Students' Emotions, Perceived Coping, and Outcomes in Response to Research-Based Challenges and Failures in Two Sequential CUREs

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ABSTRACT

The ability to navigate scientific obstacles is widely recognized as a hallmark of a scientific disposition and is one predictor of science, technology, engineering, and mathematics persistence for early-career scientists. However, the development of this competency in undergraduate research has been largely underexplored. This study addresses this gap by examining introductory students' emotional and behavioral responses to research-related challenges and failures that occur in two sequential research-based courses. We describe commonly reported emotions, coping responses, and perceived outcomes and examine relationships between these themes, student demographics, and course enrollment. Students commonly experience frustration, confusion, and disappointment when coping with challenges and failures. Yet the predominance of students report coping responses likely to be adaptive in academic contexts despite experiencing negative emotions. Being enrolled in the second course of a research-based course sequence was related to several shifts in response to challenges during data collection, including less reporting of confusion and fewer reports of learning to be cautious from students. Overall, students in both the first and second courses reported many positive outcomes indicating improvements in their ability to cope with challenge and failure. We assert that educators can improve research-based educational courses by scaffolding students' research trials, failures, and iterations to support students' perseverance.

INTRODUCTION

More than ever before, given the complex scientific problems facing society in the 21st century, tomorrow's scientists need to be risk-taking, resilient individuals able to navigate challenges and deal with failures quickly and efficiently. However, while this ability to persevere through challenges and cope with scientific failures is widely recognized as a hallmark of proficient scientists and may be a key predictor of persistence for early-career scientists (Hunter *et al.*, 2007; Laursen *et al.*, 2010; Harsh *et al.*, 2011; Thiry *et al.*, 2012; Simpson and Maltese, 2017; Henry *et al.* 2019), relatively little is known about how undergraduate students develop these skills as part of their scientific disposition (Henry *et al.*, 2019). Further, instruction on how to productively cope with failure is rarely emphasized in science classrooms (Traphagen, 2015; Simpson and Maltese, 2017). This may be especially true in confirmation-oriented laboratory courses that engage students in activities known to yield given scientific results (Buck *et al.*, 2008) with little opportunity for iterative refinement like troubleshooting and collecting additional data to address uncertainty (Auchincloss *et al.*, 2014; Corwin *et al.*, 2018). Taken together, this knowledge gap leads to practical questions about

Erin Shortlidge, *Monitoring Editor*

Submitted May 24, 2021; Revised Feb 2, 2022; Accepted Feb 8, 2022

CBE Life Sci Educ June 1, 2022 21:ar23

DOI:10.1187/cbe.21-05-0131

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how students learn to navigate obstacles and how we, as instructors, can "best" support them in doing so.

Undergraduate research experiences (UREs) and course-based undergraduate research experiences (CUREs) have potential to provide an environment in which students can learn to engage productively with challenges and cope with failure. These research-based approaches engage students in the exploration of original questions where the answer is unknown both to students and their instructors or mentors (Buck *et al.*, 2008; Auchincloss *et al.*, 2014; National Academies of Sciences, Engineering, and Medicine [NASEM], 2017). Such opportunities for discovery have the potential to expose students to situations in which they may encounter unintelligible results and must engage in iteration and refinement to make sense of their data (Laursen *et al.*, 2010; Auchincloss *et al.* 2014; Dolan, 2016; NASEM, 2017; Corwin *et al.*, 2018; Gin *et al.* 2018; Lopatto *et al.*, 2020). This, in turn, affords students practice in coping with scientific challenge and failure and can contribute to the development of this skill. Extensive qualitative investigations by Hunter, Laursen, Thiry and colleagues (Hunter *et al.*, 2007; Laursen *et al.*, 2010; Thiry *et al.*, 2012) highlighted students' development of perseverance and coping with setbacks and failures as a key outcome of UREs. Students in summer and course-based UREs frequently report gains in the CURE and SURE survey item: "Developing tolerance for obstacles faced in the research process" (Lopatto, 2007; Jordan *et al.*, 2014). Similarly, retrospective accounts of graduate students and practicing scientists highlight exposure to frustration and failure in "doing science" as a valued long-term benefit of URE participation (Harsh *et al.*, 2011). Recent work described the iterative processes in CUREs as frustrating yet formative, ultimately contributing to learning (Lopatto *et al.*, 2020; Goodwin *et al.*, 2021). Finally, the ability to navigate scientific obstacles was seen as an important outcome of a CURE in which students experienced many scientific failures and had the opportunity to address their failures with additional experimentation, troubleshooting (i.e., iteration), and psychosocial support from their instructors/mentors (Gin *et al.*, 2018). It is clear from these studies that research-based experiences have potential to improve students' ability to cope with challenge and failure (e.g., Laursen *et al.*, 2010; Hernandez *et al.*, 2013; Corwin *et al.*, 2015; NASEM, 2017; Gin *et al.*, 2018; Lopatto *et al.*, 2020).

Despite the encouraging results of the research described, this line of inquiry is still in its nascent stage (Henry *et al.*, 2019) and has certain limits to its utility. Most existing evidence is inferred from studies investigating the outcomes and processes of STEM undergraduate research broadly (Laursen *et al.*, 2010; Harsh *et al.*, 2011; Lopatto *et al.*, 2020) rather than studies with clear, specific intentions to examine how students cope with research challenges and failure. Thus, prior claims regarding this outcome and its link to apprenticeship-like and course-based undergraduate research (UR) models are difficult to substantiate, particularly as past research included very limited measures focused on students' ability to navigate obstacles. For instance, the aforementioned SURE and CURE surveys (Lopatto, 2005), include only a single Likert-type item to describe the outcome "tolerance for obstacles." This design limits measurement validity, as multiple items are typically used to best assess a complex latent construct such as "tolerance" (Knekta *et al.*, 2019), and validity evidence for these instruments have not been established in general. In their respective qualitative studies examining science, technology, engineering, and mathematics (STEM) UREs, Harsh and colleagues (2011) and Laursen and colleagues (2010) found that the theme of scientific resilience emerged from participants and faculty mentors in interview prompts on student gains. They did not, however, specifically ask about resilience or coping. More recently, Gin and colleagues (2018) conducted a qualitative study to explicitly describe the links between students' encounters with scientific obstacles, opportunities for iteration, and outcomes within a CURE. However, this work represents only a single classroom context with relatively few students, which may limit generalizations to other research experiences. It could also be argued that student access to caring instructors in this course was more powerful than the course design in determining their outcomes. Other studies have further suggested that coping responses to academic challenges may be influenced by race, ethnicity, and gender identities (e.g., Cheong *et al.*, 2004; Hawley *et al.*, 2007; Acheampong *et al.*, 2019) as well as their mental health (Cooper *et al.*, 2020a); however, little work has explored the interplay of demographic characteristics on how one copes with failure in STEM UR. It is with this in mind that we conducted the present study, in which we aimed to explore students' responses to science research challenges and failures in two large, sequential, research-based courses.

Our investigation of how students respond to research-based challenges and failures is particularly salient for several reasons. First, and foremost, the characterization of the types of challenges and failures encountered in the research setting and how students respond to them is essential to informing our understanding of how failure might contribute to attrition and what behaviors and coping mechanisms may contribute to scientific resilience and the ability to navigate obstacles. Second, insight into how specific teaching contexts and strategies support student resilience, adaptive coping, and—ultimately—persistence can benefit classroom practices. CUREs, with their focus on research and introduction of unexpected results, provide an ideal context in which to do this. CUREs are rapidly gaining traction in undergraduate biology, as they offer an alternative scalable way to engage students in UR (Wei and Woodin, 2011; Auchincloss *et al.*, 2014). Many positive outcomes have been characterized that students may experience as a result of CURE participation, such as gains in content knowledge (e.g., Shaffer *et al.*, 2010; Caruso *et al.*, 2016), learning to think like a scientist (e.g., Brownell *et al.*, 2015; Olimpo *et al.*, 2016; Killpack *et al.*, 2020), publishing scientific work (e.g., Shaffer *et al.*, 2010; Lin *et al.*, 2020), project ownership (e.g., Hanauer *et al.*, 2017; Cooper *et al.*, 2019; Corwin *et al.*, 2018), increased positive affect and motivation toward science (e.g., Olimpo *et al.*, 2016; Hanauer *et al.*, 2017; Greenman *et al.*, 2021), and persisting in the sciences (e.g., Rodenbusch *et al.*, 2016; Corwin *et al.*, 2018). Furthermore, because these courses scale research and lack the barriers to entry typical of most UREs, they are more accessible to *all* students and have the potential to increase diversity within STEM fields (Bangera and Brownell, 2014; Rodenbusch *et al.*, 2016). It comes as no surprise, therefore, that national reports championing involvement in UR frequently highlight the role of research-based courses in achieving this goal (American Association for the Advancement of Science

[AAAS], 2011; President's Council of Advisors on Science and Technology [PCAST], 2012; NASEM, 2015, 2017). These benefits, in addition to the potential of research-based courses to expose students to scientific failures and offer opportunities for iteration, make CUREs excellent contexts in which to study how students cope with challenge and failure. Finally, and importantly, recent work has highlighted that CUREs may be especially suited to support underserved students' success (Rodenbusch *et al.*, 2016). Yet, if and how coping in CUREs differs as a result of student demographics have not been investigated. Thus, we set out to investigate this topic, and we detail in the following section the frameworks relevant to this work and subsequently describe the current study context and questions.

Conceptual Frameworks and Definitions

For all constructs of importance, we strive to provide clear definitions so that our readers may gauge the relevance of our work to their own (Rowland *et al.*, 2019). In addition, we briefly outline established frameworks that have informed us to guide readers in considering the implications of this study.

The recent proliferation of research-based courses has brought with it many attempts to describe and distinguish between different types of learning experiences. Here, we use the framework proposed by Auchincloss and colleagues (2014), and later tested by others (e.g., Brownell and Klosser 2015; Corwin *et al.*, 2018; Esparza *et al.*, 2020), to describe CUREs. For the purposes of this work, we define a "CURE" as a course in which students participate in research with the intention of making discoveries that are novel and relevant to a community beyond the classroom. We consider the pursuit of making "relevant discoveries" as the hallmark of a CURE. CUREs also involve students in science practices and often involve students in iteration and collaboration to varying degrees (Auchincloss *et al.*, 2014; Corwin *et al.*, 2018; Cooper and Brownell, 2018).

As is often the case with terms used in common language, definitions of the word "failure" abound and range from the more extreme—one "fails" when one eventually disengages completely from attempting the task at hand (Thomas, 2014)—to the milder—one "fails" when anything in the process one is attempting does not align with a desired result (Cannon and Edmondson, 2005). For this paper, our definition of "failure" is decidedly mild. We consider a "failure" to be any instance when a student is unable to meet the demands of a task involving a set expectation that defines success and requiring competencies to be executed (i.e., an achievement context; see Cacciotti, 2015; Henry *et al.*, 2019). Therefore, a failure might constitute *not* successfully extracting DNA from a sample when the expectation is that the actions performed will lead to a DNA extraction. While this type of failure is often "fixable" with repetition and troubleshooting, it is still a "failure to achieve the expected outcome of the task" and therefore falls within our definition. Importantly, we define failures as different from errors, which are perceived as they happen, can be rectified quickly in the moment, and do not preclude accomplishment of a specific goal (Tulis *et al.*, 2016). For example, in the context of DNA barcoding, an error may be mis-pipetting DNA into the wrong lane in a gel or forgetting to add a reagent during DNA extraction and then realizing these missteps shortly after they occur. These missteps, once noted, can be rectified and would not lead to a failure to extract DNA, because actions can immediately be undertaken to correct them.

In accordance with our definition of failure and similar to the work of Henry and colleagues (2019), we define a "challenge" as an achievement context that carries the risk of failure. Our theoretical conceptualization of how students interact with STEM challenges is also informed by Henry and colleagues' work (2019). They present a model that draws on theory and studies in educational psychology investigating mindset (Dweck, 2000, 2006), goal orientation (Pintrich, 2000a,b), and fear of failure (Conroy, 2001; Martin and Marsh, 2003; Noguera *et al.*, 2013) to explore how STEM students might approach challenges. The model goes on to describe how attributions (Weiner, 1979) and coping responses (Skinner *et al.*, 2003) influence both how students respond when failure occurs and the outcomes (positive or negative) of those responses. Our work in this study draws from this model and is most strongly informed by the work done by Lazarus (1993) and Skinner and colleagues (2003) to explain coping with stressors.

We broadly define coping as an individual's behavioral response to a stressor. In our case, the stressors of interest are research challenges and failures. While this broad definition is agreed upon by most coping theorists, other aspects of coping vary. In a 1993 review, Lazarus makes a case for coping as context dependent and dynamic as opposed to stable and unchanging, meaning that coping responses may vary with the context in which a challenge or failure occurs and can change over time. This view aligns with our own, as we anticipate that undergraduates' coping responses will be specific to their STEM learning contexts and are malleable. However, our views also align with those expressed by Spencer and colleagues (1997) that coping responses in a given context will become more stable over time. We therefore feel it is particularly important to establish adaptive coping responses early in undergraduates' careers when they may first encounter research failures. Coping responses range from avoiding the stressor, coping indirectly with the emotions caused by the stressor, or engaging directly in trying to solve a stressor (see our codebook in Supplemental Materials for descriptors of coping responses). Notably, "emotions" in this context refer to the conscious mental reactions experienced as feelings that result from experiencing a stressor. Many coping responses have been characterized in the literature and are comprehensively reviewed by Skinner and colleagues (2003). In this review, the authors argue that coping can either be adaptive, when it helps to maintain well-being, or maladaptive, when it prevents well-being or extends the effects of the stressor. Importantly, they argue that any kind of coping can play both roles; for example, avoidance may be adaptive when the stressor is unchangeable but maladaptive when it could be easily alleviated with a different approach. For the purpose of this work, we define "adaptive research coping" as coping that *both* maintains a students' well-being and allows advancement toward research goals. "Maladaptive research coping" is damaging to well-being *and/or* precludes the research agenda. Certain types of coping are more likely to be adaptive or maladaptive using these definitions (Henry *et al.*, 2019; Supplemental Table 2). Finally, because Skinner et al.'s (2003) work constitutes the most comprehensive review of coping that we were able to find, we used their work to generate our a priori codes, adding only one inductive code of our own. Definitions of the coping categories stem directly from the definitions included in Skinner and colleagues' review.

The Current Study

The study presented here strives to expand knowledge of the landscape of student coping in research-based courses by addressing the following research questions within the context of two sequential introductory biology CUREs:

RQ1. What are biology undergraduates' emotional responses to research-based challenges and failures in two sequential CUREs?
RQ2. What are biology undergraduates' perceived coping mechanisms in response to research-based challenges and failures?
RQ3. What outcomes do students perceive as a result of encountering research-based challenges and failures within the CURE context?
RQ4. Do emotional responses, perceptions of coping, and outcomes students experience differ across demographic groups and sequential CURE courses?

We investigated these questions using a qualitative to quantitative approach in which we qualitatively characterized emotions, coping mechanisms, and outcomes; converted these codes to binary variables; and analyzed these data for trends using mixed models. Our qualitative analyses aimed to explore and characterize how students cope with research challenges (RQs 1–3). Our quantitative analysis aimed to identify trends in how students in different courses and across different demographic groups responded to a particular type of technical research challenge: challenges in data collection (RQ4). With our quantitative analyses, we aimed to elucidate relationships unlikely to have arisen solely by chance between our variables in order to inform and guide future questions and research in the field. We included investigations of demographic variables for race/ethnicity and gender identity, because we predicted, based on prior work, that these may affect coping responses. We included year in college, anticipating that coping responses may be subject to a developmental trajectory that could be influenced by academic experience, in line with suggestions that coping is malleable (Lazarus, 1993; Spencer *et al.*, 1997). We included biology majors, given the context-dependent nature of coping and that this academic identity was likely to interact with the context (Lazarus, 1993). This approach provides a preliminary glimpse into biology undergraduates' perceptions of how they respond to challenge and failure in a research-based course. Emotional responses to research-based challenge and failure (i.e., the conscious mental reactions experienced as feelings that result from experiencing a challenge or failure) and students' perceptions of their coping responses (i.e., conscious behavioral responses precipitated by experiencing a challenge or failure) are of interest, because they reflect the relative adaptivity of coping practices and predict students' coping-self-efficacy (Saklofske *et al.*, 2012; Watson and Watson, 2016). Coping self-efficacy is one's perceived ability to cope effectively with challenges and has potential to influence a person's future engagement within a subject or career trajectory and subsequent success (Li and Nishikawa, 2012; Saklofske *et al.*, 2012; Barrows *et al.*, 2013). Therefore, this work will help to inform efforts to retain students in career tracks involving STEM research.

METHODS AND RESULTS

This work was conducted in accordance with methods reviewed by the University of Colorado, Boulder's Institutional Review Board and found exempt (no. 17-0540).

Course Descriptions

In line with national calls to engage all students in authentic research practices early in their academic careers, the Biology Department at James Madison University (JMU; a large master's-granting institution) redesigned its introductory majors laboratory courses as a two-semester research experience focusing on the common theme of DNA barcoding.[1] In the JMU curriculum, the sequential introductory biology courses (BIO140 Foundations of Biology I and BIO150 Foundations of Biology II) serve as a program trailhead for students pursuing majors in the field (biology and biotechnology) and the health sciences. As well, the first semester (BIO140) fulfills requirements for other select science programs (e.g., biochemistry, geology) and general education science course work for non-STEM students. Students typically take these courses in the first or second year of their academic careers, but it is not uncommon for non-STEM students to take BIO140 in the third or fourth year to complete their general education requirements. These large-scale courses (n = ~600–800 total students per semester) include lecture and laboratory components—each meeting 3 hours per week—that are independent in content from each other. Moving from a more traditional lab course curriculum, the BIO140 and 150 lab courses were redesigned using Auchincloss and others' (2014) essential dimensions of CUREs (authentic community practices, discovery, relevance, collaboration, and iteration) as well as an emphasis on scientific communication and time-on-task/duration, which are identified in apprentice-like UREs as key activities in students' progression as scientists (Laursen *et al.*, 2010).

Students in the first-semester laboratory course (BIO140L) are engaged in the research question of how habitat type and degradation can influence biodiversity. In a series of collaborative and inquiry-oriented labs, BIO140L students learn concepts and practices from ecology as well as general research skills (e.g., transect sampling, data analysis, graphing) to quantitatively compare biodiversity at the forest edge and interior habitats in the campus arboretum. During this sampling, students collect an unknown organism that they use DNA barcoding to identify, engaging them over multiple weeks in the learning and application of ideas and techniques from molecular biology, phylogeny, evolutionary biology, and bioinformatics. Student findings are presented as posters, and their species diversity data are combined and compiled in a publicly available database that can be accessed for research or conservation purposes as well as to assist arboretum goers with species identification (for a detailed account of the BIO140L course design, see Hyman *et al.*, 2019). In the second-semester laboratory course (BIO150L), students use the skills and knowledge acquired in

[1]For more information on DNA barcoding, please see Cold Spring Harbor Laboratory DNA Learning Center (n.d.).

TABLE 1. Open-ended reflection prompts

Please describe any research-related challenges or failures that you have encountered over the past 2 to 3 weeks. These can include things such as challenges or failures during data collection and analysis, difficulty in interpreting data, or any other challenges associated with the research practices you engaged in. Please do not discuss experiences associated with taking quizzes, exams, or non-research lab assignments.
Please reflect on how you felt when these challenges or failures occurred. What was your emotional reaction?
Please describe how you acted in response to these challenges or failures.
If you feel that dealing with these challenges or failures helped you learn or provided an opportunity for growth, describe what you learned or how you grew as a result of dealing with these challenges or failures.

BIO140L to design and carry out their own research projects using DNA barcoding. Students are coached in framing their research around questions they anticipate will be of broad relevance to a community outside the classroom. Examples of collaborative student-driven research projects include: the identification of mold species present in housing, identifying the composition of pollen species in making local honey, and evaluating the appropriateness of sushi labeling. In addition to technical practices, scientific writing is strongly emphasized as a course component, as students compose a group research proposal as well as individual abstracts and discussions to communicate their project findings. Given that both courses engage students in the pursuit of making scientific discoveries that are intended to be relevant and informative for communities beyond the classroom, we consider that both constitute CUREs. Importantly, both courses involve students in collaboration, iteration, and science practices as defined by Auchincloss and colleagues (2014).

Early findings from longitudinal studies on the impact and effectiveness of these lab courses have documented a range of conferred cognitive, affective, and behavioral outcomes self-identified by students upon exiting the experience and then as they progress through their academic programs (Harsh *et al.*, 2018; Hyman *et al.*, 2019). Students commonly reported the positive short- and intermediate-term contributions of the lab courses to their science self-efficacy, sense of belonging, ability to navigate scientific obstacles, and a variety of technical and research-related skills (e.g., scientific writing). Retrospectively, former participants majoring in biology indicated the lab courses influenced their choices in advanced course work and pursuit of independent research. Consistent with prior UR literature (Corwin *et al.*, 2018; Gin *et al.*, 2018; Cooper *et al.*, 2019, 2020b), student feedback highlighted design features such as project ownership, collaboration, iteration, and extended time on task as being valuable to their learning.

Another upside to the BIO140/150L course sequence is that students have the opportunity to "fumble around" in the research process and gain exposure to scientific challenges, aspects regularly identified by former participants as being among the greatest outcomes of the experience (Hyman *et al.*, 2019). By its nature, DNA barcoding is rife with potential pitfalls for students, especially during DNA extraction and PCR amplification, which in part, may be attributed to the selection of challenging specimens and common novice missteps in performing molecular techniques (Hyman *et al.*, 2019).[2] Observed results of student gels suggest that ~50% of students in both courses are successful in producing a usable PCR product for sequencing on the first attempt and then ~30% more (or ~80% in total) are successful after a second attempt, as 2 weeks of devoted lab time are set aside in the case initial efforts fail.

Data Collection

Data collection in both classes consisted of asking students to anonymously complete a set of open-ended prompts (Table 1) delivered via Qualtrics in Spring 2018 during laboratory class time. These questions asked students to describe their research-related challenges and failures, to comment on how they felt when these occurred, to describe their actions in response to these events, and to describe any opportunities for learning or growth that might result from these experiences. Earlier iterations of these prompts were pilot tested with BIO140 students in Fall 2017. Questions were adjusted based on Fall 2017 BIO140 responses and with guidance and feedback on question wording provided primarily by undergraduate authors E.W., S.M., and N.G. and three additional undergraduate researchers (all of whom had participated in biology research and could critique the questions). Question wording was adjusted iteratively over several rounds of revision. This pilot testing resulted in two important edits. 1) We changed the term "failures" in an earlier iteration first to "challenges, difficulties, or failures" and then to "challenges or failures" in the final version. This change was made because the term "failures" was too narrowly defined by some students and did not elicit information about the "mild" research-based failures we wished to study. The second edit was to adjust the language on the last question from "How did encountering and dealing with these challenges influence your interest in and motivation to do scientific research in general?" to the current version found in Table 1. Our edit was designed to be less leading by beginning with the "If" clause that more explicitly implies that the answer may be "no gains" and also to broaden the possible positive outcomes students might discuss.

In both classes, the students were asked to complete the open-ended prompts at a point in the semester when they were most likely to have recently experienced a research challenge or failure. For students in BIO140L, this point fell approximately 11 weeks into the semester after all students had the opportunity to first analyze their PCR products via gel electrophoresis (in week 9) to ensure successful DNA extraction and amplification from their specimens. Those students unable to initially successfully extract and amplify their DNA were provided a second opportunity to do so in week 10 (as described in Hyman *et al.*, 2019). For students in BIO150L, this point fell approximately 9 weeks into the semester, again after students had analyzed their first attempts at extraction and amplification

[2]Brief descriptions of the molecular techniques referenced in the article can be found in Supplemental Table 5.

(in week 7) with an opportunity for iteration as needed (week 8). This timing for data collection allowed us to capitalize on students' recent experiences with challenge and failure in order to better capture their emotions post-challenge/failure and their perceived coping responses and outcomes. Students' prompt responses ranged from one word (e.g., "yes" in response to the last prompt) to nearly 300 words describing a challenge, but most were approximately two sentences (between 40 and 80 words) in length. From an instructional perspective, these reactive prompts also acted as a light-touch intervention to engage students in reflective practices about their research challenges; metacognitive exercises, in general, have been found to contribute to one's learning and growth (Tanner, 2012). Demographic data used in this study were gathered from pre surveys administered at the onset of the term to students as part of a larger ongoing project assessing how the lab courses impact participants.

Study Participants

A total of 668 students agreed to participate and generated usable data (339 from BIO140L and 329 from BIO150L) out of 842 recruited between the two courses. Ninety-seven percent of the students enrolled in BIOL150 had taken BIOL140 previously. Demographics for this group are presented in Supplemental Table 1. Half of all BIO140L and BIO150L students (n = 334) were asked to complete all of the prompts in Table 1, and half were asked to complete only the first two prompts. This design was intentional so as to investigate the encountered research challenges and respective responses from all students, while also permitting data to be collected from half of the students for a separate research project (results of that investigation are beyond the scope of this study). Out of the 334 students who were asked to respond to all prompts, 226 (68%) had complete data (including complete demographic information) and reported specifically on technical research-related challenges during data collection or analysis. Because we were specifically interested in investigating students' responses to technical research-related challenges (and not to academic, logistical, or other challenges per se), the qualitative results we report represent data from just this subset of 226 students. Our quantitative data further narrowed our sample to students who reported only technical research challenges related to data collection (180 students) for reasons described in the *Qualitative Analyses* below. Overall, these students were generally in their first or second year of college (>73% across all samples), white (>62%), female (>63%), and biology majors (>63%; see Supplemental Table 1 for a complete breakdown of demographics).

Qualitative Analyses

We report first on the methods and results for the qualitative analysis of our data, which addresses RQs 1–3, and then follow with a description of the quantitative analyses and results. Our discussion and conclusions section addresses the overall findings and implications of this work.

Open Coding and Thematic Analysis. We used an exploratory phenomenological approach in our qualitative data analysis. Specifically, such an approach explores transcribed text for patterns related to specific phenomena (Sloan and Bowe, 2014). We (the coders: L.A.C., S.M., N.G., and E.W.) aimed to set aside prior knowledge of the phenomena under study—students' experiences with challenge and failure in research-based courses—and explore the phenomena while allowing interpretations to emerge. We explored codes in four broad categories: *Types of Challenges Encountered*, *Emotions*, *Coping Responses*, and *Outcomes of Challenges*. These code categories were chosen to roughly match each of the open-ended questions asked on the midsemester survey (Table 1). However, all codes were considered when coding all responses, enabling us to capture information on outcomes or emotions from students' responses to *any* question.

We used both a priori codes and inductive emergent coding to generate a codebook for the data. The categories *Types of Challenges Encountered* and *Emotions* were established entirely through inductive processes, while *Coping Responses* and *Outcomes of Challenges* were primarily derived from reviews by Skinner and colleagues (2003, Table 6) and Corwin and colleagues (2015), respectively. To establish the initial codebook, all coders independently read 30% of the data (225 randomly selected student responses) to get a sense of participants' experiences and thoughts. As these members read, they considered whether the a priori codes from the aforementioned reviews (Skinner *et al.*, 2003; Corwin *et al.*, 2015) were appropriate, and they recorded potential inductive codes for *Emotions* and *Types of Challenges Encountered*. The coders then came together to combine, discuss, and resolve definitions for codes in order to build the initial codebook (Supplemental Tables 2–5). This codebook was then presented for feedback to author J.A.H., who leads the assessment of the BIO140L/BIO150L courses and contributed to their development, as well as one instructor and two former students of the classes as a check for code validity. This check had a similar purpose to member-checking, in that it was designed to ascertain whether the codes and definitions were credible, accurate, and resonated with individuals who were actually involved with the course in question. For example, during this check, the coders confirmed the meaning of acronyms and discussed the uses of tools mentioned in student quotes. The coders confirmed which part of the research process tools like BLAST and DNA Subway affected. With this information, they were assured that their codes captured the full spectrum of what students were discussing and that they were accurately capturing the student experience. After this check, the codebook was then edited and reapplied to the 30% subset of student responses to evaluate its utility. This was repeated twice until all coders were satisfied with the initial codebook and felt that they could independently code using any of the four categories.

Coding the entirety of the data was achieved using a two-team approach. Authors L.A.C. and E.W. coded the data set for the *type of challenge* reported by students and for *outcomes of challenges*. S.M. and N.G. coded the entire data set for *emotions* and *coping responses* reported by students. In both cases, coders examined students' responses to all questions for each code category; however, it was rare to find codes pertaining to a category outside the question designed to address it (e.g., it was rare to find emotions described in prompt 4). Within each team, authors first coded students' responses independently and then met with their partners to discuss any discrepancies and determine a final code applied to each unit of meaning (i.e., a complete discrete thought). Throughout the coding process, the entire four-person group met weekly to discuss coding difficulties and clarify coding definitions. In this way, all team members became experts on the codebook, even though the codes were split among teams.

After each team coded all student responses for their respective categories, 30% of the coded quotes for each code category were randomly selected to be coded by the other team to test for interrater reliability (e.g., L.A.C. and E.W. coded 30% of the *emotion* and *coping response* code instances). The two coders in each team first coded independently and then came to consensus. Consensus codes were then compared between teams to generate interrater reliability. Because coding for different categories was independent (i.e., categories did not affect the coding in other categories), it was appropriate to calculate interrater reliability separately for each category. Cohen's kappa was 0.87 for *Types of Challenges Encountered*, 0.89 for *Emotions*, 0.85 for *Coping Responses*, 0.79 for *Outcomes of Challenges*. All discrepancies between the two coding groups were resolved with discussion.

Frequency Calculations. We quantified the total number of participants reporting each code (Supplemental Tables 1–4) for the entire data set. Because our research questions pertain only to those students experiencing technical research challenges/failures, we also calculated frequencies for *emotions*, *coping responses*, and *outcomes* within the subset of 226 students reporting that type of challenge/failure. Using theory and prior knowledge, we combined codes within categories into several "master code themes" that more broadly described the trends in the data. A student was recorded as reporting a master code when they reported any one of the codes that made up the master code. The two *emotions* master codes were *positive aggregate* and *negative aggregate* emotions; the two *coping responses* master codes were *adaptive aggregate* and *maladaptive aggregate*; and the three *outcomes of challenges* master codes were *increases in an understanding of the culture of science, increase in research skills*, and *increase in coping skills*. The subcodes that were combined to make each of these master codes are reported in the codebook (Supplemental Tables 1–4).

Qualitative Results

Here, we report the results from our open coding of *types of challenges*, *emotions*, *coping responses*, and *outcomes of challenges*. Our discussed results are limited to broader trends and specific description of codes that were reported by at least 15% of students (cutoff chosen based on a natural break point in the data).

Challenges. The codebook (Supplemental Table 5) describes reports of research challenges (technical and non-technical), social challenges, personal challenges, academic challenges, and no challenges. For the purpose of this paper, to investigate students' responses to unanticipated research challenges, we only explore one challenge category in-depth: technical research challenges—challenges associated with executing technical research tasks. Such challenges are common in research, and for the students in this study, usually led to failure in successfully interpreting their data from the first iteration of extraction, amplification, and barcoding. Sixty-five percent (n = 435) of all students surveyed reported technical research challenges.

Most observed technical research challenges were associated with data collection (80% of technical research challenge responses). For example, problems related to gel electrophoresis, DNA extraction, DNA amplification, and PCR (Supplemental Table 3) led to uninterpretable data: "The first time our group conducted gel electrophoresis, the positive control showed no amplification. So, our PCR could not be trusted" (Student [S] 3, BIO140, white, male, first-year, biology major). Students attributed these minor failures to "contamination," "low primer quality," and the DNA "not amplifying." Others had success during DNA extraction and amplification but expressed that their data were unintelligible during data analysis (21% of technical research challenge responses). These were most frequently related to BLAST hits and DNA Subway: "My DNA extraction worked and there was a successful amplification but when I did the DNA Subway it told me my sample was something that it clearly wasn't" (S16, BIO140, white, male, fourth-year, non-biology major). Students grappled with how to proceed when they encountered this issue, explaining that the results "messed up my project and [phylogenetic] trees in a big way" (S83, BIO140, white, female, first-year, biology major). Nearly all students responded with a description of only one technical challenge, either a challenge with data collection or a challenge with analysis, with only two students describing more than one technical challenge.

Emotions. Not surprisingly, negative emotions arose most frequently in response to technical research challenges (85% of respondents; Supplemental Table 2). These ranged from mild annoyance, "I felt a little annoyed" (S297, BIO140, white, male, first-year, biology major), to anger and defeat: "I felt angry as this is the third time I've done an experiment like this and it still failed. At this point, I feel somewhat defeated when it comes to completing this lab" (S157, BIO150, white, female, first-year, biology major). Most often, however, negative emotions were moderate, neither strong nor weak.

The emotion of disappointment, or feelings of sadness at a loss or inability to get results, was the most frequently expressed by those experiencing technical challenges (36%). Students often used the word "disappointed" or used colloquialisms with similar meaning: "I was bummed out that it did not work the first time but became focused on the second time" (S168, BIO150, white, male, first-year, biology major). Frustration was also quite common (30%). Frequently, an origin of the frustration was that students felt they had worked hard or "spent so much time" only to see their work fail. Occasionally, frustration came from comparisons of themselves to other classmates: "I felt frustrated when I messed up because everyone was still on track, and I was somewhat behind" (S58, BIO140, white, female, first-year, biology major). The only other single emotion to be reported by 15% of students was confusion, which included expressions of not understanding or having uncertainty surrounding what had occurred. Students became confused when they perceived that they had done things similarly to group others but obtained different results: "I was confused as to why mine didn't work like my group members" (S87, BIO140, white, female, fourth-year, biology major).

Positive emotions were reported less frequently (24% of respondents; Supplemental Table 2), though not infrequently, and ranged from relief and determination to satisfaction and enjoyment. Generally, these emotions arose after students had worked through a problem and were often mentioned in conjunction with the negative emotions described earlier: “When the challenges occurred, I was stressed, but when I was able to overcome and do it well, I felt relief and a sense of accomplishment” (S46, BIO140, white, female, first-year, non-biology major). However, less often, students experienced excitement or enjoyment despite challenges: “I was upset that it did not work because I wanted to better explore my organism, but I enjoy conducting the experiments, so I didn’t mind much” (S129, BIO140, multiethnic, female, second-year, biology major). Though they experienced many negative emotions, the majority of students subsequently responded with adaptive coping mechanisms, some of which were related to emotion management.

Coping Responses. Overall, students reported what we propose are adaptive research coping responses (69%) far more than maladaptive research coping responses (7% of students reporting technical challenges, categorizations of adaptive and maladaptive are consistent with Henry et al., 2019). As described in the *Introduction*, adaptive research coping is much more likely than maladaptive research coping to lead to mental well-being and advancement of the research agenda. Supplemental Table 3 lists all types of both adaptive and maladaptive coping for which we coded.

The most frequently reported type of coping was taking direct action to solve a problem. Direct action was generally considered adaptive, and students’ descriptions of their actions were either relatively vague, “I pressed on” or “I tried again,” or more specific, “I continued on with my DNA Subway with just my forward sequence and everything appeared to work fine” (S135, BIO140, no demographics available, 135). Such statements about direct action or action in the moment were reported by 23% of students. However, many more (52%) reported taking direct action by repeating the experiment. There were two distinct ways in which students discussed repetition. They either stated, simply, that they repeated the experiment, “I did the experiment again and it was successful” (S152, BIO140, multiethnic, female, third-year, biology major) (29%) or they reflected (23%) on what might have gone wrong and repeated the experiment while describing changes made to pursue success in the second round: “I thought through what I had done in the first DNA extraction and tried to find areas where I might have fallen short. Using that information, I did the experiment again” (S184, BIO140, white, female, fourth-year, non-biology major). While there is evidence that those who reflected learned from their first attempt because they used that information to inform subsequent iterations, we cannot deduce whether those who simply tried again without expressing reflection learned from their mistakes. In addition, instructors told students to repeat their experiment if they did not get intelligible results the first time. Thus, while we chose to include direct action and repitition with reflection in the list of codes contributing to adaptive coping, we did not include the reports of only repetition without evidence of reflection (Supplemental Table 3).

Emotional regulation, which involves taking actions to alleviate or mollify one’s emotional distress and to appropriately express emotions, was the second most frequently reported adaptive coping code (17%; Supplemental Table 3). When engaging in emotional regulation, students worked to maintain their “calm” or develop an optimistic, positive attitude while proceeding with their work: “I kept an open mind and didn’t let it bother me too much or get me off focus. So, I found it to be helpful to stay lighthearted and just try again” (S248, BIO140, Asian, male, fourth-year, biology major). Others described efforts to directly regulate negative emotions resulting from the work: “I got really frustrated when my DNA Subway was not working out like I wanted it to. I felt pretty mad, and anxious, but I was able to calm myself down and finish working on it” (S258, BIO140, white, female, first-year, biology major).

Finally, support seeking, or using available social resources to either help solve a problem or obtain emotional comfort, was frequently reported (15%). Although we coded support seeking to encompass both seeking of technical help or knowledge *and* the seeking of emotional support, the vast majority of students asked for technical help: “I sought out help from someone who had completed it correctly, the teacher or teacher’s assistant [TA]” (S95, BIO140, white, male, first-year, non-biology major). As illustrated here, help could come from a variety of sources, including their peers, TAs, or the instructor in charge.

Only 6% of students reported maladaptive coping. These codes included such coping responses as rumination or dwelling on negative outcomes and destructive thoughts: “It was difficult to interpret the data at some points of the experiment and there were so many steps that I often kept thinking to myself that I was going to mess something up” (S121, BIO140, white, female, second-year, non-biology major). Several students expressed opposition, by displaying anger, aggression, or throwing “tantrums.” A few experienced helplessness or seeing the situation as out of one’s control and thus acting as if one cannot change the situation: “I just kinda left the picture as is and said I was done with it … I got a lower grade, but it helped my stress out by giving up” (S290, BIO140, white, female, third-year non-biology major).

Outcomes. Outcomes expressed the student-reported positive results of encountering and coping with the challenge/failure. We identified the broad theme increases in coping skills based on codes that aligned with adaptive coping responses described by Skinner and colleagues (2003) and Henry and colleagues (2019). Many students experiencing technical challenges (73%; Supplemental Table 4) reported that their ability to cope with challenges had improved as a result of their experiences (Supplemental Table 4). Within this broad theme, they either discussed increased ability to navigate obstacles (59%) or increased ability to regulate their emotions in response to obstacles (28%). Among students who expressed an increased ability to navigate obstacles, statements indicating that they had learned how to persevere and persist when obstacles arise were common: “I learned that you have to be persistent and patient because not everything works out the first time, especially in biology” (S87, BIO150, Hispanic, female, first-year, biology major). Students also accepted that failure is a part of science or life in general and were determined to view failures as opportunities for learning in the future: “I learned that not everything goes as planned when doing science, and one should not treat a challenge as a failure, but as a way to learn” (S96, BIO150, white, female, first-year, biology major). Increases in ability to regulate their emotions in response to failure were commonly reported as direct statements about the ability to control emotions: "I learned that nothing good comes from being upset or dwelling on the problem and it is much more productive to focus your energy into finding a solution that works" (S9, BIO150, white, female, first-year, biology major).

A second broad theme was a greater understanding of the culture of science (23%; Supplemental Table 4). Students who made gains within this theme came to understand that science involves failure and often described the myth of a universal scientific method[3]: "I think I just reinforced my belief that research is a growing process in which it does not always happen in a straight line. Sometimes you need to go back and redo things" (S28, BIO150, white, female, fourth-year, non-biology major). They sometimes described that science involves unexpected results: "I learned that just because you don't get the results you want, does not mean your research wasn't valid and that getting no answer is an answer" (S94, BIO150, white, female, first-year, unknown major). Those who made broader statements about their understanding of science culture were also included in this theme: "I learned that science isn't perfect, and it doesn't always prove to be successful" (S116, BIO140, white, female, third-year, non-biology major).

Finally, a single code, learning to take more care and be cautious, accounted for its own broad theme and was reported by 27% of students (Supplemental Table 4). Students who reported learning to be cautious during research recognized the value of being careful and paying close attention when doing experimental procedures: "In the future, I will know that every little thing matters, and you have to be extremely careful in the lab because one little mistake can ruin the whole thing" (S169, BIO140, white, female, second-year, non-biology major). They used the words and phrases "meticulous," "precise," "careful," "not careless," and "not make mistakes" when describing this outcome.

Seventeen percent of students reported that they had experienced no outcomes as a result of challenges and failures encountered in the class. In these instances, there was rarely a reason given for experiencing no outcomes. However, in some cases, this was because they did not view these experiences as valuable: "It was not [useful] because I was not able to find out what I did wrong" (S316, BIO140, white, female, first-year, biology major). Others expressed that they felt they already knew how to deal with challenges: "I don't really think I learned this semester how to deal with failure. I was mostly able to deal with that in high school" (S245, BIO140, white, female, first-year, non-biology major).

Mixed-Model Analyses

To provide further insight into data trends and themes and address RQ4, we choose to perform mixed-model regression analysis on *emotions*, *coping responses*, and *outcomes* that arose from students' experience of technical challenges arising specifically from data collection. We specifically chose this subset of technical challenges to analyze, because students in both courses frequently experienced this type of challenge and had equivalent time and opportunities to cope, iterate, and potentially solve this type of technical challenge. We selected a subset of response codes on which to perform regression analyses. This subset was selected based on two criteria: 1) We predicted that differences in response submission across demographic variables would be interesting and meaningful. 2) A response rate of at least 15% was obtained for each response code. Specifically, we performed quantitative analyses to examine patterns related to students' reporting of the following codes and master codes:

- **Emotions:** frustration, confusion, disappointment, positive aggregate
- **Coping Responses:** repetition, repetition with reflection, emotional regulation
- **Outcomes:** increased coping skills aggregate, increased understanding of the culture of science, increased caution

Mixed-effect logistic regression using the lme4 package in R (Bates *et al.*, 2014; R Core Team, 2021) was used to analyze the effect that demographics and course participation (BIO140L or BIO150L) had on students' reporting of each of the codes. Assumptions of logistic models (i.e., linearity of the logit, lack of influential outliers, no multicollinearity) were graphically examined and confirmed. Demographic variables considered in this analysis included: course (BIO140L vs. BIO150L), gender identity (male vs. female; we had no students fall into different categories and therefore could not analyze for additional gender identities), major (biology vs. non-biology), ethnicity (white v. non-white), and year in college (first-year student vs. non–first year student). Here, ethnicity and year in college were converted to binary categories for simplicity of analysis and interpretation and to ensure a sufficient sample size in each category to perform reliable analyses. For all models, a random intercept for "section" was included to account for the potential variability that course section and instructor have on the reported response. In particular, based on prior work (Cotner *et al.*, 2011; Cavanagh *et al.*, 2018) and observed variation in BIO140/150L instructor backgrounds (e.g., graduate students, full-time faculty), it was anticipated that the instructor effect may introduce variability in how students view and deal with scientific challenges—which would be accounted for by the random intercept. Our initial analyses included all possible interaction effects among course and demographic variables. These analyses did not show any significant interactions among variables. Comparison of Akaike information criterion (AIC) values among models with and without interactions also indicated that models without interactions were of higher quality (i.e., they had lower AIC values), and so the final analyses reported here are based only on models without interaction terms included. Equation 1 represents the general form for all mixed-effect logistic regressions analyzed in this work, with curly brackets indicating the inclusion of the random effect:

$$\begin{aligned}&[\text{Emotion/CopingStrategy/Outcome}]\\&\quad= \text{Course} + \text{Ethnicity} + \text{Gender Identity} + \text{Biology Major}\\&\quad+ \text{Class Standing} + \{\text{Section}\} \qquad (1)\end{aligned}$$

Mixed-Model Results

Of the original 668 students who participated, we performed quantitative analysis for only those students who reported technical research challenges associated with data collection

[3]As described in McComas (1996).

TABLE 2. Model coefficients in odds ratios (and *p* values)[a]

	Major (biology)	Course (BIO150)	Race/ethnicity (white)	Gender identity (female)	Class standing (first-year)
Emotions					
Frustration	1.41 (0.51)	0.63 (0.21)	1.92 (0.12)	2.20 (0.07)	0.54 (0.17)
Confusion	1.49 (0.52)	**0.26 (0.02)**	1.01 (0.97)	**0.35 (0.04)**	0.68 (0.47)
Disappointment	1.34 (0.49)	1.78(0.14)	1.10 (0.78)	0.89(0.75	1.02 (0.96)
Positive Aggregate	2.34 (0.11)	0.72 (0.49)	1.56 (0.16)	0.55 (0.16)	1.17 (0.72)
Coping Mechanisms					
Repetition	1.71 (0.18)	**2.48 (0.007)**	1.12 (0.76)	1.18 (0.64)	0.98 (0.96)
Repetition with Reflection	1.54 (0.37)	1.70 (0.20)	1.18 (0.68)	0.59 (0.18)	1.65 (0.25)
Emotional Regulation	0.94 (0.91)	1.72 (0.20)	0.76 (0.52)	1.14 (0.77)	1.02 (0.97)
Outcomes					
Coping Skills	0.48 (0.15)	1.13 (0.75)	**0.35 (0.03)**	1.09 (0.84)	0.76 (0.23)
Culture of Science	0.81 (0.66)	0.81 (0.67)	0.93 (0.87)	1.59 (0.29)	1.36 (0.47)
Increased Caution	2.07 (0.11)	**0.40 (0.02)**	0.81 (0.58)	1.03 (0.93)	1.12 (0.78)

[a]Coefficients are displayed in odds ratios (*p* values are displayed in parentheses). Response variables are listed in the first column. Predictor variables are listed in the top row. Values in parentheses beside or below predictor variables indicate the direction of the reported effect when comparing groups. For example, the values in the first column of data show how being a *biology* major would affect a student's odds of reporting an emotion compared with a student who is not a biology major, all else being equal (all predictors are binary, not categorical). An odds ratio of 1 means that the two groups are equally likely to report the outcome; <1 means being a biology major makes one less likely to report the outcome, and >1 more likely to report the outcome.

and completed the entire question set, leaving 180 subjects in 37 different sections. Model coefficients (odds ratios) and corresponding *p* values are presented in Table 2. Odds ratios indicate the odds that a given group will report an outcome in comparison to the other group. For example, a value of 2 would indicate that the given group was twice as likely as the other group to report the outcome.

Emotions. Our analyses include the most frequently reported negative emotions associated with technical challenges in addition to analysis of the master code positive aggregate. We did not analyze trends for the master code negative aggregate, because almost every student reported at least one negative emotion in connection with a technical challenge, and thus the analyses would not have provided insight into trends.

The two variables related to students' reports of emotions were enrolled course and gender identity. Students in BIOL140 had a 20.5% probability of reporting confusion and those in BIOL150 had only a 7.1% probability of reporting confusion ($p = 0.02$). Male-identifying students had a 19.6% probability of reporting confusion and female-identifying students only had a 9.9% probability of reporting confusion ($p = 0.04$). However, the observed trend with regard to gender identity was different for frustration; female-identifying students had a 32.2% probability of reporting frustration, whereas male students only had a 17.6% probability of reporting frustration ($p = 0.07$). However, this did not make our 0.05 cutoff for significance. Neither disappointment nor positive emotions could be predicted based on course or demographic variables (all $p > 0.11$).

Coping Responses. Our analyses include the three most frequently reported coping responses: repetition, repetition with reflection, and emotional regulation. Course had an effect on the probability of repetition, but no other significant effects were observed. Specifically, students in BIOL150 had a 65.7% probability of repeating their experiments when encountering a technical data-collection challenge, whereas students in BIO140 only had a 41.1% probability of reporting that they had repeated their experiments.

Outcomes. Our analyses of outcomes include mainly analyses of main codes that are aggregates of codes for more specific outcomes. We analyzed increases in coping skills, increases in understanding of the culture of science, and the single code, which was highly reported by many students, increased caution when doing science. Non-white students had a higher probability of reporting increases in coping skills compared with white students (85.7 vs. 69.4% respectively, $p = 0.03$). Students in BIO140 were much more likely to report increases in the caution with which they conducted experiments compared with those in BIO150 (43.8% vs. 24.2%, p = 0.02).

DISCUSSION

When Asked to Report on Research-Related Challenges, a Majority of Students Reported on Technical Challenges. As DNA manipulations are technical and invisible to the naked eye, novice researchers will often experience common failures in molecular techniques such as the extraction and amplification of DNA from samples. Thus, CUREs that authentically expose students to work with DNA are highly likely to afford in situ opportunities to introduce technical challenges and the navigation of failure (e.g., Gin *et al.*, 2018; Hyman *et al.*, 2019). Here, we specifically hoped to study the types of unplanned technical challenges encountered by introductory students in two DNA barcoding CUREs as well as their respective perceptions of and responses to the challenges. Thus, we used targeted, intentional prompt language and timing that would allow us to do so. Given this, it is not surprising that a high proportion of technical challenges were reported, but it is nonetheless important, because it indicates that these experiences were salient enough to warrant inclusion and exploration within student reflections.

It is also likely that students' standing as early-career researchers—likely the first time for many—influenced their responses. This is in line with work on apprenticeship-like UREs that describes a developmental trajectory in which students first master basic skills (e.g., data collection and analysis) before progressing on to higher-order skills, such as data interpretation (Feldman *et al.*, 2009; Thiry *et al.*, 2012; Adedokun *et al.*, 2014). This finding, which reflects data across multiple courses and course sections, further supports that molecular and genomics-based investigations can be a useful way to incorporate predictable technical challenges and failures into CUREs, which is notable, considering how many CUREs make use of similar techniques (e.g., Hanauer *et al.*, 2017; Gin *et al.*, 2018; Greenman *et al.*, 2021; Lopatto *et al.*, 2020; Zelaya *et al.*, 2020). We can use this information to think more deeply about what *type* of challenges and failures we should anticipate—or intentionally plan for—when considering how to help novice students navigate scientific obstacles and when designing courses for this outcome.

Almost All Students Experienced Negative Emotions when Encountering Technical Research Challenges, yet They Engaged in Adaptive Coping

The students in our study frequently reported disappointment and frustration as well as confusion to a lesser degree when experiencing technical research challenges and failures. All in all, while 85% of students reported negative emotions, which is typical of post-failure emotions in academic achievement contexts (Pekrun, 2006), most reported the use of at least one adaptive coping mechanism. Furthermore, when students reported positive emotions, they usually referenced them after overcoming negative emotions and re-engaging with a challenge. Pekrun's (2006) work states that, if a student perceives that they have control over the future, they are more likely to experience positive emotions and overcome negative ones in response to failure. Our results support this, as we found evidence that providing the opportunity for iteration, which supports students' autonomy (Gin *et al.*, 2018; Goodwin *et al.*, 2021), allowed students to overcome failure and alleviate their negative emotions. These findings imply that negative emotions are *not* always a barrier to student success or detrimental to student well-being *if* students are allowed time to productively cope.

Building upon this, it can be argued that we should move beyond the idea of negative emotions as something to "overcome." Frustration, confusion, and disappointment are described by some researchers as emotions "inherent to" and "characteristic of" doing science; they are part of scientific "epistemic affect" (Jaber and Hammer, 2016). In the process of scientific discovery, these negative emotions can arise from or give rise to more positive emotions. For example, the pleasure of discovering something new can be enhanced by prior feelings of confusion and the struggle to solve a difficult question (i.e., frustration; Jaber and Hammer, 2016), and these emotions become more intense when the work is valued (Pekrun, 2006). Thus, far from being a detriment, experiences of frustration, disappointment, and confusion and subsequent opportunities to iterate in order to alleviate these emotions may actually be beneficial for many undergraduate researchers. These feelings may have the potential to increase students' sense of scientific identity and their sense of the authenticity of their work (Jaber and Hammer, 2016; Goodwin *et al.*, 2021).

Taken together, these points suggest that we should not limit students' exposure to research-related challenges and failures. Yet, as instructors, we are far more likely to target positive affect as an experiential outcome during classroom activities (Pekrun, 2006; Rowland *et al.*, 2019). This is not surprising, given that positive affect contributes to many constructs (e.g., interest and emotional project ownership) that predict persistence in STEM (Hanauer and Dolan, 2014; Rowland *et al.*, 2019; Knekta *et al.*, 2020). However, our results, in addition to other recent work (Gin *et al.*, 2018; Goodwin *et al.*, 2021), highlight the role of technical research failures that require CURE participants to navigate *negative* emotions in the development of coping skills. Thus, as educators, allowing students to experience these negative emotions and to overcome them could be seen as an important step in helping them develop resilience as scientists (Gin *et al.*, 2018; Henry *et al.*, 2019). Importantly, however, we must consider closely *how* we structure and scaffold challenge and failure experiences so that they *do* benefit students. In this work, differences exist in the types of negative emotions reported by students who identify with different genders (male-identifying students were more likely to report confusion, female-identifying, frustration). As this finding highlights how the emotional experience may differ across groups, strategies that support students in coping with emotions arising during research-based challenges may need to consider gender identity. Also, recent exploratory work has highlighted that some undergraduates, particularly those who suffer from depression, emotional stress, and/or other mental health ailments, may experience negative outcomes from research-based failures in UREs at research-intensive institutions (Cooper *et al.*, 2020a). This research suggests that specific instructional actions, such as providing undergraduates praise, working to develop positive relationships with students, and normalizing failure may alleviate students' depressive feelings (Cooper *et al.*, 2020a). Considering that CUREs are recognized as a more inclusive model than UREs and may reduce the social barriers that exist between students and faculty (Bangera and Brownell, 2014; Elgin *et al.*, 2016), it would be interesting to investigate whether similar patterns exist in research courses. These findings, and careful attention to scaffolding around failure experiences as, should be carefully considered when exposing students to research-based challenges in which they may encounter failures.

Almost All Students Report Coping Responses Associated with Problem Solving

Students in this study largely coped with challenges by taking direct action, repeating the experiment while reflecting on one's results, regulating emotions, and seeking instrumental support. Such coping responses are predicted to be adaptive in academic STEM contexts based on prior literature (Struthers *et al.*, 2000; Brdar *et al.*, 2006; Alimoglu *et al.*, 2010; Sevinc and Gizir, 2014; Henry *et al.*, 2019). They typically support students' well-being as well as their progress on a project or degree program (e.g., Struthers *et al.*, 2000) and persistence in a field of study or career track (e.g., Shin *et al.*, 2014). A majority of the reported coping responses fall under the broader coping umbrella of "problem solving," in which an individual actively tries to solve the problem causing the stressor (Skinner *et al.*, 2003).

We hypothesize that problem solving was frequently reported because the course design allowed time and course materials for iteration, without which students would not have been able to engage in much of the problem solving reported. In alignment with prior research by Gin and colleagues (2018) and Hunter, Laursen, and Thiry, and colleagues (Hunter *et al.*, 2007; Laursen *et al.*, 2010; Thiry *et al.*, 2012), allowing students time to grapple with failure and uncertainty likely also afforded students opportunities to develop coping responses beyond problem solving, including emotional regulation, support seeking, planning, instrumental action, collaboration, and cognitive restructuring (Skinner *et al.*, 2003). Students often described these coping mechanisms as necessary to support problem solving (e.g., a student who engaged in emotional regulation expressed the need to "calm myself down and finish working on it"). These results align with Pekrun's control-value theory of achievement emotions (Pekrun, 2006), which describes how emotional experiences and regulation are directly linked to problem-solving actions when students encounter challenges.

These results expand prior work in this area by highlighting that students in large CUREs, consisting of multiple sections with multiple instructors, engage in adaptive problem solving when encountering technical research challenges. Prior work has not examined this question at this scale or with the intention to look at coping responses specifically. This work also further highlights the importance of offering opportunities to iterate, which may vary widely among CURE courses (Auchincloss *et al.*, 2014; Corwin *et al.*, 2018). It would be interesting for future work to examine CUREs which do and do *not* afford students the opportunity to iterate in order to compare students' coping behaviors.

We anticipate that the findings presented here—that a majority of students did engage in adaptive coping—are likely to be true (i.e., we anticipate that students' perceptions of what they did are reasonably accurate with respect to adaptive coping). However, we recognize that students might underreport maladaptive coping mechanisms. As explained in our *Limitations*, this may be because it is not socially desirable to report on one's own "bad" behaviors (Krumpal, 2013) or simply because we tend to remember our positive and productive actions better than our unproductive negative ones (Walker *et al.*, 2003). Thus, although it is likely that most students used adaptive coping, we cannot say that they did *not* also engage in maladaptive coping based on our results. A future study that engaged in behavioral observations and "in the moment" assessments (e.g., using ecological momentary assessment as in Shiffman *et al.*, 2008) might be more appropriate to uncover instances of maladaptive coping.

Students Report Gains in Coping Skills, Understanding the Culture of Science, and Learning to Take More Care and Caution during Research

We specifically asked students to report on the gains, if any, they perceived as a result of challenges and failures encountered during their lab class. The three central themes described—coping, culture of science, and care and caution—align with prior work by Gin and colleagues (2018) and Goodwin and colleagues (2021). Both of these former studies, in addition to ours, support the idea that students develop a more complete and comprehensive understanding of the culture of science via the practice of coping with challenges and failures. Thus, our findings lend further support to prior work seeking to understand the basis of research "authenticity" and what elements of a research-based course help students to perceive the work as "authentic" (Rowland *et al.*, 2016; Goodwin *et al.*, 2021).

One pattern related to students' racial/ethnic identities emerged from reported outcomes. Non-white students, consisting mainly of Black, Hispanic, and Asian students, were more likely to report gains in coping skills than their white peers. While prior work has found differences in coping behaviors across racial identities (e.g., Davis-Bowman, 2021), past studies are not particularly helpful in interpreting our results. More detailed work, ideally incorporating qualitative data wherein students might describe the rationale for their responses, would help us to understand whether these results arose due to non-white students valuing coping skills to a greater degree, experiencing greater improvements in coping skills, or some other explanation. Further disaggregation by race would be necessary to understand this result with nuance.

Differences Exist with Respect to What Students in the Two Sequential Courses Emphasize with Regard to Emotions, Coping Responses, and Outcomes

As compared with students in BIO140L, students in BIO150L are less likely to report confusion in response to technical research challenges associated with data collection and are more likely to report repeating an experiment (i.e., they report readily engaging in iteration). Students in BIO150L are also less likely to emphasize learning to be cautious when reflecting on engaging in DNA barcoding methodology than students enrolled in BIO140. We interpret these results from our statistical analyses with caution, given that they are drawn from qualitative data, and thus we cannot say for certain that students did *not* feel other emotions or use other coping mechanisms in addition to those reported. However, we can use these as a starting point from which to posit potential explanations.

Nearly all students who enroll in BIO150 have taken BIO140 previously (~97% of the BIO150 students in this study took BIO140 as the prerequisite) and therefore have the benefit of being previously trained in the techniques of DNA barcoding and having experience troubleshooting. Similar to prior work on how participants experience different outcomes over different stages of a URE (Sadler *et al.*, 2010; Adedokun *et al.*, 2014), our results point to a potential shift in what students perceive as the most salient outcomes of research as they develop expertise and have the time to grasp the nature of scientific research. We posit that the lower levels of confusion reported in BIO150L could result from a greater understanding of the data-collection processes and therefore less confusion as to why collection methods did not work. Similarly lower reports of learning to be cautious from students in BIO150L may reflect that this outcome was not as salient to students in this course, because they already may have developed the ability to be cautious during DNA barcoding processes in a previous semester. In addition, our results may describe the emotional results that parallel students' development of expertise. Namely, that more expert students experience less confusion as a result of challenges.

Finally, we are unsure why students in BIO150L reported that they repeated their experiments in response to challenges more than students in BIO140L. Both courses had equal opportunities to iterate, and the challenges examined in our statistical analysis were the same across courses (we only examined technical challenges related to data collection). There is no apparent explanation related to course design or experimental methodology that can explain these results. One possible explanation is that, as students develop expertise as researchers, they also adopt the research culture of iteration (Elliott, 2012) and thus more readily report on and engage in repetition. However, this is only speculation and would require a more in-depth qualitative investigation to elucidate.

It is largely an open question how multi-term research-based course experiences impact students. Recent work suggests that engaging in a second term of CURE participation supports continued development of students' self-efficacy, but not in all areas (Martin *et al.*, 2021). Our results provide preliminary evidence demonstrating potential shifts in how students describe their emotions and behaviors in response to common technical challenges in two sequential CUREs. While these data are self-reports and represent a single temporal snapshot instead of a longitudinal perspective, they indicate that students' emotions may shift away from confusion, and they may be more likely to respond with iterations aimed at solving the issue at hand. Both of these may be positive outcomes of longer-term participation in research. More targeted work in this area will be needed to definitively investigate whether participation in multiple sequential CUREs is beneficial and is the cause of the outcomes we observe here. Longitudinal mixed-method investigations of multi-term CUREs or research-focused programs (e.g., Hanauer *et al.*, 2017; Martin *et al.*, 2021) would be suited to investigate how outcomes of CUREs change for students over time.

Limitations

First, these data are the result of students opting-in to participate in the research and are students' own reports of their coping mechanisms. Because 80% of all students who were asked to participate in this study chose to participate, and those students represent a population that is demographically similar to the class overall, we are less concerned about biases arising due to students choosing to participate. With regard to self-reported data, student perceptions of their own coping mechanisms (i.e., their self-reports) may not be entirely accurate or present a complete picture of students' behaviors. Students might underreport maladaptive coping mechanisms, because it is not socially desirable to report on one's own "bad" behaviors (Krumpal, 2013) or simply because we tend to remember our positive and productive actions better than our unproductive negative ones (Walker *et al.*, 2003). Thus, we avoid making inferences that maladaptive behaviors did not occur simply because they were not stated. Nonetheless, these reports yield important information, as they provide access as to how students view their own coping practices. These perceptions are important, because they inform us about students' coping self-efficacy (Saklofske *et al.*, 2012; Watson and Watson, 2016) and, given students' self-awareness of these behaviors, they may serve as tractable targets for change. We frame our discussion with the recognition that these are students' perceptions of their coping.

Second, and related to the previously made points, a common limitation of this type of qualitative work is that the results are predicated on subjects' ability and willingness to communicate information in response to a writing prompt. While the written prompts provide rich insight as to how introductory students perceive that they deal with research-related challenges, our findings may have been influenced by how descriptive participants were in their responses and their ability to provide descriptions in the time allotted in class. As this was anticipated, students were encouraged "take their time" in the activity with reference to the documented benefits of such reflective practices (Papadimos, 2009; Tanner, 2012), though it is likely that this extrinsic motivator alone may not have compelled all participants to be complete and thoughtful in their writing. Thus, as intended, future work will use mixed methods (both qualitative and quantitative measures; i.e., surveys) to ascertain whether the trends we observe here are repeatable and, if possible, to infer cause.

Third, the findings reported here are based on data representing students in one set of introductory laboratory courses at a single comprehensive institution, which may limit study generalizability. As described earlier, the BIO140/150L research courses have a relatively unique design (i.e., scale, length, common-themed research practices that expose the majority of participants to scientific challenges, and sequential nature)—and we therefore recommend caution translating the findings across all CURE contexts. With that said, our results are consistent with a prior exploratory qualitative study conducted by one of our authors (L.A.C.) with principally second- and third-year biology students engaged in a CURE at a large public research institution (Gin *et al.*, 2018). Beyond context, while participation in the CURE studied is required for biology and other majors (e.g., health sciences), which has been identified as an inclusive means to engage members of underserved groups in research (Bangera and Brownell, 2014), the sample—comparable to institutional demography—is largely composed of traditional-aged, white students. This limits the implications of our work for persons excluded due to ethnicity or race (PEER) students and for other underserved groups, such as first-generation students. To expand on this work, future research should deliberately sample a variety of CUREs that enroll more diverse students of different academic maturities in order to better understand how all students navigate challenges in these research experiences.

An additional contextual limitation is that the collected data represent a single temporal snapshot of students in two sequential courses (i.e., data were collected in only one semester with students who took either BIO140 or 150), which constrains the inferences that can be drawn with regard to how completing both courses sequentially would affect students' ability to navigate obstacles in the research setting. While former students regularly self-identify the ability to deal with scientific challenges and failures as being one of the most valuable participatory outcomes of participating in both classes (Harsh *et al.*, 2018), future longitudinal studies are needed to observe transfer between challenge episodes and contexts to better understand the learning of research-related coping responses and the development of coping self-efficacy.

Fourth, although the current findings lend unique insight as to how students navigate technical challenges and failures in the research, we do not have information on many other factors that could affect resilience in the research setting. For example, we did not investigate students' experiences dealing with challenges and failures in other contexts (e.g., personal issues, earlier course work) or the influence of social interactions within the classroom space (e.g., Hojat *et al.*, 2003; Hurst *et al.*, 2013; Cavanagh *et al.*, 2018), or the influence of mental health status on coping (e.g., Cooper *et al.*, 2020). Additional work will be needed to elucidate these relationships.

CONCLUSION

> The greatest teacher, failure is.—Yoda (*The Last Jedi*, George Lucas)

In response to national calls for engaging *all* students in UR given the documented benefits, CUREs have become an increasingly popular means to broadly provide participants a window to authentic scientific practices. With this opportunity to "do" real research also comes the potential for students to encounter scientific challenges and failure—the first exposure for many students. Yet, while one's ability to cope with failure is both a hallmark of a scientific disposition and predictor of STEM persistence (e.g., Simpson and Maltese, 2017; Henry *et al.*, 2019), few studies have explored how students learn to navigate obstacles in the research setting.

A major contribution of this study is that it provides one of the first accounts directly addressing students' perceived responses to challenges and failures in research-based courses. Collectively, our analyses of the two semesters of DNA barcoding CUREs indicate that: 1) Students encounter a variety of research challenges; 2) students regularly experience negative emotions when facing research challenges; 3) students typically report using coping responses predicted to be adaptive in STEM contexts; 4) students' ability to cope with scientific obstacles can likely be instructionally scaffolded; and 5) students report developing a deeper understanding of the culture of science and an appreciation for caution via the practice of coping with authentic challenges and failures. As well, the in-depth qualitative approach used in this study produced a literature-based coding framework characterizing CURE students' challenges faced, emotions, coping mechanisms, and outcomes that may be of interest to researchers (see Supplemental Tables 1–4).

This work also provides additional empirical support for the incorporation of moderately challenging tasks, in which students are likely to experience both challenge and failure, into research-based courses *with intentional time included for iteration and structured instructional support*. Like other studies emphasizing the value of challenge, struggle, and failure in UR (Hunter *et al.*, 2007; Laursen *et al.*, 2010; Thiry *et al.*, 2012; Harsh *et al.*, 2011; Gin *et al.*, 2018; Lopatto *et al.*, 2020; Goodwin *et al.*, 2021), this study demonstrates that these experiences do, indeed, add to the potential for student learning and development during research experiences. However, this work goes beyond former work by characterizing how the incorporation of time for iteration ultimately influences student responses to challenge and their perceived outcomes. We find that structured, instructor-supported opportunities for iteration are essential in allowing students the time to enact adaptive coping processes that enable research progress. Given these results, instructors of CUREs may be able to improve adaptive coping outcomes by 1) actively planning activities that expose students to appropriate levels of challenge (and failure); 2) including planned time for students to iterate within course schedules; and 3) enacting specific scaffolding and pedagogical approaches that support adaptive coping across gender, ethnic, and racial identities. These are not small or easy tasks for instructors. In implementing these instructional changes and innovations, we expect that some failures may occur, and iteration will be necessary! However, we urge instructors to embrace this challenge. Together, through trial, failure, and iteration, we can gradually improve research-based educational experiences. A first step may simply be asking our students, "If you had to do it again, what would you change?"

ACKNOWLEDGMENTS

We are grateful to our student participants and the instructors of the BIO140L/BIO15L courses in the Biology Department at James Madison University. We especially thank Oliver Hyman, Elizabeth Doyle, and Andrea Pesce for their ongoing support, constructive feedback, and substantial contributions to the data collection for this project. We acknowledge Julia Cumins and Sarah Coleman as well as the other members of the JMU Biology Education Research Group for their valuable insight at various project stages. We thank members of the Research in Education for Action and CHange (REACH) Lab group at CU Boulder for their constructive feedback on the article. We are grateful to members of the Factors Affecting Learning, Attitudes, and Mindsets in Education Network (FLAMEnet, RCN UBE Incubator no. 1827160, RCN UBE no. 1919953) for their support and discussions that helped to guide this work.

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