiting faculty research programs, scientific progress, and student learning (Ballen et al. 2017). Following participation in a CURE, students reported increased interest levels, preference for authentic lab experiences, and the ability to “think like a scientist” (Brownell et al. 2012). Huntoon et al. (2001) demonstrated that participating in independent research increased students’ intentions to pursue graduate school or a profession in a science field, particularly for underrepresented groups. Thus, the implementation of CUREs throughout undergraduate education also has the potential to promote historically underrepresented students in science, increasing diversity within the field.

These documented positive impacts of CUREs come from investigations of lower-level major courses (i.e., first or second-year courses) and may not be entirely generalizable to upper-level courses, which are unique in several ways (Table 1). For example, upper-level courses tend to be smaller, more focused, and composed of students who have experience taking undergraduate level science coursework, in comparison to introductory courses. While CUREs have been described as "*scalable* laboratory learning environments" that expose students to research at "an *early* point in their college careers" (Ballen et al. 2017), this characterization excludes upper-level courses that are inherently more challenging. Therefore, it is reasonable to assume the effectiveness of these experiences may vary based on the course level and associated complexity, but research on the impacts of CUREs on upper-level courses is lacking.

Given the increased course complexity and the nature of authentic course-based research experiences, instructors must consider the appropriate level of independence and autonomy for students in these courses. This is important because some students may not have previous research experience and/or may not be familiar with the new, more complex, subject material. Instructors can address gaps in student preparation by providing structured, skill-building content before they encourage students to pursue more independent research within a CURE framework. While some skill-building in upper-level courses is critical for students to be able to apply research skills to address their scientific questions, generally skill-building lab activities follow a more linear path to a known outcome rather than encourage student autonomy, creativity, and curiosity. Thus, instructors must titrate the relative amounts of structure (i.e., skill-building) and independence (i.e., exploratory, with trial and error) to suit their students' learning needs. These two attributes represent trade-offs in a laboratory environment, detectable as negative correlations between the two, where increasing the level of the structure decreases student independence.

In this perspective paper, we share our experiences teaching an upper-level CURE in two different formats and contrast those formats using student survey data. As we are unaware of any studies examining the relative importance of course structure and student independence in the context of upper-level CUREs, we address the following research question: how does the delicate balance between structure (emphasis on distinct skill-building prior to research) and independence (emphasis on trial-and-error research experiences) impact student confidence and perceived applicability of the laboratory experience in an upper-level CURE? We addressed the unique learning environment in upper-level laboratory courses (Table 1) through the development of a series of skill-building activities over 2 years ($N=63$ in four sections). Considering the unique elements of upper-level courses, we discuss our experience adapting a CURE to the needs of upper-level biology students as well as the benefits and drawbacks to increased structure versus increased independence. Our conclusions will assist instructors as they adapt the large body of literature on lower-level CUREs to their upper-level courses, and aid them in choosing the most appropriate formats for their classrooms based on unique student bodies and course curricula.

## Upper-level CURE implementation

### Course and research design

We implemented a CURE in a semester-long upper-level biology laboratory course taught twice weekly (110 minutes each) in two iterations that were 1 year apart. In each iteration, students were responsible for cloning and purifying a reptilian protein in a bacterial system as part of a larger ongoing research project in collaboration with a research laboratory on campus. At the beginning of the semester, the collaborating laboratory introduced the study system and the significance of the research project. Within the scope of the collaborative research project, students worked in pairs to develop specific research questions, providing opportunities for autonomy in their selection of a specific gene and how to alter their focal gene. This resulted in the creation of a variety of specific research questions that differed between pairs, but questions remained highly related of the overall research question. The specific research questions and methodological protocols differed slightly between semesters, as is expected when implementing CUREs in the classroom (Supplementary Fig. S1 contrasts the designs for each semester). However, the instructor, the topic of research, the collaborating laboratory, and the general methodology to conduct the research were the same across semesters.

In the first iteration, we taught the course in a Guided Format, structured with defined skill-building at the beginning of the semester followed by a more independent research portion. The skill-building introduced students to the methodology required to clone proteins by allowing students to practice in a traditional cookbook teaching format on a system known to work efficiently and consistently. We then asked students to apply those skills to their novel research project. This first iteration, that included the skill-building portion, is hereafter referred to as the "Guided Format." Due to student reports that the skill-building portion was unengaging, in the second iteration of the course, we decided to test the

Table 1 Description of the qualities that differ between lower- and upper-level classes

| Qualities | Unique aspects of lower-level courses | Unique aspects of upper-level courses | Potential implications for upper-level CUREs |
|---|---|---|---|
| Balancing student experience with course complexity | (1) Students have few basic, hands-on skills.<br>(2) Students are expected to recall and apply relatively little information from previous courses (Zheng et al. 2008).<br>(3) Projects are accessible for students at all skill levels (Auchincloss et al. 2014). | (1) More likely to have had exposure to independent apprenticeships in research laboratories.<br>(2) Students have developed a relatively advanced knowledge base.<br>(3) Students are expected to apply skills developed in prerequisite coursework and incorporate complex protocols. | • Advanced skill sets increase the possibilities for potential CURE designs and complexity.<br>• Instructors must be cognizant of a balance between providing student's independence and assisting them in recalling previously developed skills.<br>• There is potential to build common themes across multiple levels with coordinated curriculum development. |
| Student confidence | (1) Participation in CURES at the introductory level has previously led to increased confidence levels (Kloser, 2013; Harrison et al. 2011; Thompson et al. 2016). | (1) There is very little information available on student confidence reports in response to a CURE. | • If protocols are more complex and require advanced skills, students may perceive they are slow to progress through an experiment, or are not accomplishing their research objectives.<br>• Confidence gains may be different for upper-level CUREs than for those previously reported in introductory CUREs. |
| Potential for authenticity | (1) Students have minimal existing skillsets and exposure to problem solving and scientific practices (Hoskinson et al. 2013). | (1) Students have a well-developed incoming skillset and confidence gained in introductory courses.<br>(2) Students are more likely to have previous exposure to hypothesis formation, methodology, and interpretation of scientific materials. | • A well-developed incoming skillset means that the instructor can commit less time to skill-building before students can address authentic research questions.<br>• Existing skillsets and exposure potentially increases the depth and breadth of potential collaborative projects. |
| Professional applicability | (1) Students are less likely to have well developed plans in relation to careers in STEM.<br>(2) Students are less likely to see the direct applicability of methodology to use in the "real world" (Wieman 2017). | (1) Students are more likely to have well developed plans in relation to careers in STEM.<br>(2) Students are less likely to alter future plans in response to participation in a CURE. | • Students may be more likely to see the applicability of the skills they are learning to the future plans that they have, if these correspond well to one another.<br>• Students' may care more about their ability to complete an exercise that is similar to a common skill applied in their field, as they see its applicability. |
| Reduced class size | (1) Larger class size, and sample size<br>(2) Many lab sections<br>(3) More likely to have primary instruction from Graduate Teaching Assistants and Undergraduate Teaching Assistants | (1) Smaller class sizes, and sample sizes<br>(2) Fewer lab sections<br>(3) Increased one on one instruction with faculty members | • The instructor or primary researcher can work directly with students to achieve learning and research goals.<br>• Small samples of students in upper-level CUREs make it difficult to generalize findings from research.<br>• Research is currently biased toward introductory courses, but results at different stages of education are required to optimize CUREs for all students. |

The potential implications related to conducting CUREs in upper-level courses are discussed with respect to course structure and student independence.

**Table 2.** Timelines between the Guided and Autonomous CURE format iterations

| Guided | | Autonomous | |
|---|---|---|---|
| **Week** | **Exercises** | **Week** | **Exercises** |
| 1–6 | Skill-building | 1–2 | Research introduction and design |
| 7 | Research introduction and design | 3–10 | Research project experimentation |
| 8–14 | Research project experimentation | 11–13 | Troubleshooting |
| 15 | Discussion | 14–15 | Discussion |

In the Guided Format, the first 6 weeks of the course were used to develop the methodological skills necessary to complete the novel research projects. In the Autonomous Format, the students began the authentic research project immediately, following one day of review of basic lab skills. At the end of the semester, the students used the excess time to troubleshoot their projects.

effect of removing the skill-building and starting immediately from research focused lab activities where the students would learn the techniques through independent research experimentation as they needed to use them. This second iteration, which was taught in the absence of a skill-building portion, is hereafter referred to as the "Autonomous Format." This change inherently increased student independence and decreased course structure. With this change, students had more independence in selecting the specific research questions and had to do more troubleshooting, similar to the experience of an undergraduate or first year graduate student working in an actual research lab (see Table 2 for more details). In the "Autonomous" Format, time dedicated to skill-building was replaced with a series of troubleshooting days near the end of the semester, providing students with an opportunity to repeat skills that may have failed during their independent research.

Without incentives, we requested all students enrolled in the Guided ($N = 27$) and Autonomous ($N = 36$) Format participate in a pre- and post-course survey, resulting in participation rates of 89% and 86%, respectively. We used anonymous identifiers to track individuals, and all data were deidentified. The survey questions covered general constructs including student perceptions of Confidence, Applicability, and CURE Format (Table 3). The survey instrument was a Likert-scale response system ranging from 1 (strongly disagree) to 5 (strongly agree), designed for this study by the lead author (A.E.B.). The survey items were piloted by five individuals to ensure consistent interpretation. All handling of data and survey administration was approved by the Auburn University Institutional Review Board (Approval 18-314).

Student demographics were comparable between the two formats in terms of self-reported disciplines, previous research experience, and self-reported grade point average (GPA) (Table 4). The ratio of undergraduate to graduate students enrolled in each CURE was also comparable across formats and was comparable with reported university-wide statistics from 2018. The distribution of men and women students did vary between the two course formats (71.43% women in Guided and 50% women in Autonomous).

We were unable to validate constructs through factor analyses (Knekta et al. 2019) due to limited statistical power given the course size; therefore, we loosely grouped questions that were similar into measures of students' perceptions of confidence, applicability, and CURE Format, as increased student reports of confidence and views of applicability to their professional aspirations are commonly reported benefits of CURE implementation at the introductory level. For the purposes of presenting the results and discussion, we analyzed individual survey items within those three aforementioned measures of perceptions (Table 3). We analyzed data using linear mixed models (Pinheiro et al. 2020), testing for reported gains (differences in pre- and post-survey reports) in the measures (i.e., confidence, applicability, and CURE Format) between iterations. When pre- and post-survey responses were co-analyzed, pre-survey responses were included as a random effect to control for incoming variation in student responses. We then utilized Tukey *post hoc* analyses (Lenth 2019) for pairwise comparisons of pre- and post-timepoints within years, and pairwise comparisons between calculated gains of post-surveys between formats. In each case, anonymous identifiers were used in the model to account for multiple repeated sampling. Select comparisons are discussed below.

## Guided versus autonomous

### Applicability—value of skills in everyday life and career

When comparing the two laboratory formats, our results showed that students in the Autonomous Format were more likely to identify the applicability of their skills to everyday life (Estimate $= 1.062 \pm 0.44$; $P = 0.017$) and were more likely to express perceptions of contribution to scientific

**Table 3** Survey questions and responses

| Construct | Survey question | Implementation | Strongly disagree (1) (%) | (2) (%) | Neutral (3) (%) | (4) (%) | Strongly agree (5) (%) |
|---|---|---|---|---|---|---|---|
| Student perceptions of the CURE | I was often excited to attend class and see the previous weeks result. | Guided | 0 | 8 | 38 | **45** | 8 |
| | | Autonomous | 4 | 25 | **37.5** | 25 | 4 |
| | I believe students benefit from a class taught in the CURE format.* | Guided | 4 | 4 | 8 | 38 | **45** |
| | | Autonomous | 4 | 16 | 16 | **38** | 21 |
| | The skills I gained were worth the time investment in comparison to a traditional lab course. | Guided | 8 | 4 | 0 | 25 | **58** |
| | | Autonomous | 4 | 8 | 25 | **38** | 21 |
| | The CURE curriculum allowed instructors to become more engaged with students.** | Guided | 0 | 0 | 13 | 25 | **63** |
| | | Autonomous | 4 | 0 | 33 | **42** | 16 |
| | I would recommend this course to another student.** | Guided | 4 | 4 | 8 | 29 | **54** |
| | | Autonomous | 4 | 13 | 33 | **33** | 13 |
| | The CURE broadened my interest in research. | Guided | 8 | 8 | 21 | 29 | **33** |
| | | Autonomous | 8 | **29** | 16 | 25 | 16 |
| | Participating in the CURE helped to prepare me for participating in a research lab. | Guided | 4 | 0 | 25 | **38** | 33 |
| | | Autonomous | 4 | 8 | 25 | 21 | **38** |
| | I feel as though the CURE curriculum was more engaging than traditional teaching methods. | Guided | 0 | 8 | 13 | 25 | **54** |
| | | Autonomous | 0 | 13 | 25 | **33** | 25 |
| | I participated in a project that will lead to scientific discovery.** | Guided | 4 | 8 | 13 | **45** | 29 |
| | | Autonomous | 16 | 8 | **42** | 21 | 8 |
| | I feel as though the CURE curriculum will help me retain knowledge for a longer period of time. | Guided | 4 | 8 | 13 | **38** | 29 |
| | | Autonomous | 4 | 8 | 21 | **50** | 13 |
| | The CURE required more time input than traditionally taught laboratory courses.* | Guided | 4 | 13 | 4 | **50** | 30 |
| | | Autonomous | 0 | 4 | 21 | 30 | **46** |
| Confidence | I can perform an experiment without aid, when given a protocol. | Guided | 0 | 0 | 13 | **50** | 38 |
| | | Autonomous | 0 | 0 | 8 | **50** | 42 |
| | I can design an experiment from beginning to end. | Guided | 0 | 17 | **38** | 34 | 13 |
| | | Autonomous | 4 | 13 | 29 | **46** | 8 |
| | I am confident in my ability to keep a well-structured lab notebook properly detailing experiments. | Guided | 0 | 8 | 8 | **46** | 38 |
| | | Autonomous | 0 | 8 | 8 | **42** | 42 |
| | The CURE curriculum made it easier to identify and address my weaknesses throughout the semester.** | Guided | 8 | 4 | 8 | 29 | **50** |
| | | Autonomous | 4 | 25 | **29** | 21 | 17 |
| Applicability | Research that I do in lab courses will lead to scientific discovery.*** | Guided | 4 | 8 | **42** | 38 | 8 |
| | | Autonomous | 4 | 4 | **58** | 30 | 4 |
| | In laboratory classes, I gain skills that will be applied in my future career. | Guided | 4 | 0 | 13 | 38 | **46** |
| | | Autonomous | 0 | 8 | 21 | 25 | **46** |
| | The practices taught in molecular biology courses are applicable in everyday life. | Guided | 17 | **25** | **25** | 21 | 13 |
| | | Autonomous | 4 | 8 | **42** | 29 | 17 |

For each of the three theoretical constructs—confidence, applicability, and CURE format—students answered a series of survey questions addressing their perceptions on a Likert scale (strongly disagree to strongly agree). The distribution of responses following CURE implementation is displayed by authenticity level. Bolded survey questions represent a statistical different between the Guided and the Autonomous groups. Level of significance is represented with an asterisk (*<0.05, **<0.01, ***<0.001). The highest response rate (%) for each question is underlined and bolded for comparison between implementations. Note responses are raw post-survey scores, unadjusted for pre-survey responses. See Fig. 1 for graphical depiction of statistically significant relationships.

**Table 4** Demographic information from both the Guided and Autonomous CURE Formats

| Gender | Guided ($N=28$) (%) | Autonomous ($N=35$) (%) | University demography (based on 2018 enrollment) (%) |
|---|---|---|---|
| Male | 28.57 | 50 | 50.7 |
| Female | 71.43 | 50 | 49.3 |
| Degree type | | | |
| Bachelor | 87.5 | 81.8 | 84.54 |
| Graduate | 12.5 | 18.2 | 15.46 |
| Self-reported discipline | | | |
| Microbial, cellular, and molecular biology | 81.5 | 78.8 | — |
| Agricultural biology | 3.7 | 6.1 | — |
| Biomedical | 7.4 | 3.0 | — |
| Pre-professional | 0 | 6.1 | — |
| Other | 7.4 | 6.1 | — |
| Self-reported GPA | | | |
| 2.0–2.4 | 8 | 4 | — |
| 2.5–2.9 | 16 | 17 | — |
| 3.0–3.4 | 36 | 29 | — |
| 3.5–4.0 | 52 | 50 | — |
| Previous research experience | | | |
| No experience | 4 | 12 | — |
| <1 year | 15 | 20 | — |
| 1–2 years | 44 | 52 | — |
| 3+ years | 37 | 16 | — |

discovery (Estimate $= 1.625 \pm 0.44$; $P = 0.0003$). However, they were not any more likely to identify the applicability of their skills to their future careers than students in the Guided Format (Estimate $= -0.708 \pm 0.44$; $P = 0.11$; Fig. 1A).

## Confidence

Pairwise comparisons between the two formats revealed students in the Guided Format were more confident in their ability to identify their own weaknesses following participation in a CURE (Estimate $= 0.86 \pm 0.279$; $P = 0.021$). Despite this, students reported being equally prepared in their ability to design an experiment (Estimate $= -0.229 \pm 0.282$; $P = 0.417$), produce a comprehensive lab notebook (Estimate $= 0.229 \pm 0.282$; $P = 0.42$), and perform an experiment using a protocol (Estimate $= -0.188 \pm 0.282$; $P = 0.507$), regardless of format (Fig. 1B).

## CURE format

We identified five survey items that showed significant differences between the Guided Format and Autonomous Format iterations of the course (Fig. 1C; Table 3). Of these survey items, students consistently responded more positively in the Guided Format. For example, students in the Guided Format reported they were more likely to recommend the course to another student (Estimate $= 0.85 \pm 0.317$; $P = 0.007$), more likely to believe students benefit from the CURE format (Estimate $= 0.60 \pm 0.317$; $P = 0.058$), and to report that CUREs are more likely to lead to scientific discovery than traditional lab courses (Estimate $= 0.918 \pm 0.317$; $P = 0.004$). Student responses also indicated that instructor engagement was highest in the Guided Format (Estimate $= 0.80 \pm 0.317$; $P = 0.014$). While both formats indicated that CUREs take more time than cookbook lab courses, students expressed this more strongly in the Guided Format (Estimate $= 0.61 \pm 0.320$; $P = 0.057$; Fig. 1C). The combination of these findings indicates that students responded more positively to the Guided CURE Format.

Additionally, students in the Guided Format reported that the CURE was more likely to broaden their interest in research and reported increased excitement to attend class. Although the estimates were large, these findings were not statistically significant at our pre-defined cut-off of 0.05 (Estimate $= 0.578 \pm 0.317$; $P = 0.06$ and Estimate $= 0.54 \pm 0.317$; $P = 0.08$, respectively), possibly due to our small sample size.

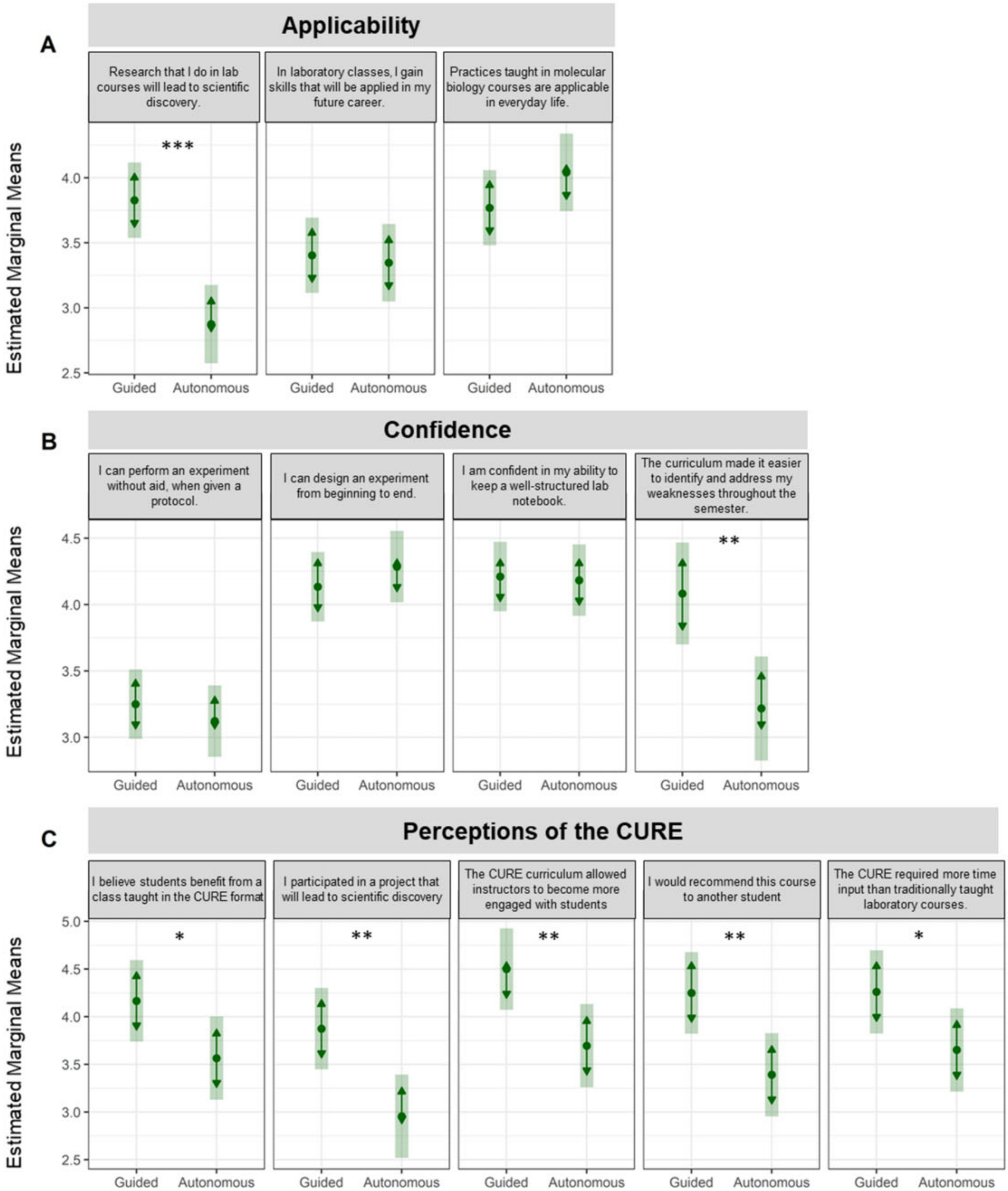


**Fig. 1** Student post-survey gains. Student measures of gains in applicability, confidence, and perceptions of the CURE were compared between the Guided and Autonomous Formats. Least squared means were plotted with 95% CI displayed by shaded regions, and arrows represent comparisons among the means, with overlapping arrows indicating non-significance based on Tukey *P*-value adjustments (Lenth et al. 2021). Statistical significance is noted by an asterisk (*<0.05, ** <0.01, ***<0.001). Only statistically significant measures were plotted for the CURE format. See Table 2 for comprehensive post-survey response comparisons.

## Discussion

The goal of this work was to reflect on the most salient elements of upper-level CUREs and identify how teaching approaches—specifically the inclusion of skill-building activities—may affect student perceptions of confidence, applicability, and CURE structure. Our main conclusion is that implementing upper-level CUREs that require advanced knowledge calls for a balance between structure *and* independence. And while we acknowledge that failure is an important part of the scientific process, too much failure can deter some students from scientific research and minimize their feelings of scientific discovery. Below we reflect on our experiences and our empirical results and make several suggestions for future implementations of upper-level CUREs.

## Balancing student experience with course complexity

Increasing complexity may increase the potential for students to perceive failure, or a difference in an expected or desired result and the one that the student experiences. In this course, failure could occur at many stages. Students may fail at producing their final protein product or minor methodological failures could occur throughout the experiment. An emphasis on skill-building in the Guided Format filled knowledge gaps that were apparent in the Autonomous Format, allowing for complex protocols to run more smoothly (Supplementary Fig. S1). The Autonomous Format, that de-emphasized skill-building, meant students did not have as many opportunities to practice skills that were required for a successful project, leading to more frequent methodological failures. Additionally, the increased freedom for hypothesis formation decreased the amount of project overlap among students; therefore, students were less able to engage in peer instruction and they could not ask their peers for additional shared materials if a step in their project failed.

The increased complexity of research projects in the Autonomous Format led to an increased workload for teaching assistants and instructors. However, students in the Autonomous Format indicated it required less time investment than student reports from the Guided Format; students in the Autonomous Format also reported less benefits of education through a CURE format (Estimate $= -0.601 \pm 0.317$; $P = 0.05$). Consequently, they were less likely to recommend the course to another student (Estimate $= -0.859 \pm 0.317$; $P = 0.007$). Without significant demonstrable benefits from the Autonomous Format over the Guided Format, and with increased workload for instructors and teaching assistants in the Autonomous Format, we conclude that a Guided Format, or a related approach, represent an effective balance of skill-building and independence.

## Student confidence

When we examined the individual survey items, we observed that students in the Autonomous Format reported a decreased confidence in their ability to identify and address weaknesses throughout the semester. This was surprising because this skill was especially important in the Autonomous Format, as students had to troubleshoot to complete experiments. Previous empirical research on lower-level biology students showed that a CURE, compared to a cookbook lab, resulted in gains in student confidence in biology majors' ability to execute biology-related laboratory tasks (Kloser et al. 2013).

We make sense of these results through one of the following possible explanations. First, committing time to skill-building may increase student confidence because as they performed the experiments, they knew more about what to expect and they knew that they could complete the task under controlled conditions. Alternatively, students in the Autonomous section had to troubleshoot problems more. While troubleshooting leads to the development of communicative and metacognitive skills that are crucial components of the science process, these experiences may have felt like failure and an inability to complete laboratory tasks.

## Potential for autonomy

One of the leading recommendations for professors looking to implement CUREs in their classroom is to cultivate a classroom environment in which students can embrace uncertainty (Shortlidge et al. 2016). However, in the Autonomous Format of our upper-level course, this meant much of class time was spent troubleshooting methods for diverse research questions. This may have been in part because we did not provide them with enough foundational knowledge to address their research question, and because relative to the skill-building section, we did not provide as much guidance about what types of questions could productively be addressed. Conversely, the skill-building experiences in the Guided Format built a knowledge base for students, giving them the confidence to effectively strategize a troubleshooting plan that was meaningful in their independent projects, which overall led to increased productivity and less reliance on the instructors. Additionally, they had a better understanding of realistic research questions that they could address during the semester. It also led to more in-depth, meaningful discussions between instructors and students, rather than mostly troubleshooting inquiries.

## Professional applicability

As this CURE was implemented in an upper-level biology course, we expected students in both formats to report that they could apply the methods from the lab course to their everyday life and their future career. Yet, we observed a decrease in student perception of applicability in the Guided Format in terms of scientific discovery and applicability in everyday life following participation in the CURE, whereas students in the Autonomous Format reported positive gains of scientific discovery and applicability to everyday life. However, students were more likely to view the applicability of skills to their future careers following participation in the Guided Format, although this finding was non-significant.

This was a surprising result, given that none of the groups in our Autonomous Format were able to yield a tangible product, compared to the 67% of groups in the Guided Format that were able to produce their chosen protein product. It is worth noting that a lack of protein as an end product does not necessarily indicate that students in the Autonomous Format did not gain technical research skills and perform skills effectively. In fact, students in both formats had plenty of opportunities to learn technical skills that will be applicable in scientific professions. We recognize the importance of students' view of professional applicability, and discuss below how to adjust this balance in order to improve perceptions of applicability in a Guided Format.

As most students only have exposure to cookbook laboratory experiences in lower-level science courses, they are not exposed to the realities of struggle and failure that are common in science. Previous studies show that overcoming failure is essential in producing competent scientists (Lopatto 2007; Laursen et al. 2010; Thiry et al. 2012; Andrews and Lemons 2015; Simpson and Maltese 2017). However, other work has shown that not all students perceive challenges associated with failure as a learning experience (Marra et al. 2012). For example, students who believe intelligence is a fixed, unchangeable trait are more likely to quit in response to challenges or setbacks (Henry et al. 2019). In our study, student mindset likely influenced students' decisions to persevere when faced with challenges and adversity (Hochanadel and Finamore 2015; Duckworth 2016). While students in the Autonomous Format did not produce tangible products (the end product of the experimental workflow), they were given the opportunity to troubleshoot their methodologies, which has been shown in the past to positively impact views of failure and persistence (Henry et al. 2019). Due to time restrictions, students in the Guided Format were given the opportunity to discuss possible steps for troubleshooting, but were not able to troubleshoot failed methodologies. Encouraging a growth mindset in students who encounter failure may be the difference between their viewing scientific failures as learning experiences rather than unconquerable barriers.

### Reduced class size

Class size has been recognized as one of the most highly reported instructor barriers to CURE implementation (Shaffer et al. 2014; Spell et al. 2014). The class size per section for this course was a maximum of 15 students, at 2 sections per year. With the increasing complexity of upper-level courses, we believe that the personal interaction with instructors was essential for student success. Increased class size or additional lab sections would have made the advanced methodologies used in these CUREs unfeasible, reducing authenticity. With two sections, instructors and teaching assistants co-taught each session, allowing increased opportunities to engage with instructors. The positive impacts of these interactions were reflected by student survey responses through consistently high scores of student and instructor engagement. We recommend continued implementation of CUREs in upper-level biology courses of small class size, as we found them manageable for instructors, and they allowed for valuable personal student–instructor interactions.

## Conclusions

Both the Guided and Autonomous course formats had distinct benefits and drawbacks. However, based on our results and experiences in the classroom, we recommend instructors front-load upper-level CUREs with skill-building exercises to maintain structure and consistency and encourage students to then apply their advanced skillset to develop and execute independent projects in their research experience. The extent of structure and skill-building required for students to carry out an independent project will vary depending on the project. In our course, the skill-building portion of the Guided Format required approximately half the semester. Depending on the level of independent project complexity, the skill-building to novel research ratio could be adjusted to the length necessary to fill pre-existing knowledge gaps. An alternative format adjusting the proportion of skill-building to novel research may also allow for maximization of the student and instructor benefits of skill-building, while increasing student gains of perceived applicability.

One limitation of this study is that all measures are based on student perceptions collected at one time point. Due to these constraints, as well as our small sample size, it is worth noting that these data are exploratory in nature and warrant further investigation. We were unable to collect information on long-term impacts or meaningful measures of learning gains. For example, students in the Autonomous Format gained trouble-shooting skills that may lead to measurable gains in scientific critical thinking. In the future, we plan to adapt the course to incorporate student reported benefits from each iteration, while also measuring learning gains using validated pre- and post-course concept inventories. While we believe the experiences of failure and troubleshooting are still essential in preparing students for careers in the fields of science, technology, engineering, and mathematics, it is important to highlight small successes throughout the semester to build student engagement and confidence. To accommodate these needs, we plan to introduce the research topic followed by a shortened skill-building section in the future. This will allow students to learn practical applications of the skill-building methodology and encourage the connection of learned skills and concepts to research applications. In turn, resulting confidence will increase student engagement during more independent research, and likely incorporate the views of professional applicability reported in the Autonomous Format. Another limitation of this research relates to observed differences in binary gender ratios across semesters, which in turn might impact student responses to survey questions. We acknowledge demographic characteristics such as gender impact student experiences in science, and future work will benefit from an explicit focus on how these laboratory experiences hinder or enhance learning for different subsets of students.

Historically, research on CURE formatted courses has not focused on upper-level students or analyzed upper-level performance in response to different laboratory experiences. However, there is tremendous potential to support this fledgling group of students through evidence-based approaches as they transition from upper-level coursework to post-undergraduate career development. We hope this report provides instructors with questions to ask during course development, knowledge of potential barriers to studying upper-level CUREs, and methods to incorporate pedagogical research into their own inquiry-based teaching. Collaborative efforts to share results among institutions will be essential in making general recommendations of best practices for teaching CURES across different contexts—inclusive of upper-level CURE courses.

## Acknowledgments

We would like to thank Sara Berk, Ariel Steele, and Sara Odom for their valuable input during the editing process and Dr. Todd Steury for statistical advisement. Additionally, we would like to thank all Gene Expression Recombinant DNA Laboratory Graduate Teaching Assistants for their instruction time and the students for their participation and valuable perspectives.

## Funding

This work was supported by the National Science Foundation [DEB-1751296] to R.M.G., the National Institutes of Health [NIA-1R15AG064655-01] to T.S.S. and R.M.G., the Cellular and Molecular Peak of Excellence Fellowship to A.E.B., and Auburn University Start-up funds to T.S.S.

## Conflict of interest statement

The authors declare that they have no possible conflicts of interest.

## Data availability statement

All data, statistical code, code output, and supplemental files are publicly available as a GitHub repository (https://github.com/aeb0084/CURE_SkillBuilding.git)

## Supplementary data

Supplementary data available at *ICB* online.

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