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Investigating introductory astronomy students' perceived impacts from participation in course-based undergraduate research experiences

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[This paper is part of the Focused Collection on Astronomy Education Research.] This study investigates students' perceived impacts regarding their participation in course-based undergraduate research experiences (CUREs) in astronomy. Each research experience adopted one or more projects from the Research Based Science Education for Undergraduates (RBSEU) curriculum, which teaches analysis of astronomical data coming from various national observatories. Participating students were enrolled in introductory astronomy courses at one of four universities using the curriculum. They were invited to respond to several instruments, including surveys ($N = 199$), essays ($N = 94$), and interviews ($N = 19$). Each university implemented the curriculum differently with respect to content covered, length of instruction, and whether students' research results were contributed to the astronomical community. We found that participation in all versions of the curriculum had the potential to significantly increase students' perceived confidence participating in science. However, participation in experiences wherein results were contributed to the scientific community more often led to students' nuanced perceptions of science processes, including increased understanding of the role of analysis and the utility of scientific communities and collaborations. We frame our study according to a pathway model under study by discipline-based education researchers of CUREs and explore our findings' connections with psychological theories.

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I. INTRODUCTION

Promoting research experiences among all undergraduate students, both inside and outside the classroom, has been deemed important by the National Academies [1], the American Association for the Advancement of Science [2], and researchers of science teaching and learning [3–8]. Participation in scientific research experiences encourages cognitions related to scientific epistemology, such as uncertainty and global consistency, rather than the certainty and local consistency practiced in "simple" textbook experiments [9,10]. Such cognitions are important in learning how scientific knowledge is ascertained. Further, for those students who later teach science, participation in research may also lead to a greater likelihood of using methods of inquiry in their teaching [11], which has been shown to increase students' engagement in learning science [12]. Additionally, when students participate in research contexts, they encounter the technologies used by scientists, enabling a sense of these technologies' contextual embeddedness, limitations, and means toward increasing efficiency in scientists' work [13]. Despite these findings, there have been an underwhelming number of studies devoted to studying the effects of participation in astronomy research experiences in contexts other than those of undergraduate research experiences (UREs) [14,15].

The call for a greater number of research experiences in secondary and post-secondary science instruction has been engaged across the scientific disciplines, including biology [9–11], chemistry [12,13], environmental science [16,17], geoscience [18,19], and physics [20–22]. In this paper, we introduce and study course-based undergraduate research experiences for both science majors and nonmajors enrolled in introductory astronomy courses. Introductory astronomy courses generally serve as a general education requisite and survey the broad enterprise of the field of astronomy, including but not exclusively the historical development of astronomy, observational techniques, stellar and planetary system evolution, galaxy formation, and cosmology.

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In the remainder of this Sec. I, we begin by surveying the language and concepts used by scholars studying educational scientific research experiences in order to position our own study among them.

A. Nomenclature related to undergraduate research experiences

The myriad of approaches to infusing instruction with research experiences has been expressed by a wide variety of nomenclatures. For example, some studies denote research experiences as "authentic" if they imitate scientific research practices [23,24], contexts [25,26], activities [27,28], skepticism [29], or collaborations with scientists (such as internships or independent study, i.e., UREs) [14,15]. Others deem authentic research experiences to be necessarily open ended or seeking answers to questions that are currently unknown [9,12]. Still others suggest that authenticity is an emergent property of the productive interactions between students, teachers, and scientists, something that may only be aspired toward because of the inherent continuous change of science practice and understanding [30,31]. Strikingly, surveys attempting to identify scientists' impressions of authentic scientific inquiry, as a means to grasp the experience of science "from the horse's mouth," revealed responses similar to those presented in school science textbooks [32] and disagreements as to whether authentic science is more closely related to asking novel questions or participating in science process [5].

The research experiences at the core of the RBSEU curriculum correspond with only a subset of the multiple meanings of authenticity, as adapted within the research on science teaching and learning. We therefore turn our attention toward the biology education research community, which in recent years has contributed substantial effort toward the definition of course-based undergraduate research experiences (CUREs) and meta-analysis of their outcomes. CUREs have been defined as those course-based research experiences that include all of the following [33]:

1. Multiple *scientific practices* are enacted that are student or instructor driven.
2. *Discovery*, or the process by which new knowledge or insights are obtained, is driven through student-instructor interactions. The outcomes of the process are unknown and the findings are novel.
3. The *broader relevance* or importance extends beyond the course, and students' work often presents opportunities for action beyond the classroom (e.g., publication, or impacting the local community).
4. *Collaboration* occurs among students, teaching assistants, and instructors in the course, where the instructor acts as guide and mentor.
5. *Iteration* is built into the process, and there is an inherent risk of generating "messy" data.

These characteristics are relevant to each of the scientific disciplines, and so we comfortably adopt the acronym CURE to characterize several of the RBSEU experiences. Some of our universities and courses used an adaptation of the RBSEU curriculum that did not involve *discovery* or *broader relevance*. We invented and invoke the acronym QCURE (for "Quasi" CURE) to refer to these, since they did not meet all of the CURE criteria but went beyond the traditional laboratory experience by requiring *scientific practice, collaboration*, and *iteration*.

B. The benefits and challenges of CUREs and QCUREs

The benefits of students' participation in CUREs and QCUREs include learning from mistakes [34], increasing confidence and competence at science process, [10,34,35], improving science writing [11], improving understanding of content knowledge [17,22,36], increasing interest in scientific careers [11,12], and improving critical thinking skills [35]. Further, positive affectual responses have also been found, such as enjoyment in project participation [37] and the cooperative, collaborative nature of the projects [12,17,37].

Despite multiple positive impacts of QCUREs and CUREs, changes in students' content knowledge, skills, and interest in science have not been significant in some courses [11,36]. Possible contributing factors include teacher effects [34,36], perceived repetition of prior participants' results [17], tediousness of scientific practice [13], and students' differing abilities (i.e., majors vs nonmajors, performance level, and major type) [17,36]. Further, some difficulties expressed by faculty in introducing CUREs include institutional constraints, such as fitting the experience into the wider curriculum, finding teaching assistant and technology support, facing resistance to innovative instructional methods [38], as well as increased expense and lack of student motivation [34].

Still, these projects are often easy to package and disseminate to other faculty, mitigating the faculty time needed to develop similar materials, especially when there is a "shared core support system" [38]. In response to these findings, the biology education research community hosts the website CUREnet [39], where numerous biology curricula are available, with possible expansion to other scientific disciplines on the horizon [40].

C. The RBSEU curriculum

The RBSEU curriculum [41] features five different astronomical research projects: (i) reducing uncertainties in observable asteroids' orbits, (ii) searching wide-field high-resolution images of the Andromeda Galaxy for novae, (iii) analyzing spectra of variable stars, (iv) determining the properties of active galactic nuclei from optical spectra, and (v) using photometry to identify and determine redshifts of very distant galaxies. Data come from the WIYN 0.9 m telescope [42], Skynet Robotic Telescope Network [43], the NOAO Deep Wide Field Survey [44], the Sloan Digital Sky Survey (SDSS) [45], and the VLA's FIRST survey [46]. The RBSEU curriculum models the processes of scientific inquiry and exploration used by scientists to discover new knowledge. In each research-based project, students first participate in tutorials to learn techniques for analyzing data relevant to their project. Next, they are given a research question and asked to work in small groups to apply their data analysis skills to work toward an answer. The curriculum is and will continue to be freely available to any university interested in adopting one or more of these projects [47].

D. Authors' roles

T. R. and A. P., experts in the disciplinary content knowledge grounding these projects, were the primary authors of the curriculum. They iteratively modified the curriculum during the decade prior to this study, based on their observation of students' ability to understand and engage with the material via their own instruction. M. W. and K. C. primarily designed and completed the research protocol and analysis. They have training in disciplinary content knowledge as well as educational research practice and were also instructors of the curriculum.

E. Our research questions

This study is one of the first to examine the impact of participation in CUREs and QCUREs in astronomy. The instructional mode encountered in these courses differs from other research experiences available to introductory astronomy students. In Project CLEA [48], the University of Washington's Introductory Astronomy Clearinghouse labs [49], and the ESA/ESO Astronomy Exercise Series [50], students do not face the potential of having their results published; and in Zooniverse [51] and The Planetary Society's Citizen Science projects [52], participants encounter real scientific data but do not engage in extended analysis of the objects that they measure. Further, this is one of the first studies among the various scientific disciplines to compare effects of QCUREs and CUREs at the undergraduate introductory science level.

In order to assess the perceived impact of participation in the RBSEU curriculum, several research questions guided our study:

1. How do introductory astronomy students characterize their previous science learning experiences?
2. When students are asked about how RBSEU instruction compared to previous science instruction, what characterizations and affective themes emerge?
3. How do students' perceptions of their confidence in doing science process tasks change from before to after instruction?

In Sec. II, we describe the circumstances of adoption of RBSEU projects at each university and in each course, and we provide information about the participants in each of these adoptions. Thereafter, we describe our method of addressing the research questions and interpret the results.

II. CURRICULUM ADOPTION AND PARTICIPANTS

The development of the RBSEU curriculum along with tests of its effectiveness have been the workings of seven partner institutions since 2003. In this study, we focus on four institutions that participated from Fall 2012 through Spring 2013: (1) a medium-sized comprehensive university, (2) a minority serving university, (3) a community college, and (4) a private liberal arts college. The RBSEU curriculum was adapted and administered according to the four participating universities' introductory astronomy instructors' interests, particularly with respect to choice of project(s), time invested (short or long), and whether or not the results of students' research had the potential to contribute to the scientific literature (CURE or QCURE).

At Universities 2 and 3, and in some of the laboratories at University 1, the projects took place over two to four three-hour laboratories. We call these "short" projects. At University 4 and in the remaining University 1 laboratories, the research-based curriculum was taught over the entire semester; which we therefore refer to as "long" projects. In all cases, students also received instruction in introductory astronomy content from non-RBSEU sources during the same semester in which the research experience occurred. Such instruction was either "concurrent," i.e., delivered in a lecture course that was co-requisite with the lab course, or "integrated" into the same course as the RBSEU project instruction.

Depending on how each university adapted one or more of the five possible research projects, engagement with the RBSEU curriculum constituted either a CURE or a QCURE. For example, in both the CURE and QCURE adaptations of the asteroids project, students learned the process of reducing uncertainties in an asteroids' orbits using technologies used by scientists, but only in CURE adaptations did students apply this practice to an asteroid that they had imaged themselves. Students in both the CURE and QCURE versions of the asteroids project analyzed images that contained scientific data and used other classmates as resources for trouble shooting and comparing findings, thus engaging in *scientific practice, collaboration*, and *iteration*. Only in the CURE version did students practice *discovery* via prediction, imaging, identification, and measurement of an asteroid's position, and *broader relevance*, in contributing the asteroid's measured locations to the scientific community.

III. METHODS

A. Framework and assumptions

Studies of CUREs became pronounced within discipline-based education research beginning in 2013, especially among biology education researchers who coined the acronym [47,53]. While we were unaware of the research being done by these disciplinarians at the time of our own study during 2012–13, we find it advantageous to posit our study's method and findings in relationship to efforts made by these CURE researchers. Specifically, because CUREs are not inherently discipline specific in their instructional approach, recent efforts among some CURE researchers to develop a framework for studying CUREs renders our study's findings as relevant and informative to a research community beyond physics and astronomy education researchers alone. We enter the cross-disciplinary conversation by introducing a pathway model developed by these CURE researchers to enable discussion of CURE outcomes and research directions in recent years [7,33].

Pathway models are created out of collaboration between invested instructors and researchers to stimulate conversation regarding potential pathways to enable students' achievement of long-term outcomes. They appear as schematic flows, starting with activities instantiating

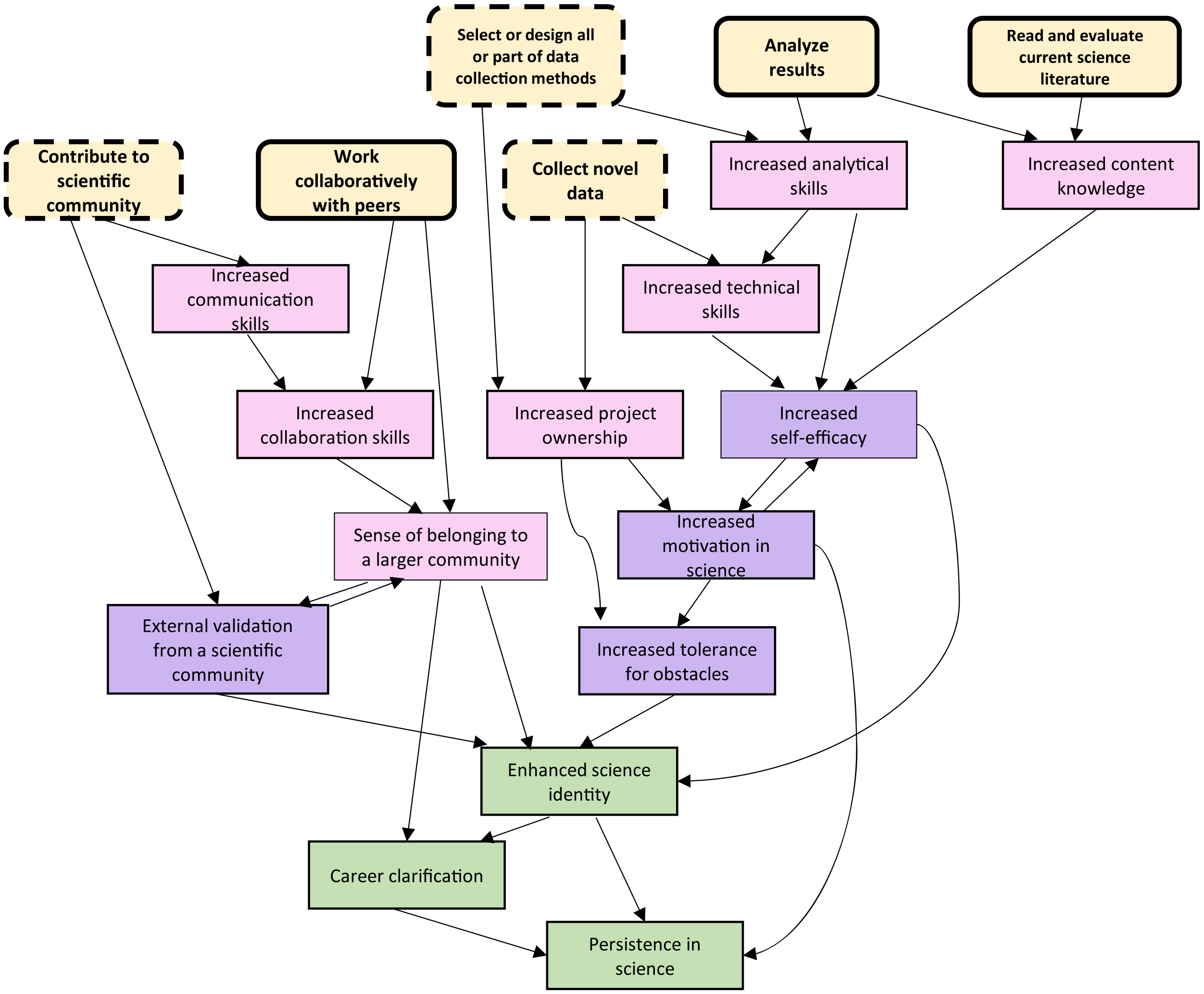

FIG. 1. Modified version of CURE pathway model posited in Corwin *et al.* [7]. Activities students participate in are represented by yellow, curved rectangles. Short-term, medium-term, and long-term outcomes under study are represented with pink, purple, and green boxes, respectively. Arrows represent relationships between activities and outcomes, and feedback loops between two outcomes are shown by arrows pointing in both directions between outcomes. In RBSEU CUREs, students participated in all of the activities. In RBSEU QCUREs, students participated in only those activities with a continuous outline, not those with a dashed outline. Previous research on CUREs has suggested that outcomes represented in this figure are either probable (including increased self-efficacy), meaning multiple studies support the expectation of this outcome, or possible (including increased motivation in science, and sense of belonging to a larger community), meaning only a few studies currently support expectation of this outcome [7,53].

potential pathways, and followed by increasing temporally displaced and hypothesized outcomes [33,54]. Pathway models are unique in their representation of feedback loops and convergent long-term outcomes as possibly made by combinations of short and medium-term outcomes [7]. We hope that in our reference to a previously posited CURE pathway model, shared language may be enabled between disciplinarians (biologists, chemists, geologists, physicists, astronomers, etc.) who approach CURE research with otherwise differing language and normative practices. Further, referring to this model may—as the authors who posited the model suggest—stimulate discussion of "how" CUREs work, not merely "what" they do [7].

Figure 1 portrays a simplified version of a larger CURE model [7,33] that pertains to the activities that students complete in the classroom (in yellow) as well as their probable and possible outcomes (short term in pink, medium term in purple, long term in green). In the figure, we have specified the differences between CUREs and QCUREs through the box outlines: RBSEU CURE students participated in all of the activities designated, while RBSEU QCURE students participated only in the activities outlined in a solid, bold line. The activity box reading "Contribute to scientific community" was changed from its original descriptor "Present work outside of class" because RBSEU CURE students presented their work to their classmates, not outside of class; RBSEU administrators disseminated students' novel contributions to the scientific community. We think of these two phrases as being interchangeable in their effect at the introductory level of instruction.

To examine the perceived impacts of the RBSEU curriculum among participating students, we began by searching for and developing assessments that were relevant to practices undertaken by students within the curriculum, in particular, scientific practice and process. We also adopted assumptions that were objectivist in nature to guide our methodological approach [55]. That is, we assumed that a reality about the impact of the RBSEU curriculum could be ascertained by studying students' responses to our assessments, and that we would have better certainty of this reality by using multiple methods (quantitative and qualitative). We assumed not only that each type of analysis would produce comparable results, but that similarities in students' responses on two or more assessments would provide stronger evidence for the curriculum's impacts. Such assumptions reflect the methodological concept of triangulation [56,57], in which data from multiple methods are compared to ascertain accuracy regarding various truth claims.

We used three types of assessments: interviews, essays, and an online survey (Science Process Skills Inventory [58]) to enable our triangulation. Some of the questions on essays and interviews came from research on science teaching and learning, and some were developed by two of the research team members. Except for the interviews, all assessments were administered both pre- and postinstruction to gauge perceived impacts relating to participation in the RBSEU curriculum. In the remainder of this Sec. III, we describe the development or adaptation of each assessment, its administration, and our analysis of students' responses. Table I presents an outline of the types of universities and courses adopting the RBSEU curriculum in this study, as well as the assessments that were used in each course.

B. Interviews

During the last few weeks of the Fall 2012 semester, students enrolled in each of the participating courses at all universities (1–4) were invited to participate in interviews. The interview questions asked students to compare their experiences participating in RBSEU projects with their previous science learning experiences, their conceptions of the nature of scientific research, and their attitude

TABLE I. Assessments administered by type of university, project, and instruction.

University number	University type	Projects facilitated	Instruction style	Project length	CURE or QCURE	Assessment(s) administered	N
1	Medium-sized comprehensive university	Asteroids	Concurrent	Long	CURE	Interviews	3
						Essays	55
						SPSI	95
		Spectroscopy, photometry	Concurrent	Long	QCURE	Interviews	4
						Essays	27
						SPSI	65
		Nova search	Concurrent	Long	CURE	Interviews	4
						Essays	12
						SPSI	26
2	Minority serving university	Asteroids, photometry	Integrated	Short	QCURE	Interviews	2
						SPSI	13
3	Community college	Nova search	Integrated	Short	CURE	Interviews	4
4	Private Liberal Arts college	Asteroids	Concurrent	Long	CURE	Interviews	2

toward doing scientific research-related tasks. Examples of questions asked during the interviews included the following:

- What is the goal of the project you are working on?
- What differences did you experience between the projects you did in this class and other types of science projects you have done?
- What new things did you learn about scientific research while doing these projects, if any?
- Do you think the scientific method is linear? Why or why not?

The interview format was semistructured, meaning that the questions asked in each interview were identical, but the interviewer had the option to ask the participant to elaborate on their thinking regarding a particular question if clarification was warranted. Each interview was conducted by a member of the research team who was not the student's instructor in a separate, private location to better support the student's sense of anonymity. Interview transcripts were anonymized before being analyzed.

In our attempt to construct a similar, representative sample across all courses, up to four interviewees per university and course project were randomly selected from those who had consented to participate, for a total of 19 interviews. The resulting transcripts are likely to represent relatively strong feelings about the RBSEU student experience, given the self-selected nature of the participant population and their willingness to share their time and their thoughts [59].

To analyze student responses to interviews, two of the researchers generated a rubric based on the practice of descriptive coding [60] of all interviews. Descriptive coding identifies themes discussed by participants in qualitative data and characterizes these themes in short phrases. The rubric was generated collaboratively to gauge the range of themes present in participants' responses. The practice of having two researchers compare and contrast codes in the generation of the rubric aligns with an objectivist assumption that the more persons involved in interpretation of data, the more accurate the analysis. Overarching categories encompassing the themes were then generated by one of these researchers and verified by another research team member.

C. Essays

As part of regular class activities, during the Fall 2012 and Spring 2013 semesters, students participating in the RBSEU curriculum at University 1 were required to write essay responses with regularity, before instruction, during instruction, and after instruction. This instructional practice was adopted to give students space to contemplate their practice and process of science during RBSEU coursework [61]. Sometimes students' responses were used to provoke class discussion and sometimes they were returned with instructor feedback. The responses attended to in this study came from pre- and postinstruction essay prompts that enabled both students and researchers to think about and learn how RBSEU instruction was different from students' prior science learning experiences:

- Pick one or two science projects you've completed before, either in a class or outside of academia. Describe what made the project(s) "science" to you.
- I think scientific research is…
- What sorts of questions do you think science can answer, and what sorts of questions can it not answer?

The first two prompts were developed by the researchers and the last one was taken from the Views of the Nature of Science (V-NOS) questionnaire [62].

The postinstruction prompt did not include the first of these questions. Instead, instructors gave students verbal instructions to articulate in their response how their participation in the RBSEU curriculum influenced their perceptions. Students were given twenty minutes of class time to respond to these prompts. Consenting students' pre-instruction responses were analyzed if there was a matching post-instruction response. Consenting students' post-instruction responses were only analyzed if students specifically mentioned how RBSEU instruction influenced their response. All responses were anonymized before analysis took place.

For the analysis of essay responses regarding students' characterization of their prior learning experiences, one researcher used In-Vivo coding [60] to locate students' phrasing characterizing their experiences. In-Vivo coding was chosen by this researcher for two reasons: (i) the essay data lent itself well to capturing students' characterizations through this type of coding because many students used identical, concise phrases to characterize science and science learning experiences, for example, "observing," "measuring," "experiment," "design," and "idea," and (ii) In-Vivo coding aligns with an objectivist assumption that using participants' language as codes leads to their accurate representation. The same researcher then generated themes encompassing these phrasings, cataloging their affiliation with science practice and process rather than evaluating them according to their accuracy. Any one of the participants' responses could be represented in two or more overarching themes considering the themes were not mutually exclusive to one another. Another researcher reviewed the analysis for consistency in approach and clarity of interpretation.

Another analysis regarded how participation in the RBSEU curriculum influenced participants' perception of and affect toward science, in comparison to prior science learning experiences. A rubric was developed by two of the research members with interest in categorically delineating participants' responses as pertinent to their perceptions of and affect toward science, per the research questions of this study. Next, one of the researchers organized the responses according to these delineations and interpreted overarching categories, which were checked by another member of the research team for consistency among identification and organization. The former researcher then compared and contrasted these themes with respective themes generated from corresponding interview responses regarding how the RBSEU curriculum differed from previous science learning experiences.

The triangulation between themes generated from qualitative analyses of essay and interview responses are discussed in Sec. IV, where they are presented within distinct categories. These categories are referenced according to the extent to which they map onto the CURE pathway model presented in Fig. 1.

D. Science Process Skills Inventory (SPSI) online survey

The Science Process Skills Inventory [58] is a Likert-scale survey that measures students' confidence in performing science process tasks, such as use of scientific knowledge to form a question or use of data to create a graph. (The full set of 11 questions is presented in Table II, along with the results of our analysis.) We modified the original four-point Likert scale (*Never, Sometimes, Usually, Always*) to include seven points (*Don't Know, Never, Almost Never, Sometimes, Usually, Almost Always, Always*) so that students could both indicate their uncertainty in performing any given task and have more options to more closely approximate their level of confidence. Changing the number of points in a Likert scale of a psychometrically valid instrument from 5 to 7 points has not reliably shown a change in the perceived psychological distance between numbers [63,64] or in the validity of the instrument [65]. We administered the survey online during class on the first week (pre) and the last week (post) of instruction during the Spring 2012 through Spring 2013 semesters at Universities 1 and 2 to measure students' confidence in doing science process tasks. Students created an anonymous identifier to match their pre- and postresponses.

Only SPSI responses with matched pre- and postidentifiers were included in the analysis. Also, if a particular respondent selected "Don't Know" either pre- or postinstruction for any given statement, both the pre- and postinstruction response for this statement and participant were also eliminated from the analysis. This elimination was performed because of the inability to reference the response Don't Know in numerical relationship to other possible responses. The kurtosis and skew of the remaining distributions of pre- and postresponses were then tested to determine whether parametric (two-tailed t test) or nonparametric (two-tailed sign test) statistics should be used for analysis of change per statement. The following hypotheses were tested for those responses requiring a sign test:

- H_0: There is no difference in the median value between pre- and postresponses.
- H_A: There is a difference in the median value between pre- and postresponses.

The following hypotheses were tested for those responses requiring a t test:

- H_0: There is no difference in the mean value between pre- and postresponses.
- H_A: There is a difference in the mean value between pre- and postresponses.

Effect sizes [66] were calculated using Cohen's d:

$$d = \frac{z}{\sqrt{X}},$$

where z represents the test statistic associated with the sign test (or t for the t test), and X represents twice the value of the number of participants at one phase of assessment (i.e., twice the value of n in Table II). A Kruskal-Wallis test was then performed to assess for differences in distributions between courses.

IV. RESULTS

We now report on the findings from our analyses on the impact of participation in the RBSEU curriculum, as

TABLE II. Significance ($\alpha = 0.05$) and effect size (E.S.) associated with changes in students' responses after instruction compared to before instruction as measured by the sign test and t test. Statements for which statistically significant changes occurred are denoted with an asterisk.

No.	Science process skills inventory statement	n	Significance (Sig.)	z	Effect size (E.S.)
1	I can use scientific knowledge to form a question.	182	*	5.35	0.28
2	I can ask a question that can be answered by collecting data.	189		1.81	
3	I can design a scientific procedure to answer a question.	172	*	$t = 5.92$	0.32
4	I can communicate a scientific procedure to others.	178	*	5.71	0.30
5	I can record data accurately.	185	*	2.55	0.13
6	I can use data to create a graph for presentation to others.	183	*	2.92	0.15
7	I can create a display to communicate my data and observations.	177	*	4.36	0.23
8	I can use science terms to share my results.	180	*	5.48	0.29
9	I can use the results of my investigation to answer the question that I asked.	182	*	3.92	0.21
10	I can use models to explain my results.	177	*	3.74	0.20
11	I can analyze the results of a scientific investigation.	179	*	4.14	0.22

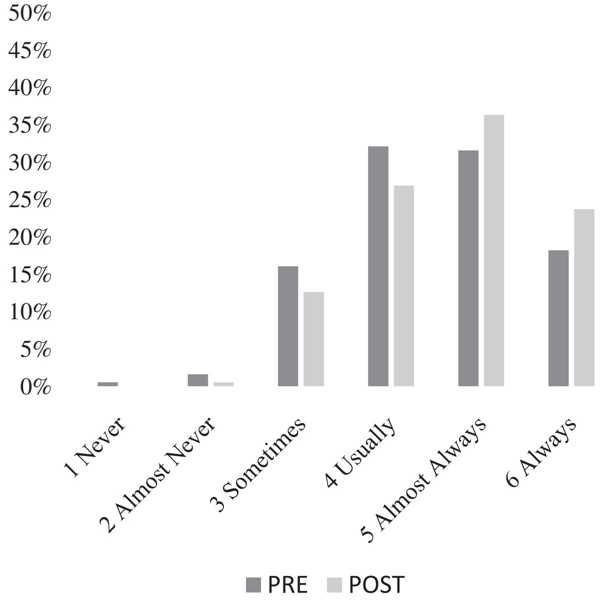

FIG. 2. The response distribution for the statement with the smallest effect size (statement 5). Dark gray bars correspond to preinstruction responses and light gray bars correspond to postinstruction responses.

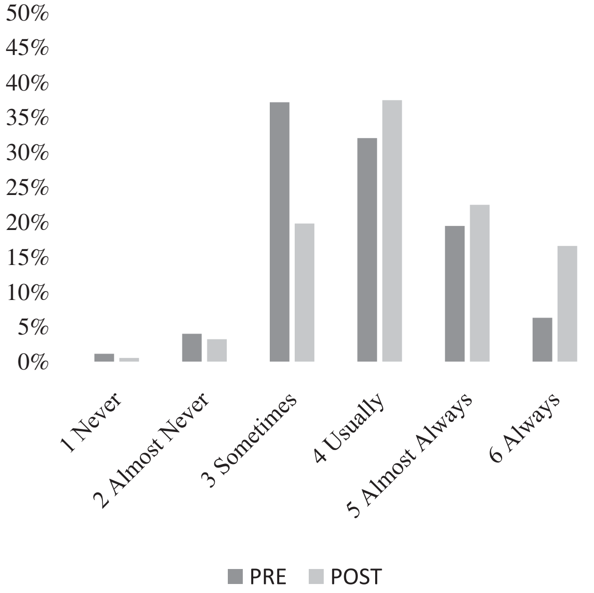

FIG. 3. The response distribution for the statement with the largest effect size (statement 3). Dark gray bars correspond to preinstruction responses and light gray bars correspond to postinstruction responses.

TABLE III. Example quotes expressing three themes related to motivation according to SDT, namely, autonomy, competency, and relatedness, respectively.

Theme	Supporting quotes
Drawing own conclusions	It wasn't what I expected it to be…doing actual further research on new stuff gave it an entirely new dimension and it got you more involved as a student, so you didn't feel like you were just following A, B, and C, it had all been done before where you could really go online and look for the answers to everything because it was nothing new, whereas this was a much better educational experience. - *CURE interview participant, University 1* It was important for us to have that experience of not quite knowing what we're going to do…or what's going to happen, or like we're just going to have to try some things and work around our problems and become innovative with it and be flexible and try different things. - *CURE interview participant, University 4*
Perceived competency	I never would have expected that I could do my own scientific research. - *CURE interview participant, University 4* This was definitely very helpful to see that I definitely do want to do science. - *CURE interview participant, University 3* I think scientific research is anything that anyone can do or study. It is not only for scientists. Students can do it too. - *CURE essay participant, University 1*
Scientific community	I really appreciate how open the whole scientific community seems to be to just let people come in and helping everybody out…you know, anybody can do some stuff. - *CURE interview participant, University 4* Finally, a project that we did in class is going to be used for something bigger and not just read once. - *CURE essay participant, University 1* It was very helpful to know that we might actually be published as official research. That was a very cool idea, and thus, it kind of put a more professional turn. - *CURE interview participant, University 1* It is also important to collaborate with people conducting the same research. - *CURE essay participant, University 1* From the labs I completed this semester it was made obvious that scientific research is a global effort. Stars and galaxies have been observed and recorded not by scientists in one country but by scientists all over the world. - *QCURE essay participant, University 1*

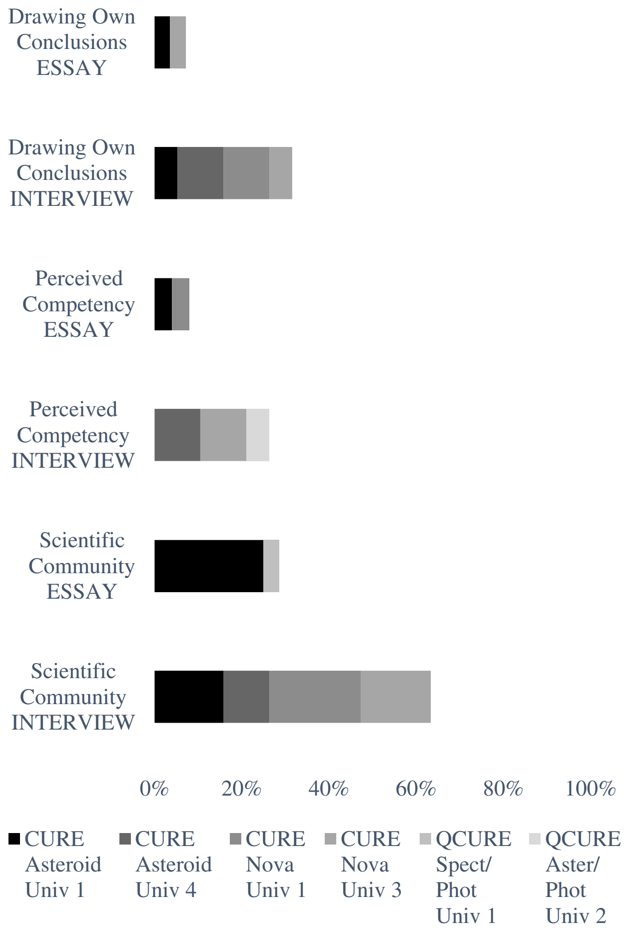

FIG. 4. Percentage of responses represented within each theme regarding the category of motivation, shaded by course type, project, and institution. Each theme is related to a motivational construct of SDT: autonomy, competency, and relatedness. Themes were generated from qualitative analyses of students' postinstruction essay ($n = 28$) and interview responses ($n = 19$) characterizing RBSEU instruction.

perceived by introductory astronomy students. For the SPSI, the number of responses with matched pre- and postinstruction identifiers was 199. For interviews, the total number of respondents was 19. The total number of preinstruction essays analyzed was 94 and postinstruction essays analyzed was 28. These numbers are reflected per university and course type in Table I. Example quotes from the categories and themes emergent from the qualitative analysis are presented in Tables III–VII. The percentage of student responses coded as mentioning each theme are presented in Figs. 4–7.

In the Sec. IV A, we discuss findings aligned with the CURE pathway model. We arrange this discussion per these findings' connection to theories of self-efficacy and motivation developed in the field of positive psychology. Afterward, we discuss those findings which are not expressed in the CURE pathway model, but which we consider relevant for introductory astronomy educators interested in nuanced outcomes associated with CURE and QCURE instruction.

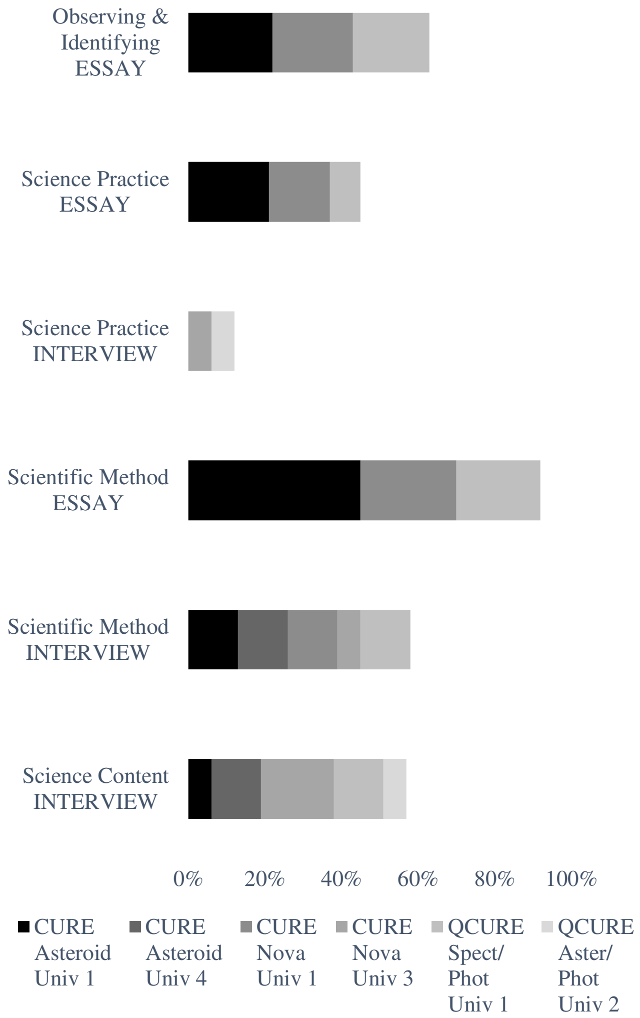

FIG. 5. Percentage of responses represented within each theme regarding the category of previous science learning, shaded by course type, project, and institution. Themes were generated from qualitative analyses of students' preinstruction essay ($n = 76$ out of 94) responses and interview ($n = 16$ out of 19) and are shaded by course type, project, and institution.

A. Findings aligned with the CURE pathway model

We begin the exploration of our results in relationship to the CURE pathway model's elements of "increased self-efficacy" and "increased motivation" shown in Fig. 1, which CURE researchers—especially in biology—have identified as "probable" and "possible" outcomes of CURE participation, respectively [7,53]. Self-efficacy theory, posited by Bandura [67], is the study of how a person's beliefs about their capability to a complete task is connected to behaviors that enable task completion. Some science education researchers have observed confidence, self-efficacy, and science identity as connected constructs [68,69], and so we examine the results of the SPSI survey analysis under the umbrella of self-efficacy. Researchers in the field of positive psychology have also studied close correlations between *autonomy*, *competence*, and *relatedness* as constructs, the

TABLE IV. Example quotes expressing four themes from qualitative analysis regarding students' previous science learning experiences.

Theme	Response
Observing and identifying	One science fair project was how soda affects teeth and we used my parents' old molars…we had Coke and Mountain Dew and Listerine and water and saw what it did to enamel and teeth. I guess it was science to me because it was just interesting to find out…how chemicals ate at enamel. - *Interview participant, University 3*
	Last semester I conducted many scientific projects in my [integrated science] course. For example, the class created "jar ecosystems." Each group created two jars to be as similar as possible and then did or added something to one jar to see how it would be affected. The group I was involved with put one jar into a refrigerator to see how the cold temperatures would affect the community of a various one-celled species. Taking known items (an ecosystem or plant) and then changing the situation in order to observe the outcomes. - *Essay participant, University 1*
Science practice	I picked a physics lab I did last semester in class. I'm not sure why the project was science to me I guess because I was doing it in a science class? We recorded numbers, did test runs of the experiment, and used formulas for what our results should've been and compared it with our actual results and calculated our percentage errors and had to explain why it was off and that felt very "science." - *Essay participant, University 1*
	We've just been running the detectors trying to see if we could distinguish between neon particles that are coming from the atmosphere and a secondary particle source. We have little radioactive disks that are alpha, beta, and gamma particles, and we're trying to see if these detectors with the computer program that we're running can distinguish between the two…we're using some basic principles and ideas, just kind of stepping outside of the box and trying a bunch of different things honestly. - *Interview participant, University 2*
Scientific method	One science project that I have done before was researching what facility grew more bacteria, a school or a hospital. My partner and I collected samples from both facilities of similar nature, e.g. a toilet seat, door handles, the floor. Then we would clean the surface with the cleaning solution that facility would use and compared the results. This was science to me because we were collecting data, made a hypothesis, recorded observations and came to an end result. - *Essay participant, University 1*
	One larger project that I enjoyed was when I took Environmental Science and we collected different leaves and samples…what made this science was that rather than reading out of a textbook, it was more of a hands-on project… We were in the field, and then we had to go back and look at other people's research in order to identify it. So we were contributing our findings with this pool of science that exists. - *Interview participant, University 4*
Science content	Labs were done as part of a class and then you wrote a lab report and presented your findings. The informational presentations—I guess those were science because we were sharing information about what we know of the natural world. - *Interview participant, University 4*
	High school astronomy it was just like here's this type of star, here's this type of star, here's a nebula, but we didn't really talk about any of the physics and all that stuff that really matters for astronomy. - *Interview participant, University 3*

simultaneous experience of which produces motivation in completing tasks (self-determination theory) [70,71]. Several themes from our qualitative analysis correspond with these constructs and, consequently, we map our results per their alignment with these theories.

Significant positive changes in students' perceived confidence in their science process skills were measured for both CUREs and QCUREs when comparing their post- and preinstruction responses on 10 out of 11 statements on the SPSI, as shown in Table II. For one of the statements (statement 3), the distributions of students' pre- and postresponses were parametric; so a two-tailed t test was used to assess for significant changes. For the remaining 10 distributions, a two-tailed sign test was used because either one or both of the pre- or postdistributions were nonparametric. The effect size calculations suggest that instruction may have had a small to medium effect on participants' perception, based on Cohen's [72] conventions: small, 0.20; medium, 0.50; large, 0.80. The Kruskal-Wallis test suggested that there were no significant differences across course type and university. Depending on the statement, the number of participants responding Don't know ranged from 2%–9% of the total sample population before instruction, and from 0%–3% after instruction.

Figures 2 and 3 depict distribution changes in students' pre- to postinstruction SPSI responses. Specifically, Fig. 2 demonstrates the response distributions to statement 5, which had the lowest effect size and Fig. 3 demonstrates the response distributions to statement 3, which had the largest effect size.

Three themes emerged from qualitative analyses of essay and interview responses that correspond with the Self Determination Theory's (SDT's) formalization of motivation [71]. The theme of *drawing own conclusions* characterized students' responses regarding their perceived ability to address uncertainties involved in the process of doing science or in the end result. We interpreted this theme as corresponding with SDT's construct of *autonomy*, per students' ownership in solving inherent dilemmas in scientific research. *Autonomy* corresponds with the CURE pathway model's possible [7] short-term outcome of "increased project ownership" (see Fig. 1), which in CURE literature is understood as perceived by students rather than measured by the number of elements in a project carried out autonomously [7,73]. Noticeably, only students enrolled in CUREs mentioned this theme.

Perceived competency regarded students' responses that suggested curriculum participation increased their belief in their ability to do science or encouraged their continuation in studying science. We interpreted this theme as connected to SDT's construct of *competency*. Further, we also consider this theme as corresponding with the CURE pathway model's probable outcome of increased self-efficacy (see Fig. 1), which like the outcome of increased project ownership, is understood as perceived by students.

Finally, the theme of *scientific community* characterized students' responses that indicated an increased sense of science's communal components, and consequently corresponds with SDT's construct of *relatedness*. Aspects of belonging to a scientific community, such as recognizing how their work fits in with that of other scientists and learning that scientific results come from collaboration with peers or colleagues was mentioned by both essay and interview participants, but at a much higher rate by CUREs participants (92% in interviews, 30% in essays) than QCUREs participants (33% in interviews, 20% in essays). Our finding that CUREs develop a sense of scientific community demonstrates resonance with findings from other CUREs [9,16,31,34,37], and corresponds with the CURE pathway model's possible short-term outcome of "sense of belonging to a larger community" [7,53] (see Fig. 1). Table III demonstrates supporting quotes for each theme and Fig. 4 depicts the percentage of responses represented in each theme according to course type, data type, and institution.

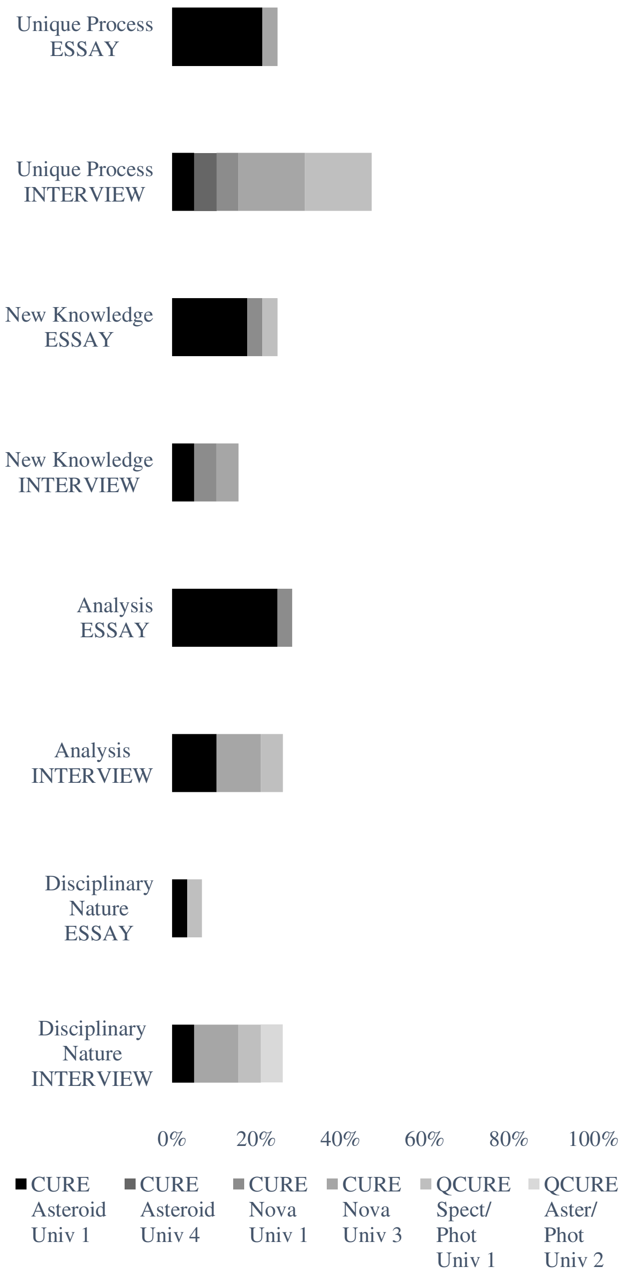

FIG. 6. Percentage of responses represented within each theme regarding the category of process of science, shaded by course type, project, and institution. Themes were generated from qualitative analyses of students' postinstruction essay ($n = 28$) and interview responses ($n = 19$) characterizing RBSEU instruction compared to previous instruction.

B. Additional findings

Our study's design was conceived and enacted before and during the years the CURE framework represented in this paper was being established. Accordingly, our research questions concerned a broad investigation into the impacts of participation in the curriculum, toward which the essays and interviews were attuned. Of special interest was students' perceptions of the curriculum as different from previously encountered forms of science instruction. We now provide findings that do not fit within the specific parameters of the CURE pathway model under study. However, we will discuss the connections of these findings with other CUREs in Sec. V.

To determine students' characterization of RBSEU instruction as compared to previous learning experiences,

TABLE V. Example quotes expressing themes related to the process of science generated from qualitative analysis characterizing RBSEU instruction as compared to previous science learning.

Theme	Supporting quotes
Unique process	Although I have done experiments in other labs throughout my educational career I have not ever fully understood that the process is what makes an act scientific research. - *CURE essay participant, University 1* It showed how you study [novae] and how you calculate the magnitude and how that's actually done with the photographs. I never knew before how it could possibly be done, with telescopes and what not. It's cool that there's pictures and times of pictures and snapshots and see it over time and how it happens. - *CURE interview participant, University 3*
New knowledge	This class broadened our understanding of the movement of asteroids. Through science we were able to get an approximation of where that asteroid will be. This type of scientific research and knowledge was not available to scholars hundreds and thousands of years ago. - *CURE essay participant, University 1* It's still a lot of fun knowing you're working with real information, knowing that you're actually collecting information that nobody necessarily knows yet. - *CURE interview participant, Essay 3*
Analysis	I think scientific research is a process to retrieve and analyze data…In this class we used scientific research as a bases of an experiment, using math and statistics… For this project we used science and repeatable method to chart asteroid movements and their possible orbits. Gathering the data was all science. - *CURE essay participant, University 1* It was definitely more like doing the math and getting down and trying to figure it out and really analyzing, like you really have to think and analyze, where I felt like in chemistry and biology, it was just like, "Oh, here's the instructions. Do it," and you don't really think about it; you're just like kind of like a robot. - *CURE essay participant, University 1*
Disciplinary nature	Science helped us answer whether or not we should keep studying our asteroid, more than other asteroids. We calculated our asteroid's Need Ratio. With that number we determined how urgently we needed to study the asteroid. - *CURE essay participant, University 1* I like being able to see on a computer what someone else would be doing as they're studying it—doing the same exact thing as them. - *CURE interview participant, University 3*

we felt it was important to first identify students' characterization of their previous science instruction. The majority of essay ($n = 76$ out of 94) and interview ($n = 16$ out of 19) respondents explicitly characterized previous science learning experiences. Analysis of essays generated themes of *observing and identifying, science practice*, and *scientific method*. Analysis of interview responses generated themes of *science practice*, *scientific method*, and *science content*.

The theme of observing and identifying included characterizations such as observing a plant grow, a chemical reaction, or a response in a manipulated system. The theme of science practice contained characterizations of activities based on sciencelike activities or topics, including dissections, classifications, calculations, trial and error, and literature reviews. The theme of scientific method included responses mentioning either the scientific method as a characterization of previous science learning or included one or more elements of the scientific method (e.g., questions, making predictions, developing and testing hypotheses, data collection, and analysis). Finally, the theme of scientific content included descriptions of science instruction as memorization as well as the completion of worksheets, example problems, laboratory reports, and tutorials. No relationship between participants' university and characterization of previous science learning was evident. Table IV demonstrates supporting quotes for each theme regarding participants' previous science learning and Fig. 5 depicts the percentage of responses represented in each theme according to course type, data type, and institution.

Students were asked, in interviews and in essays, at or near the end of instruction about how their RBSEU experiences contrasted with their previous science learning. The process of science emerged as a category, with themes of the scientific process as a *unique process* that is different from other modes of knowing and learning, a process that produces *new knowledge* that was previously unknown, a process that requires *analysis* of data or observation in order to determine results, and a process that has a *disciplinary nature* that is unique to the phenomenon under study. In both essays and interviews, the analysis theme was more common in CURE students' responses (31% interviews, 35% essays) than in QCURE students' responses (17% of interviews, 0% essays). Table V demonstrates supporting quotes for each theme regarding the

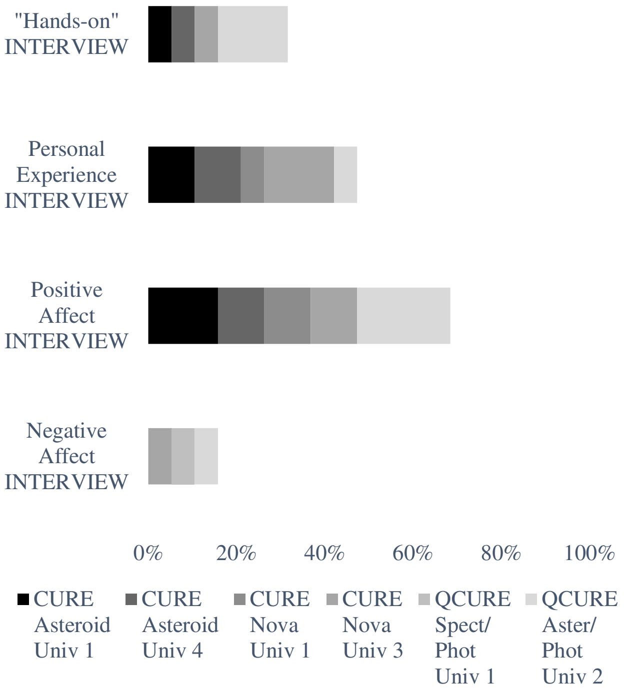

FIG. 7. Percentage of responses represented within each theme regarding the category of engagement. Themes were generated from qualitative analyses of students' interview responses ($n = 19$) characterizing RBSEU instruction compared to previous instruction, shaded by course type.

process of science and Fig. 6 depicts the percentage of responses represented in each theme according to course type, data type, and institution.

Additional themes regarding students' characterizations of RBSEU instruction compared to previous instruction included simple phrases related to the category of engagement, including its *"hands-on"* nature, providing a meaningful, *personal experience* for students to practice science, and *positive affect* (e.g., "fun," "exciting," "cool") and *negative affect* (e.g., "tedious" and "boring"). Figure 7 depicts the percentage of responses represented in each theme according to data type and course type. In both CUREs and QCUREs, respondents more frequently described positive affect (67% CUREs, 69% QCUREs) than negative affect (8% CUREs, 33% QCUREs).

V. DISCUSSION

The study described in this paper is among the first to examine the impact of course-based research within undergraduate introductory astronomy courses. Students' perceptions presented in our results suggest that for many introductory astronomy students, participating in course-based astronomy research experiences—involving scientific practices, discovery, broader relevance, collaboration, and iteration [33]) can be helpful in enhancing ideas about scientific process, improving confidence in science process skills, and increasing students' attitudes toward science.

During the period of this study (2012–2013), we were unaware of the efforts being made in biology, chemistry, and geology education research communities regarding similarly designed research experiences in introductory science laboratories. Formerly studied under the frame of authentic research within the body of science education literature, more discipline-specific studies of CUREs and QCUREs, as different types of course-based research, became prevalent in the years 2013–2016. This may be due to the increasing number of scientists participating in science education research [74,75], and their ability to bring research into their own undergraduate classrooms. Indeed, such was the case with our study, where all four of the authors' astronomy expertise led to the development and/or dissemination of the projects in their own and others' classrooms. Considering the connection between our study and similar work in other scientific disciplines, we now discuss how our findings connect to those from the research on CUREs. Specifically, we address how our findings contribute to understanding of how participation in CUREs and QCUREs influence students' affections toward participating in and perceptions of the scientific process. We also review future directions suggested in the CURE literature and their possible applications in astronomy education research.

Our study of CUREs and QCUREs in astronomy, specifically those using the RBSEU curriculum, engages in calls to "observe and characterize many diverse CUREs to identify the activities within CUREs likely to directly result in these short-term outcomes, delineating both rewards and difficulties students encounter as they participate," as suggested by CURE researchers in biology [33]. Our results aligned with short- and medium-term outcomes suggested by other CURE researchers as either probable or possible in the pathway model [7,53], namely, *sense of belonging to a larger community, increased project ownership, increased self-efficacy*, and *increased motivation*, depicted in Fig. 8.

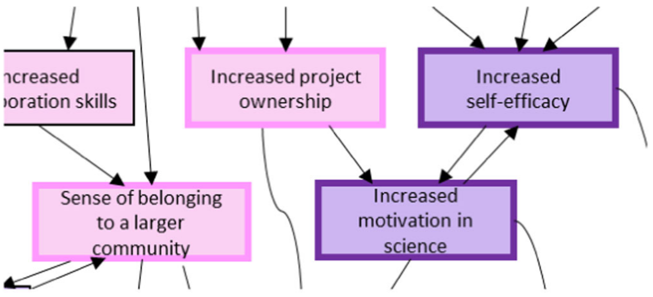

FIG. 8. A portion of Fig. 1, identifying the location of the CURE pathway model corresponding with our results (boxes outlined in bold). CURE researchers have identified increased self-efficacy as a probable outcome of CUREs and increased project ownership, sense of belonging to a larger community, and increased motivation in science as possible CURE outcomes [7,53].

A. Findings' broader relevance

1. Scientific communities

Increased awareness of and sense of belonging to scientific communities and collaborations was a result of RBSEU participation that supports findings from other studies of CUREs and QCUREs [9,16,31,34,37]. This finding corresponds with the sense of belonging to a larger community short-term outcome of the CURE pathway model which helps further substantiate this outcome as a possible CURE outcome [7,53]. Our qualitative analyses revealed that students enrolled in RBSEU CUREs were more likely to express their increased understanding of the collaborative and community-oriented nature of than those enrolled in RBSEU QCUREs.

We speculate that students' awareness of scientific community and collaboration in RBSEU CUREs stemmed from the incorporation of discovery and broader relevance. Both CUREs and QCUREs required students to work individually to analyze a phenomenon, and then collaboratively to compare results with their classmates. But such practices might occur in any science or nonscience course. In contrast, CURE participants were made explicitly aware of their coursework's potential contribution to the scientific community. Further, students participating in long CUREs at Universities 1 and 4 had enough time both to analyze data produced by the scientific community and to see the final form of their own contributions to that community. For example, CURE asteroid project students at Universities 1 and 4 not only formatted their measurements for publication through the Minor Planet Center [76], but they also analyzed those measurements in conjunction with prior observations made by professional astronomers, published in the same way. Nova Search project students at Universities 1 and 3 produced lists of nova coordinates in right ascension, declination, and magnitude that were to be cataloged through scientific publication. Additionally, when asteroid project students at University 4 faced technical difficulties while the project administrator was unavailable, they reached out to the scientists who developed the troublesome software. These students expressed amazement at the openness and responsiveness of the scientific community. Thus, the elements of discovery and broader relevance that distinguish CUREs from QCUREs may have contributed to CURE students' increased sense of contribution to the scientific community.

2. Self-efficacy and motivation

Students' increased confidence (related to self-efficacy) in their ability to do science is a medium-term outcome as posited by the CURE pathway model. Our study demonstrates that confidence increased on all but one skill on the SPSI: developing scientific questions and hypotheses. This is an understandable result because most projects in the RBSEU curriculum did not engage students with this task. Students' increased confidence in the remaining science process skills was significant for both CUREs and QCUREs. These findings are consistent with our qualitative theme of perceived competency (see Table VI), as well as results from a number of other studies on CUREs and QCUREs, independent of the scientific discipline [9,10,16,38,77,78]. Overall, our findings further substantiate increased self-efficacy as a probable outcome within the CURE pathway model. Our qualitative theme of drawing own conclusions also further substantiates increased project ownership as a possible short-term outcome in the CURE pathway model.

While we did not directly assess students' motivation, triangulation between the SPSI and our aforementioned qualitative analyses suggests that students experience SDT's motivational construct of competency as a result of participation in RBSEU CUREs and QCUREs. However, RBSEU CUREs were potentially more often motivational in nature, according to SDT, due to the greater number of CURE students mentioning a sense of relatedness with regard to scientific community, and only CURE students mentioning a sense of autonomy. These findings suggest that an arrow be drawn between sense of belonging to a scientific community and increased motivation outcomes in the CURE pathway model. These findings also stimulate questions for future research, regarding both the effect of discovery and broader relevance as related to motivation in CUREs and its variants. Future research on these medium-term outcomes have been encouraged in the literature [33,53], and may be enabled through the various validated instruments regarding these constructs [79–83]. For example, a number of instruments measuring students' motivation have been developed and validated with the help of educational psychologists [84,85]. These could be used before and after CUREs, and even longitudinally to gauge resulting changes in motivation toward learning and participating in science.

Finally, previous research has found that with increasing time spent on research projects, students' self-efficacy in scientific research increases [48,49]. One might conclude that longer-term use of CUREs would be beneficial in a variety of contexts, especially where undergraduate science majors are involved. However, we suggest that scientific self-efficacy should not be considered the primary or only goal for introductory science instruction. Even in the short versions of our RBSEU projects, some students described participation as tedious and "painstaking," perhaps signaling a reduction in their engagement, despite these being qualities of professional scientific research. Consequently, we recommend that introductory science instructors and researchers consider that project participation may have different impacts on competency and engagement, and that desirability of each outcome might differ depending on the level of the course (introductory or upper-level).

TABLE VI. Findings aligned with the CURE pathway model. Proportion of students mentioning themes, normalized to their participation in a CURE or a QCURE.

				Interviews		Essays	
Category	Themes	Constructs from Self-determination theory	CURE pathway model outcomes	CURE	QCURE	CURE	QCURE
Increased motivation	Drawing own conclusions	Autonomy	Increased project ownership	46% (6/13)	0% (0/6)	···	···
	Perceived competency	Competence	Increased self-efficacy	31% (4/13)	17% (1/6)	9% (2/23)	0% (0/5)
	Scientific community	Relatedness	Sense of belonging to a larger community	92% (12/13)	33% (2/6)	30% (7/23)	20% (1/5)

3. Science process

Our study's qualitative analyses demonstrated that many students identified the RBSEU curriculum as influencing their perceptions of scientific process, a result that connects with URE and CURE research in other disciplines [73,86]. Although increased awareness of the scientific process is not represented in the CURE pathway model, it could be considered increased content knowledge. While both

TABLE VII. Additional findings. Proportion of students mentioning themes, normalized to their participation in a CURE or a QCURE.

			Interviews		Essays	
Category	Themes	Description and examples	CURE	QCURE	CURE	QCURE
Prior experience	Observing and identifying	Observing a plant grow, a chemical reaction, or a response in a manipulated system	···	···	61% (33/54)	68% (15/22)
	Science practice	Sciencelike activities, such as classifications, calculations, trial and error, and literature reviews	10% (1/10)	17% (1/6)	52% (28/54)	27% (6/22)
	Scientific method	Mentioned either the scientific method or included one or more elements of the scientific method (e.g., questions, making predictions, developing and testing hypotheses, data collection and analysis).	70% (7/10)	33% (2/6)	98% (53/54)	77% (17/22)
	Science content	Described science instruction as memorization, worksheets, example problems, laboratory reports, and tutorials	70% (7/10)	50% (3/6)	···	···
Process of science	Unique process	Scientific process is different from other modes of knowing and learning	46% (6/13)	50% (3/6)	30% (7/23)	0% (0/5)
	New knowledge	Science process produces previously unknown knowledge	23% (3/13)	0% (0/6)	26% (6/23)	20% (1/5)
	Analysis	Science process requires analysis of data or observation in order to determine results	31% (4/13)	17% (1/6)	35% (8/23)	0% (0/5)
	Disciplinary nature	Scientific process and practice is disciplinary specific	23% (3/13)	33% (2/6)	4% (1/23)	20% (1/5)
Engagement	Hands-on	Participation provided a hands-on experience	23% (3/13)	50% (3/6)	···	···
	Personal experience	Participation provided a personal experience in the practice of science	62% (8/13)	17% (1/6)	···	···
	Positive affect	Participation was fun, exciting, cool	69% (9/13)	67% (4/6)	···	···
	Negative affect	Participation was tedious and boring	8% (1/13)	33% (2/6)	···	···

RBSEU CURE and QCURE students discussed learning about the process of science, remarkably the large majority of those students discussing scientific process as requiring detailed analysis were RBSEU CURE students. This finding helps frame a question for future research regarding how discovery and broader relevance components of CUREs may impact students' perceptions of the scientific process compared to merely practicing scientific research without these components, as in QCURES.

4. Attitudinal responses

Finally, the primary attitudinal response of RBSEU CURE and QCURE participation, according to interviews, was positive in nature. This finding is noteworthy because, as with the specific theme of science process, students' attitudinal response was not directly prompted by the interview questions. Instead, the questions asked students to compare and contrast previous science instruction to RBSEU instruction. This finding may correspond with validity issues associated with selection bias [59] of volunteer interviewees. However, we note that positive affect was expressed over all RBSEU curriculum contexts, which suggests that students' participation in CUREs and QCUREs has the potential to foster positive attitudes toward this type of science learning across multiple institutional contexts at the introductory level.

B. Benefits and limitations of study design

This study was performed during a time when research on CUREs in biology was being addressed with focus and rigor. This presents both advantages and disadvantages for the study's design. Had we been aware of these efforts, we could have attempted to strengthen understanding of CUREs' possible and proposed outcomes, as expressed in biology education CURE literature [7,53]. For example, the goals of increased tolerance for obstacles and increased positive interaction with peers may both be considered relevant for introductory astronomy courses. However, CUREs and QCUREs had not been studied rigorously in astronomy education research, so our open-ended questions enabled the possibility of generating themes that were unique to participation in the RBSEU curriculum. Further, RBSEU CUREs and QCUREs were not designed for science majors, unlike many other CURE and QCURE studies cited in this paper. Therefore, a number of the elements expressed in the CURE pathway model of Fig. 1 are not necessarily relevant for introductory astronomy students, such as increased science identity and persistence in science. However, other elements generated from this study, such as the theme process of science, may be considered a desirable outcome for nonmajors.

The CURE pathway model describes multiple frameworks that can be developed for mapping desired short-, medium-, and long-term outcomes of CURE activities [7,53]. However, we choose not to develop a pathway model specific to astronomy education CUREs, because it is currently unclear to what extent disciplinary differences play a role in possible or desirable outcomes. Instead, for astronomy education researchers, we recommend continued open-ended questioning of students' perceived impacts of different kinds of CURE studies in astronomy to investigate what kinds of outcomes are possible and desirable, respectively. We also recommend designing studies in connection to CURE research in other disciplines to determine the extent to which disciplinary differences and level of instruction play a role in possible and desired outcomes.

Although this study involved analysis consistent with objectivism, there were limitations with regard to triangulation because interview and essay assessment types did not include identical questions. Further, essays were part of class procedures while interviews were voluntary. We anticipate that both of these method design factors may have played a role in some themes being present in only the interviews, including positive and negative affect, hands-on, personal experience, and drawing own conclusions. Still, many themes had representation from both essay and interview respondents, and across differing institutional contexts, substantiating claims through triangulation and thereby improving validity [59]. A more robust data collection, with larger numbers of essay and interview responses from all universities, would help to determine how differing contexts might contribute to differing outcomes. As it stands, from Figs. 4–7, some contexts only have one or two students' responses represented in a theme, perhaps partly due some institutions' collection of only two interview responses.

C. Implementation: Contrasting RBSEU with the Genomics Education Partnership

CUREs in other disciplines have been used successfully at hundreds of universities across the country, and instructors and researchers alike speak to their benefits with enthusiasm. We now explore the discipline-specific challenges to CUREs creation and implementation by comparing our RBSEU curriculum with Washington University's Genomics Education Partnerships (GEP) [87]. In both cases, only one institution provided training and materials for all participating universities. However, whereas RBSEU was facilitated at only 4 postsecondary institutions and only at the introductory level, GEP was facilitated at over 100 postsecondary institutions and in a variety of contexts as UREs, CUREs, and QCUREs. By contemplating the difficulties of supporting and sustaining collaborations at this scale, we will consider what it would take to scale up the use of RBSEU or other future astronomy CUREs, in both size and level of content. Finally, by considering differing implementation requirements, we hope to engage prospective astronomy CURE developers and users with the level of support they might expect to receive regarding data production, software, and other equipment and personnel.

To begin, we note that several barriers that faced faculty participating in GEP also resonated with our practice and dissemination of the RBSEU curriculum. These included: *time intensiveness, technical support,* and *institutional buy-in* at participating institutions, and *challenging content* and *instructors' substantive knowledge* [38,87,88]. We use these barriers to guide our comparisons of the GEP and RBSEU curricula and their contexts, and we recommend that they be weighed against the numerous apparent benefits of CUREs and QCUREs expressed in both our study and in those related to GEP.

1. Institutional buy-in

Because the RBSEU curriculum was developed for nonscience majors, it was expected that any person qualified to be an astronomy educator at the undergraduate level would be able to learn and teach the curriculum. For example, of those universities adopting the curriculum at the time of this study, University 1 utilized astronomy adjunct and term instructors who were required to practice use of the curriculum on their own, and teach it based on the lab manuals provided, with additional assistance by a lab manager. At Universities 2, 3, and 4, the curriculum was used by astronomy faculty in their own classrooms, and the source institution helped these faculty adapt it to the faculties' instructional design interests, such as length (short or long) and course-type (integrated or concurrent) as shown in Table I. The introductory level of the material therefore required minimal training for instructors. In contrast, GEP was tailored for in-depth genomics learning that often occurs at higher levels of the biology undergraduate curriculum. Consequently, both genomics and nongenomics trained biology faculty were invited to use the GEP curriculum, and all were required to take an introductory training. Multiple follow-up and alumni workshops were made available to everyone involved in the GEP curriculum, and those faculty who taught in the program considered it to be a time-intensive investment.

Both the RBSEU and GEP curricula were adaptable to instructors' desired contexts. However, GEP instructors reported that their biggest challenge was difficulty in placing the specialized topic of genomics within the traditional biology or genomics curriculum. Even when the course was dedicated to genomics, it did not necessarily have designated laboratory time, which would have been ideal for GEP instruction. Similarly, at Universities 1 and 4, RBSEU curriculum occurred in semester-long laboratories, in which the entirety of laboratory instruction was devoted to the curriculum. However, at Universities 2 and 3, instructors significantly shortened the RBSEU curriculum to include it among otherwise demanding curriculum expectations. Therefore, depending on institutional and instructor buy-in, the specialized nature of CUREs and QCUREs topics can be problematic to the otherwise general undergraduate curriculum.

2. Technical support

A number of software components were required to complete the various RBSEU projects, including ImageJ, Excel, Starry Night Pro, and Find_Orb. These programs are used by both astronomers and other science researchers on a regular basis. While some are free, others require licensing, which may be costly. However, it was often possible to adapt the curriculum so that more expensive software was not necessary. Additionally, at each of the universities where RBSEU was implemented, there was at least one computer available to each student group. These programs often require updating, so some universities required continuous contact with their Information Technology departments to gain permissions for such updates. GEP users were given free access to web-based software, the sole technology requirement for curriculum completion, enabling its wide scale use. However, some of the project software was developed to run on platforms and operating systems that partner institutions did not support. Consequently, GEP staff were required to consistently provide work arounds to existing technical infrastructures, as institutions continued to join the partnership [87]. While some GEP faculty described difficulty in learning and using software, as well as a lack of technical support from their home institution, some faculty felt that having a "source institution" (Washington University) where they could obtain consistent technical support was invaluable to their GEP implementation [38].

3. Time intensiveness, challenging content, and instructor knowledge

Analysis of scientific data is a necessary component of both QCUREs and CUREs, and requires first access to data. In the RBSEU curriculum, access to off-campus telescopes was enabled to the source institution (University 1) through NSF grant funding and research collaborations. In the GEP curriculum, online access to large data sets, some of which are free, were accessed by the source institution through NIH HHMI grant funding [87]. Depending on the type of scientific data under study in CUREs and QCUREs, data collection may require differing levels of expertise.

In terms of time intensiveness associated with data collection, RBSEU and GEP curricula staff, faculty, and students engaged with data on differing temporal scales, depending on whether the curriculum was practiced as a CURE or a QCURE. In the CURE version of the asteroids project, for example, RBSEU staff were intermediary experts who first processed student requests for new data, and, subsequently, prepared the collected data for student analysis. Students were included in the asteroid target selection process in order to improve their understanding that they were designing an astronomical "experiment." Staff submitted these observation requests to the Skynet website after class, and then immediately began preparing for the upcoming analysis. Newly discovered near earth asteroids make excellent targets because they are in the most need of orbit refinement, but these observations are also time sensitive; in order to be useful, they must be reported quickly. Each of these tasks must be completed during the semester and must be timed carefully to match the course schedule. Similarly, GEP staff served in a mediary role: translating multiple student requests to data-collection or experimentation entities and preparing received data for student use [87]. These time-intensive semesterly efforts are unique to CUREs but may be more or less intensive depending on the project. In QCURE versions of the curricula, students studied data that had been processed before the course, and thus the time-intensive element of this part of the curricula largely disappeared. Even so, CUREs and QCUREs should be considered to have inherently different distributions in how course time is spent, compared to introductory lectures and labs aimed at content dissemination alone.

Although the introductory level of the RBSEU astronomy content was intended in part to make the curriculum easy to adapt, like GEP faculty [38], instructors at University 1 reported difficulties with CURE curriculum time intensiveness, including the following:

- Training themselves on project procedures during limited adjunct hours (time intensiveness),
- advising multiple research groups studying different astronomical objects (challenging content), and
- feeling ill equipped to advise research students in content areas outside their own expertise (instructors' substantive knowledge).

In terms of challenging content, in the long versions of RBSEU projects, students within one class worked in small groups to study different asteroids, spectral sources, and images of the Andromeda Galaxy to search for novae. This practice was intended to increase students' sense of engagement and ownership over the study of a particular phenomenon within the class. However, it also discouraged intergroup conversation because different groups might be studying different objects or performing different analyses. This required the instructor to serve as a research advisor to the number of groups in the class (typically four to six) within the timeframe of a few hours each week. Further, in both short and long RBSEU projects, complexities of the software led to complications for some students. Accordingly, instructors had to help students navigate their conceptual issues in addition to troubleshooting software errors.

In terms of instructor's substantive knowledge, GEP touted its use of trained expert biology faculty, but some of those surveyed also reported difficulties in teaching genomics content which they felt was beyond their expertise. This feeling was compounded by students' own lack of exposure to genomics and bioinformatics in previous courses. Because of our aforementioned similar finding, we recommend that when possible, new or nonexpert instructors of CUREs and QCUREs be encouraged to pursue more elementary research assignments with their students, with the possibility of advancing to the study of more difficult or multiple phenomena in later semesters.

VI. CONCLUSIONS

This study sought to examine perceived impacts of introductory astronomy students' participation in the RBSEU curriculum at four different university types. Our results suggest that both CUREs and QCUREs have the potential to increase students' perceived confidence in their science process skills, motivation to learn science, understanding of the scientific process, and attitudes toward doing science. Further, participation in CUREs are more likely to improve students' understanding of the scientific process components of requiring analysis, as well as the role of scientific communities and collaboration in discovery. No effects related to concurrent or integrated, long- or short-instructional styles were found.

Given the effects of CUREs and QCUREs on students' affect and their perceptions of scientific processes described in this study and in other scientific disciplines, we encourage the astronomy and astronomy education research communities to investigate the application of CUREs and QCUREs to their own contexts. Astronomers might consider what parts of their own research could be practiced by small groups of students in astronomy courses at their university. Astronomy education researchers could use the pathway model in Fig. 1 as an aid to develop assessments that enable interdisciplinary conversation about these experiences. We also suggest that future research on CUREs and QCUREs, both inside and outside of astronomy, should examine the complexity of instructors' roles in these contexts, due to their important role in inquiry lessons [89,90]. Finally, we urge that consistent tangible support be built into any CURE program taught by nonexpert instructors to help them feel more prepared to convey specialized research content.

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