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Course-Based Undergraduate Research Experiences in a Chemical Engineering Laboratory Promote Consequential Agency

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ABSTRACT: While students can learn both chemistry content and inquiry practices by participating in course-based undergraduate research experiences (CUREs), it is well documented that prior experiences shape perception. We conducted a case study to investigate students' first experiences with a CURE in an upper-division chemical engineering laboratory course, drawing upon interviews (n = 6), field notes, and written reflections (N = 31). We used discourse analysis to characterize students' agency as they navigated their uncertainty and made sense of the authentic research. We found that students' past experiences shaped their expectations about the CURE, with some wishing for traditional learning supports misaligned to CUREs. Offering students constrained yet consequential agency allowed them to recognize the authentic supports that were available, including help-seeking as itself a form of agency; understand failure as endemic to research rather than their own shortcoming; and position themselves as capable of navigating the uncertainty as a community of researchers. Our results suggest that instructors should model uncertainty and failure as endemic to research and position students as valued collaborators and support for overcoming abundant prior experiences with cookbook-style experiments.

KEYWORDS: *Upper-Division Undergraduate, Chemical Engineering, Laboratory Instruction, Inquiry-Based, Discovery Learning, Chemical Education Research*

■ INTRODUCTION

In chemical engineering and chemistry education, laboratory courses and the experiments within them have remained relatively unchanged for decades.[1−3] Students primarily carry out experiments based on set protocols, answering questions that have been known for decades, if not centuries. Yet scholarship demonstrates that undergraduate students benefit from research experiences with faculty that are more authentic than classroom experiments,[4−8] as these serve as opportunities for students to view what it is like to be in the professional community, receive mentorship, and participate in engaging applications of the content they are learning. For many reasons, however, it is not possible for every student to participate in this way, including limitations on faculty time and resources and student commitments.[9] This has an outsized impact on minoritized students, who may not have access to opportunities in undergraduate research.[10] To maximize the potential benefits of research experiences for students, many faculty have brought core elements of research experiences into their undergraduate classrooms. Such course-based undergraduate research experiences (CUREs) support student learning by bringing them into ongoing research tied directly to course content, giving students the opportunity to participate in the research process, while reducing the burden on faculty.[11] These experiences position students as legitimate participants in the research process, applying their knowledge to something outside the classroom.[12] A direct relationship between students and their chosen fields has been found to foster excitement[3] and a sense of ownership that translates to persistence in science, both in chemistry and chemical engineering.[13,14] Sometimes, CUREs are designed and implemented as a replacement for lectures.[15] However, most CUREs are set in laboratory courses, providing students with opportunities to design experiments.[14,16−18] While many CUREs are set in upper-division courses, this is not always

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the case, with some implemented in general chemistry.[19,20] These hands-on authentic experiences give students a glimpse into what being a professional in their field might be like,[21] while supporting increased science self-efficacy,[22] including skills beyond using basic equipment.[23] By authentic, we mean that the problems tackled have a "primary purpose and source [that is] a need, a practice, a task, a quest and a thirst existing in a context outside of schooling."[24]

■ CONCEPTUAL FRAMEWORK

To understand some of the barriers and potential of CUREs, we bring constructs together as the conceptual framework guiding this study: First, we discuss *opportunity structure* as the decisions that students perceive they can make,[25,26] shaped in part by their prior experiences in laboratory courses—which may include many cookbook-style experiments that differ from CUREs in various ways. To understand both these differences and students' decisions, we bring understanding of *consequential agency*—decisions that are consequential to both learning and the process of the laboratory experiment itself.[27] Finally, to understand how students develop from their prior experiences of limited opportunity structure in cookbook-style laboratory experiments to making consequential decisions in CUREs, we draw upon the theory of *legitimate peripheral participation*, which articulates ways individuals develop toward professional practices. We discuss these in turn below.

What Kinds of Opportunity Structure Do Students Encounter in Laboratory Experiments?

In laboratory courses, students primarily encounter experiments that have a single right solution and an optimal way to achieve that solution.[28] Even more advanced experiments often do like this. For instance, the common organic chemistry aspirin synthesis experiment is complex, in that students manage many competing variables over time, including temperature of the synthesis, adding reagents, and transferring solids.[29] However, this experiment still has a single correct procedure to achieve an ideal result—a high yield of 2-acetoxybenzoic acid. Furthermore, all relevant details of the experiment are well-documented, given that aspirin has been synthesized since the 1890s in ways that have remained largely unchanged.[30]

CUREs, on the other hand, have the potential to engage students in working on experiments in which the solution is not known. In CUREs, even the experimental objectives and procedures can be determined by the students. Including students in ongoing research means supporting them to contend with uncertainty, not just because the answers are unknown, but because the information needed to set a testable objective and plan a way to investigate it may be ambiguous.[31−33] Consider, for instance, the problem of determining a catalyst for the selective hydrogenation of acetylene. Faced with this problem context, students can make choices about the catalyst itself and the optimal conditions for the reaction. They may warrant their choices by considering the attributes of an effective catalyst for this reaction, what parameters should be tested and in what ranges, what research backs up their decisions, and what they expect the outcomes to be. There is no right answer, in that no single catalyst is inherently superior to all others.

To understand the kinds of decisions students can make in laboratory experiments, we consider the *opportunity structure*. Opportunity structure refers to the decisions that someone believes they can make, and this may differ from the decisions instructors intended.[25,26] For instance, consider an instructor who encouraged students to test the impact of different filtration methods on the yield of 2-acetoxybenzoic acid as a way to learn about the role of filtration; because the students were accustomed to their grade being linked to achieving a high yield, most were unwilling to test filtration methods that they expected to be less effective. In this example, we can understand how the prior instruction shapes the opportunity structure students notice and also how it narrows what the students learn. In understanding why their beliefs differ from what is possible, opportunity structure draws attention to the societal structures and norms that shape perception and provides insight into the ways students' prior experiences can shape their perceptions of the opportunity structure presented by an instructional design.[34]

What Agency Do Students Have in CUREs?

Agency has long been characterized as the capacity to make decisions, where the potential decisions are structurally limited.[35,36] In professional settings, a chemical engineer may make many decisions in their work; yet, they are also authentically limited in many ways. Consider a chemical engineer selecting a catalyst for the synthesis of polyethylene polymers. Their choices may be limited by the cost and safety of particular materials, the likelihood that those materials will work given the equipment available, the amount of prior research available on those materials, and their collaborators' preferences and expertise. Even with these limitations, many of their decisions are *consequential*, which we define as impacting how they will work, what they will learn, and how they will proceed in future endeavors.[27] This kind of consequential agency is seldom visible in undergraduate programs. In traditional cookbook-style experiments, students make few or no choices in carrying out the experiment and reaching a well-known solution.[37] Repeated exposure to low-agency science can discourage students from expecting to participate.[38] Research has clarified that there is value for diverse students in enhancing their agency.[39] Indeed, Burkholder et al. found that increasing agency, first in a more structured way that allows students to work together iteratively on a problem, then, in the next course, participate in student designed and led experiments, resulted in students feeling responsible for their own work, and fostered excitement even as they developed professional skills.[40]

However, a key challenge when teaching with authentic problems is that the authenticity may place the problem outside of the students' experience, making it challenging for them to make decisions. In studies of makerspaces, where tasks are similarly out of reach, scholars have identified that students display agency in the form of help-seeking in the face of uncertainty and failure—that in recognizing what they need help on and in taking actions to get that help, they feel agentive.[41,42] Making the decision to seek help is not without risk in academic settings, as it can be read as a clear indication that the student does not know or understand something. We therefore contend that in the context of a CURE, help-seeking in the face of uncertainty and failure may be a form of consequential agency, both because of the potential risk that students may perceive and because of the deliberateness of seeking information.

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How Can CUREs Provide *Legitimate Peripheral Participation*?

We draw upon the notion of learning as a process of moving from peripheral to more central roles, commonly described as *legitimate peripheral participation* (LPP).[43] In LPP, newcomers begin at the periphery of a community of practice, but develop expertise by participating in low-risk tasks that are legitimate in that they further the goals of the community.[43] Cookbook-style experiments do not support students to enter the larger scientific community because these experiments do not serve a legitimate purpose to the wider community. The answers in these "verification" experiments do not advance the goals of the scientific community.[44] CUREs, in contrast, position students in legitimate roles within the research community, jointly supporting learning while advancing ongoing research, even when the experimental results are unexpected or insignificant.[16,45]

The current study uses the idea of LPP to examine how the instructors—in central roles—facilitate learners' development from legitimate and peripheral to more central roles. Specifically, we sought to investigate learners' experiences of making consequential decisions in a CURE, in tandem with their recognition of the opportunity structure of such laboratory experiments as authentic to the community—in this case, chemical engineering.

PURPOSE AND RESEARCH QUESTIONS

While these constructs—opportunity structure, consequential agency, and LPP—individually have been previously used in the study of CUREs, our conceptual framework provides a potentially more comprehensive means of bringing them together to make sense of ways students' perceptions—built from prior experiences with cookbook-style experiments—might be a barrier to their participation and learning in a CURE, offering insight into the kinds of interventions that support their development as researchers. Specifically, we wondered how students in a senior chemical engineering laboratory course used their agency as they encountered an experiment designed to engage them in authentic research practices and inquiry. Through this, we hope to better understand how to support student learning through increased agency and understand how greater opportunity structure impacts experiences. To guide this work, we investigated the following research question:

What do students' reflections and comments about uncertainty, instructional support, failure, and expertise suggest about their perceptions of agency, the opportunity structure of a chemical engineering CURE, and their navigation toward more central roles as researchers?

METHODOLOGY

Study Design

To answer the research questions, we conducted case study research.[46] While there are various approaches to case study,[47] we take up a pragmatic and interpretivist epistemological lens. A pragmatic lens centers our inquiry on work that is valuable to practitioners.[6] An interpretivist lens foregrounds understanding the case in its context over our expectations of the case. From this epistemological lens, we find alignment with the approaches suggested by Stake.[46] In particular, Stake emphasizes flexibility and the omnivorous nature of case study, meaning that many forms of data and analysis may be folded into interpretation to produce an emic account. Like others, Stake defines cases as a bounded phenomena. The phenomenon of interest in this study is how students make sense of an authentic CURE, given repeated past experiences with well-structured, complex laboratory experiments. Given this bounding, our case is instrumental,[46] meaning it focuses on the issues of students' agency in a CURE. As such, we aim to theorize from this case,[48] contributing to theory about ways CUREs can offer an opportunity structure that invites students to make consequential decisions.

Settings and Participants

This study took place at a large Hispanic-serving research university in the American Southwest in a chemical engineering department. The department itself was the subject of a multiyear National Science Foundation (NSF) funded grant to change the way that undergraduate education is taught, focusing on elements such as design challenges, project-based learning, technical writing, and teamwork. Thus, the participants have been the subject of observation and study in the past.

The course was the fourth in a series of four laboratory courses spanning junior and senior years. The course met for three hours once a week. Of the 40 enrolled students, 36 consented to be part of the research. Almost half of the students were Hispanic/Latinx, and approximately half were women. Many of the students had care responsibilities and/or worked more than 10 hours/week. A majority of students had completed an internship (Table 1) and about half planned to attend graduate school (Table 2).

Table 1. Summary of Student Internship Experiences $N = 31$

Response	Count	%
No internship of any kind	6	19
Some type of internship	25	81
Only a research internship	15	48
Only an industrial internship	4	13
Both a research and an industrial internship	6	19

Table 2. Summary of Student Plans After Graduation $N = 32$

Response	Count	%
Only graduate school	8	26
Only industry	9	29
Both graduate school and industry	8	26
Graduate school outside of engineering	3	10
Other	4	13

Laboratory Experiment

By the time students entered this course, they had completed three laboratory courses in the major as well as various courses in chemistry and physics. In all of these courses, the experiments were highly structured in that background information was provided, and the research questions, experimental design, and methods for data collection and analysis were all provided. In contrast, in the CURE, students reviewed literature, posed their own questions, developed their experimental design, and determined what analysis to undertake (Table 3), constrained to the context of selective hydrogenation of acetylene into ethylene as part of a longer process to create polyethylene, a focus of the instructor's

Table 3. Summary of Actions for Each Week of the Experimental Cycle

Class Session	Students' Actions	Instructors' Actions
1: Orientation	Researched potential catalysts; planned experimental design; asked questions about the equipment	Provided overview on operating equipment; answered questions about laboratory set up and safety
2: Pre-Lab	Presented proposed catalyst, experimental design, and a model predicting the catalyst behavior	Gave feedback and made suggestions on presentation and experimental design
3: Experiment	Performed catalyst testing	Provided support
4: Experiment	Continued catalyst testing	Provided support
5: Post-Lab	Analyzed data and began writing conference abstract	Was available to answer questions, provide suggestions about decisions students made in their analysis
6: Peer Review	Conducted peer review; drafted conference posters (presented at the end of the semester)	Provided peer review worksheets and answered logistical questions about preparing the abstract and poster

ongoing research and an area of interest in industrial research.[49] The goal of the experiment was to understand the behavior of the catalyst to optimize it for selectivity and conversion rate. These catalysts are typically bimetallic, with each catalyst having pros and cons (such as selectivity and price). The experimental activities took six class sessions, meeting once a week, from the introduction to the problem to peer review of the drafted conference abstract.

To illustrate how the instructors supported students, we detail the context and approaches they used. The instructors approached the experiment as a collaboration *with* the students, positioning them as legitimate participants in several ways. First, in the prelab, students had to program their own models (while the instructor did not specify the program to use, students generally chose MatLab). The instructor contributed by making suggestions, raising questions, and troubleshooting, much as he would when working with a graduate student. Second, in postlab discussions of results, rather than correcting students, the instructor tasked students with coming up with ways to test their assertions. For instance, a team explained that they believed that the ineffectiveness of their catalyst stemmed from a lack of conversion, an explanation that the instructor did not agree with. Instead of saying as much, the instructor asked the students to explain how they could determine if that was the case. The students were startled to be asked to defend their interpretations in this manner, and they grappled with how to demonstrate why they believed their idea was right. The instructors allowed them to retain their (inaccurate) belief during the session but pressed them to think about the features of their data that might support their assertion. Ultimately, in attempting to defend their assertion, they realized why their explanation was inaccurate—the issue was related to selectivity—and corrected it on their own. Third, the instructors shared their own passion with the students, who seemed to be swept up as part of the team. The students could observe the instructor's status as an authority in the field and were positioned as peripheral but legitimate coinvestigators.[43] This was also suggested, as students informed the instructor that they believed those who conducted the experiment later in the semester benefited from the insights of their peers, evidenced by choosing "better" catalysts; such observations indicate the students were engaged in their research in ways reflective of the scientific community, building knowledge in shared and cumulative ways.

The instructors sought to model uncertainty and failure as endemic and to position students as legitimate peripheral collaborators. Before students began the experiment, the instructor and teaching assistant debated technical aspects of the experiment in front of students, such as whether coking (the buildup of hydrocarbons on the catalyst) was likely to happen, given the experimental design. This display of scientific discourse and disagreement was authentic because it stemmed naturally from their collaborative research. It communicated the authenticity of the problem to students, as the instructor showed that he did not know what the outcomes of the experiments would be. This situation is in contrast to cookbook-style experiments, in which answers are known. The authentic uncertainty repositioned not knowing something as endemic rather than as an assessment of ability or worth.

To support students in managing the psychological/social risk and uncertainty present in the experiment, the instructor reassured them that their experiments were a chance to practice, reassurance that situated the experiment as somewhat less authentic, suggesting that the stakes were lower than students thought they were. Next, the instructor shared that even if they did not find what they hoped to find, the data were still useful for learning about the catalyst. Such explanations situated the experience of unexpected results and failures as endemic to authentic research. Responsively, the instructor offered examples of mistakes made by experienced researchers. For instance, when students made a mistake in their stoichiometry, they shared a story of reviewing a proposal that relied on erroneous stoichiometry, a story that suggests researchers make such errors.

Data Collection

Following IRB approval and consent procedures, we conducted interviews with six focal students selected to have a broad but representative range of perspectives and identities (Table 4). Semistructured interviews lasting twenty to thirty minutes were recorded and were automatically transcribed by Descript software before being corrected by the researchers.

Table 4. Focal Student Demographics and Research Experiences

Pseudonym	Demographics and prior research experiences
Mateo	Latino, concurrent research experience at a national lab
Susan	Asian woman, nontraditionally aged, completed a summer research internship at another university
Emma	White woman, nontraditionally aged; no prior research experience
Dinesh	Latino and South East Asian, nontraditionally aged first-generation student; no prior research experience
Lien	Asian woman, ESL learner and international student, prior research experience at the university and at a national lab
Sophia	Latina, nontraditionally aged, took a break from college, concurrent research experience in course instructor's research lab

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The interviews took place at two points—after students presented their initial ideas to the instructors to capture how they viewed the agency of the design of experiments process and after they had completed initial data analysis to understand how they viewed the execution of their design and the results they collected. The interviews focused on students' prior research experiences and their perceptions of agency and opportunity structure of the CURE (Table 5).

Table 5. Interview Questions Probed Students' Prior Research Experiences, Perceptions of Opportunity Structure of the CURE and Their Agency

Prompt
Do you do research in a lab outside of class?
On the first day of the experiment, how did you figure out what to do?
How did you make decisions about what catalyst to use?
How did you decide on the operating conditions?
To what extent did [the TA/the instructor] support you?
Did the experiment go to plan?
What was the result?
How did this experiment feel like research in a real research lab?
What would you suggest changing in the future?

We conducted approximately 75 h of observations over the course of the semester. One researcher took field notes by hand, including quotes from students and observations of student interactions with the instructor, teaching assistants, and peers. Observations included all consenting students as they oriented to the tasks on the first day and as they completed the experiments. Additionally, we observed the prelab sessions for focal students.

At the end of the semester, students completed a short written reflection during class for completion credit (Table 6).

Table 6. Student Reflection Questions

Question (and answers if applicable)
To what extent did this experiment help you understand what research is like?
What decisions did you make and how did you make them?
What should stay the same?
What should be changed?

The instructor allotted 15 min for the activity, though some students chose to continue working at home and turned their responses in at the end of the day. Students completed this reflection at the end of the semester to support them to consider their experiences with greater context and to allow the most prominent and lasting aspects to be foregrounded. While we might have collected such reflections immediately after they completed the experiment, the time delay allowed us to access more durable memories.

Data Analysis

We conducted first cycle analysis of interviews and written reflections through in vivo coding,[50] a technique that emphasizes developing codes expressed in participants' own words. The first author developed initial codes from emergent themes based on observations and learners' comments: anxiety over lack of direction; frustration at the instructional team; calls for more support; things can go wrong; valuing freedom; pride in decisions; connecting to ongoing research; it is real life. The first two authors discussed these codes, and the second author conducted second-cycle axial coding,[50] rereading all data, looking for dis/confirming evidence, and seeking relationships between initial codes, which they organized into themes (Table 7), which were drawn from the conceptual framework. Specifically, the opportunity structure of CUREs creates uncertainty for learners[31−33] especially when they fail to find traditional supports; endemic supports, like help-seeking, and the varied ways they use expertise position students as agentive,[41] especially in light of the potential for failures in CUREs, providing opportunities for learners to develop toward more central roles as researchers.[42]

We then employed elements of discourse analysis to attend to students' agency.[1,34,51] Specifically, we characterized the level of agency/control of verbal clauses in terms of the subject and verb type, using Excel formulas to automate much of this analysis (Table 8), a process that requires human correction to distinguish between generic and specific uses of "you", instances where "you" is an object rather than a subject, instances where there is no verb, and to classify nouns that are the subject of a sentence. More specifically, we adapted a prior agency toolkit[1] that drew attention to ways speakers express and mitigate their agency via the subjects and verbs they use. For instance, a student could describe their laboratory experiment in one of the following ways: "We tested the impact of different temperatures on the catalyst"; "The experiment was about the impact of different temperatures on the catalyst"; or "We had to test the impact of different temperatures on the catalyst." The agency toolkit clarifies that these statements are not equivalent, and that attending to ways speakers mitigate their agency, such as by using passive voice or attributing agency to an unnamed instructor, provides insight about speakers' views of their role in these contexts.[1] Our prior work built on this, extending the agency toolkit into

Table 7. Themes in the Interview and Reflection Data

Level	Description. Student Discusses:	Example
Negotiating uncertainty	The ambiguity of the task or articulates emotional or regulatory responses	"It was confusing"
Endemic supports	Help seeking and other supports present in authentic research	"It's just up to the students to ask questions"
Traditional supports	Supports received in prior cookbook style experiments, such as video intros, procedures	"if there's videos or there's really, really crystal clear, easy to understand explanations"
Positioning in relation to expertise	How they used sources of information and the role of their experiment in knowledge production	"We are going to go with the one that [TA B.] is working with, rather than the one we picked based off the literature. [···] I mean, catalysis, that is his expertise. "
Failure is endemic	That failure is endemic to the research process, and even a learning opportunity	"That's just experiments. That's how science works."
Purpose of CURE	That engaging in the CURE provided a chance to try to prepare them for professional practices	"You have to kind of prove yourself, that you can make it out there in the world. So I understand why—why we did this."

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Table 8. Level of Agency Based on Subject and Verb Type

Level	Subject and verb types	Example
High individual agency	First person singular pronoun, nonmodal verb	I do this
Individual framing agency	First person singular pronoun, modal ability verb	I could do it
Designated control	Second person pronoun, modal obligation verb	You must do it
Invitation to another to take up framing agency	Second person pronoun, modal ability verb	You could do it
Indicated control	Second person pronoun, nonmodal verb	You do it
Shared agency	First person plural pronoun, nonmodal verb	We do it
Shared framing agency	First person plural pronoun, modal ability verb	We could do it
Low distributed potential agency	Third person subject, modal ability verb	It could
Low distributed agency	Third person subject, modal obligation or nonmodal verb	It is/It must
Offloaded/no agency/control	First person pronoun, modal obligation verb	I/we must do it

science and engineering learning settings, where some forms of mitigation are highly valued; specifically, using modal ability verbs like could, should, and might indicate a tentative and open stance that is helpful when scientists or engineers are negotiating about possible problems to investigate or potential solutions.[34] Termed *framing agency*, this form of agency involves making decisions, with others, that are consequential to the work being undertaken.

Finally, we brought these methods together to consider what the students expressed agency over, with whom they shared agency, and in what situations they offloaded their agency. In our results, when sharing transcript, we use color, as defined in the transcript, to draw attention to sentence subjects and modal verbs aligned with the levels in Table 8, as these are among the clearest markers of agency in discourse.[7]

Trustworthiness and Positionality

To enhance the trustworthiness of our interpretations, we relied on several typical approaches: long-term engagement, individual coding, member checking, peer scrutiny, and triangulation.[52] We shared preliminary coding with a peer who validated that the findings were reflected in the data. We independently reviewed transcripts and coding and then discussed our interpretations, refining code, and theme descriptions. We discussed preliminary findings with the course instructors to better understand whether our interpretations comported with their experiences. We shared our interpretations directly with interview participants over email, asking them to offer feedback and corrections. Three participants responded to the member checking; they reported that our interpretations accurately represented them.

We also position ourselves in relation to this study.[53,54] The first author (they) is a PhD student in learning sciences with a background in chemical engineering. They support several core courses throughout the undergraduate curriculum, acting both as a researcher and as a conduit for issues between faculty and

Negotiating uncertainty

Emma: So I think that it was confusing to an extent about like, what was the point of the experiment? [...] It's like, is, are we supposed to be picking the best catalysts or are we just supposed to be evaluating the properties of the catalyst that we do choose? [...] Like just give us the work so we can do it. [...] I think all throughout the degree, people are really scared to be the dumb one and be like, "I don't understand how this math works."

Susan: It's definitely more, um, kinda like thrown out there to the wolves kind of thing. [...] So comparatively to the other labs though, there's always somebody, especially like the TAs sit there and like, kind of like, hold your hand the entire time. Um, whereas this time, no, there was no, no handholding. Yeah. No hand holding.

Lien: So we were a little bit confused. Like, which catalyst? [...] I think we didn't really understand what we were supposed to do. We picked the catalyst we thought would be best? [...] I mean, it feels a bit disorganized because we are not used to this. And not having to turn stuff in at a time. We are just not used to it at all. [...] But yeah, this is an interesting approach. I feel like we were not very prepared.

Dinesh: We sought out the TA and, um, he, uh, was working with another group on helping them run their lab experiments. And then, uh, we kinda. I didn't know. When we got in there, we didn't know, okay. Do we go over there? Do we stay at the table? What do we do? It, it was kind of like, there's no structure to it, which was a little alarming to me. And so we just went over there and we introduced ourselves to him. And, um, he kind of tried to run us through the experiment. [...] It's just, um, there should have been something like a structure on what to do. Uh, like, okay. So like you, you walk in there, do you, do you wait at the table? Do you go meet with the people? [...] Um, it just feels like there's a little bit, no direction, you know?

Mateo: And, um, yeah. And then I guess then the next thing was we realized, or we, yeah, we, we needed to pick a catalyst.

Sophia: I was just confused about how well we were going to, um, measure and what our results were.

High agency marker. First person singular subject
Shared agency marker. First person plural subject
Framing agency marker. Verbs show potential control
Low agency marker. External person/object subject
Low agency marker. Verb indicates lack of control

Figure 1. Color-coded transcript from focal students about how they perceived the ambiguity of the CURE. The same key is used throughout the figures.

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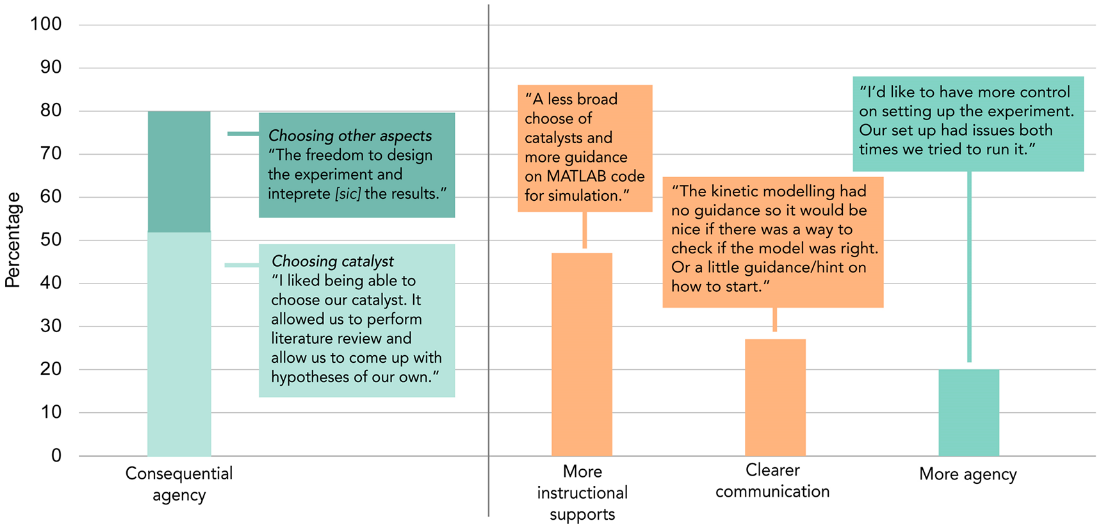

Figure 2. Students jointly wanted more supports and more control

students, resulting in established relationships going back to the first course of the program.

The second author (they) is an associate professor with appointments in the learning sciences and chemical engineering. They collaborate with chemical engineering faculty to support them in designing, implementing, and studying the impact of pedagogical innovations. They coinstruct the first-year course, creating an opportunity to build a relationship with students.

The third author (he/him) is a second year PhD student in chemical engineering who works in the research lab of the fourth author. In the role of teaching assistant, he brought his own research experience to bear, aiming to position students as coresearchers. His experience supported him to provide expert guidance to students and offer insight into what working as a research assistant is like.

The fourth author (he/him) is the department chair of chemical engineering and course instructor. He has collaborated on engineering education research, in addition to his technical research on catalysts, including renewable energy and single-atom catalyst behavior. He was also the instructor of the introductory course and had built an early relationship with students.

■ FINDINGS

To understand the results as they relate to the study aims, we discuss our results with attention to students' reflections and comments about (a) uncertainty, (b) instructional support, (c) failure, and (d) legitimate expertise in sequence, drawing interpretations about their perceptions of agency and the opportunity structure. Specifically, we discuss the varied reactions we identified as students reflected on the CURE and how they used their agency across these: they recognized and navigated uncertainty; they wished for traditional supports as well as recognized endemic supports; they recognized failure as endemic to research; and they positioned themselves in response to researchers and expertise.

Negotiating Uncertainty

All of the focal students reported negotiating uncertainty in the CURE (Figure 1), and this trend also showed in the students' written reflections. Students' comments speak vividly to the ways they experienced the increase in opportunity structure and decrease in oversight. One student explained, "This experiment helped me understand how you start with no guidance and must know what equations are needed to model the process."

In reflecting on the uncertainty of the experiment, most of the focal students used the plural personal pronoun "we," which is indicative of sharing agency with peers. This aligns to past research on how students manage their uncertainty by relying on collaborators.[33] They expressed uncertainty about the nature of the task, the instructional approaches, and their roles in the process. Emma, Lien, and Mateo offloaded their agency onto the task, mitigating their agency using verbs showing a lack of control (i.e., supposed to, needed to). Such expressions reveal much about their expectations—built from prior instruction (evidenced by students references to "the other labs"; "we are not used to this")—that they should not have such consequential agency.

Despite concerns about their uncertainty, many students reported that they appreciated the ability to make consequential decisions. Emma articulated this with "I liked having the freedom, to kind of decide what it was that we wanted to do. And kind of, you feel like you're running your own experiment." Similarly, in the reflections, students explained "the freedom to design the experiment and interpret the results" and "being able to choose our catalyst. It allowed us to perform literature review and allow us to come up with hypotheses of our own." In this way we noticed a tension develop between valuing the lack of oversight and being concerned by it (Figure 2).

Typical and Endemic Instructional Supports

In response to the uncertainty, students reflected on their desire for greater support. Most of the focal students named specific supports misaligned to the CURE (Figure 3). This included requests for clearer instructions and direction, be it in the form of feedback or guidance such as videos of how to do the experiment (something provided in previous lab courses). This was communicated by most students' use of the higher-agency first-person singular pronoun "I" paired with lower-agency third-person subjects. In such requests, we noticed a desire to enter the laboratory well-prepared, something students were able to do in prior courses; in the context of a CURE, they were unsure how to demonstrate their readiness,

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Wanting more typical supports

Emma: Honestly, I like, like prompts and straightforward. Like, this is what I want, is structured. It's easier. [...] At least letting them know, like this model is not correct so you need to work on it before you compare your data to it.

Susan: I do wish that we also had a video, like an intro video, like we did with, uh, with [the lab manager] in the other labs. [...] There wasn't any real intro to any of these labs this time around, which is a big difference from the other ones. So I honestly didn't really know what I was doing. Like even, I didn't know what to research.

Lien: The description is a little bit vague. So um, talking to the other group—the one that did it before us, the other group didn't understand it well—confused me.

Dinesh: I think [there] should have been a video or something like, um, there was in a previous semesters. [The lab manager]—he did like some videos introducing the apparatuses and all that stuff and exactly pointing out what, everything. [...] [Dr. D.] gives us a chance to correct something if we made a mistake. [...] Explain this as the easiest way possible. So then you know it. No—there's no confusion. [...] Like I said, if there's videos or there's really, really crystal clear, easy to understand explanations of things, you know?

Mateo: I think a little more guidance on the MATLAB model? [...] Just saying, "Make a model of this system," expecting us to know how to do that based on our reactors engineering class.

Sophia: At least having a, like telling us what we're going to get out of the GC so that we know what we have to work with. Because without knowing that we get area counts and mole percent, then it's like, okay, well, what are we going to do with all these numbers? And we have equations, but it's like, what do we do with the equations and these numbers?

High agency marker. First person singular subject
Shared agency marker. First person plural subject
Framing agency marker. Verbs show potential control
Low agency marker. External person/object subject
Low agency marker. Verb indicates lack of control

Figure 3. Most focal students distributed their agency when making requests for more typical supports that would have lessened the authenticity of the CURE.

given their past experience ("in the other labs"; "in a previous semester"). Students specifically referenced supports they had in prior classes and expressed that they expected or wished for those supports to be present in this course as well. This indicates that student expectations about this course were influenced by their experiences in prior courses.

In addition to wanting typical supports that would have narrowed the opportunity structure, students also recognized endemic supports that maintained the structure (Figure 4). Some students noted the context as a support. Mateo specifically indicated that the context itself as motivating, and others noted endemic feedback, as when Emma's model was "super weird," when Dinesh's experiment was not "going right" or, as Sophia suggested, that the published research could offer insight about the choices they should make. This finding extends past research showing that the context of CUREs can support student sense-making,[14,17,31] suggesting context might operate in more complex ways. In these expressions, students attributed agency to the context, displayed as consistent use of third-person subjects (e.g., "the model," "it"). Yet, this third-person subject as a feedback-provider is notably different from the instructor-as-feedback-giver, because *someone* must take action and have agency into order to make these objects yield their feedback; the models and apparatus remain as silent partners unless acted upon. By using third-person subjects that require an actor, we can recognize this as a dialogic,[55] meaning interactions depend on both entities participating.

Second, students realized that they could seek help. While help-seeking has long been studied as an indicator of metacognitive awareness,[41,42] we interpret these examples of help-seeking in light of recent work that positions help-seeking as itself a form of agency.[41] For instance, Emma and Lien, who most clearly articulated they should have done so more, both shared agency with their peers through the use of the first-person plural pronoun "we" and mitigated their agency somewhat in using the modal verbs "could" and "should." Sophia, in expressing a similar sentiment, attributed her agency to the context more generally. These linguistic constructions remind us of the risk students may perceive in asking for help, shaped by prior coursework, and especially in cookbook-style experiments, where not understanding the guidance provided would be interpreted quite differently. In the CURE, seeking help is, as Sophia indicated, up to and permissible for students to do. Indeed, these behaviors are common in effective interdisciplinary research teams.

Authentic supports and help-seeking-as-agency

Emma: We even presented our model at the pre-lab and no one really told us "That's completely wrong." And so it wasn't until the day of the post-lab that we figured out how to fix our model. And so we were getting all this data and the model was, like, super weird and didn't make a lot of sense. And so, I don't know, that was kind of hard, but then, um, I think, we could have like, maybe asked someone about it and probably gotten the help that we needed.

Lien: [The TA] did what he was supposed to do. He showed us the equipment. He also—he gave us pointers on which equations to use for our model. We should have used him more. [...] He gave us feedback on the presentation. Which is important if you go into research. You have to worry about stuff like typos and references.

Dinesh: So, I really appreciated that and how [the TA did] sort of help you work through the fact it wasn't going right. He was trying to do some, uh, diagnostic tests and trying to tell us, okay, drop it down to this temperature. Now, try it and see if it was happening.

Mateo: [The TA] kind of told us the things that we could change and gave us a little bit more of an idea about what we'd actually be doing. [...] We went through that whole, you know, going through that for each slide for 45 minutes. [...] I think a lot of the stuff that they were pointing out was not all of it, but most of it was kind of super surface level, you know? [...] And then we didn't even really get to talk about the actual experiment and what parameters we should change. 'cause like, one of the questions we were hoping to ask is like, "What are the reasonable flow rates to start out with?" [...] Thinking about like, why the, why, why we're doing it in terms of like, you know, acetylene removal for an industrial process. I think that was really nice. Put some context to it.

Sophia: I didn't have that much guidance because I mean, [our TA] didn't give me answers or he didn't like, tell me what to do. Right. It was just me asking him questions, trying to understand what I was doing. And then he would guide me towards me figuring out. So I didn't have guidance at all. [...] When I was [working on faculty research] in the lab, they would tell me, do this, do that, you know, just so I wouldn't mess it up. And he—it's just like, you guys have to figure it out. What we had to figure out—what temperatures we're running it to and why? Because we've—have research that backs it up. [...] Now it's just up to the students to ask questions. If you don't know about these, understand that. That's okay.

High agency marker. First person singular subject
Shared agency marker. First person plural subject
Framing agency marker. Verbs show potential control
Low agency marker. External person/object subject
Low agency marker. Verb indicates lack of control

Figure 4. Most focal students both shared agency with their team and distributed agency to instructors, the experimental context, and the published research in describing authentic supports and help-seeking

Failure is Endemic to Authentic Research

Just as help-seeking carries different meanings across settings, failure must be understood in context. In the cookbook experiments students previously encountered, the experiments were designed to go smoothly; in such situations, failure can clearly be attributed to the student as an indication of poor rule-following or comprehension. In a CURE, the complexity—the number of interconnected variables—paired with real (time, financial) limitations on the number times any experiment can be run situates failure not only as endemic but as expected. Indeed, none of the students' experiments went completely according to plan. Just as models and apparatuses can provide useful feedback, they can also offer confusing results. This was apparent in the focal students' abundant use of third person subjects in discussing failures (Figure 5). Dinesh and Mateo also expressed their own expectations and hopes in light of these failures, while Emma articulated failure as a learning mechanism. Even when students accepted responsibility for failures, they likewise noted the opportunity to learn, "This experiment and the problems that came with it (problems with our experiment design) showed me that in research we do not always arrive at an answer. My group learned from our mistakes, and we had to think of ways to avoid similar mistakes." And, in reflections, some students explained why their specific choice of catalyst was sound, even if it ultimately did not work—again affirming the endemic nature of failure. Our results align with research on CUREs showing that they offer opportunities for students

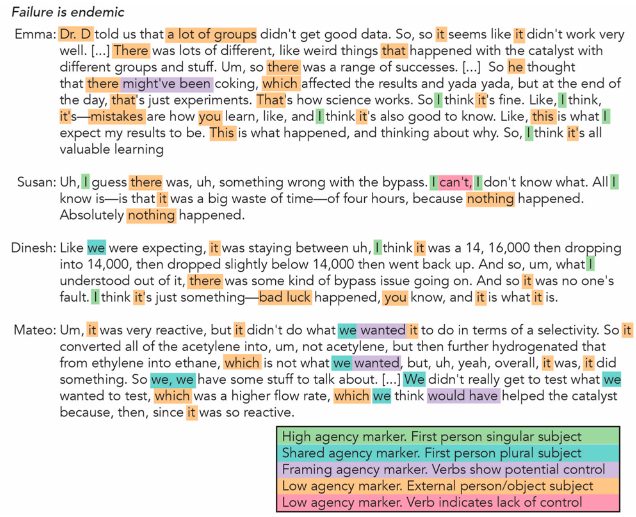

Figure 5. For those focal students who discussed failures, most distributed their agency, situating failures as endemic to authentic research, sometimes in tension with researcher aims.

to reinterpret the meaning of failure, especially as an indicator of authenticity.[45] We extend this by considering it as a tool for more specifically understanding student agency.

These experiences of failure speak to the fact that the instructional team did not occupy the traditional roles of making sure everything went smoothly, and indeed, they did not intervene to stop students from making choices that would not produce optimal results. In one case, a group discovered that the combination of catalyst they selected and the parameters they intended to test would not work together, and one student commented, “Are we expected to just know things? It is not like you can google this stuff.” Such comments reveal the tension formed by past interpretations of failure as sorting those who can follow complicated procedures from those who can—or simply do—not.

Students Positioned Themselves in Relation to Expertise, Taking up More Central Research Roles

Students demonstrated consequential agency in selecting a catalyst. No two groups picked the same catalyst, and many students became attached to the one they selected, evidenced by an outburst in the lab “Look! That’s our catalyst! That is so cool!” In taking up consequential agency, students showed both intention and excitement. The focal students’ comments about their decisions demonstrate that these were not straightforward. They described the ways their groups came together to make a catalyst decision, initially drawing upon their investigations of the published research but, in some cases, switching to a catalyst that was actively being studied by the instructors. Thus, they drew upon research conducted at the university, as well as in the wider scientific community. They used the literature to back up the decisions they made about parameters. For instance, Sophia explained how her group decided the temperatures at which they were planning to test the catalyst. Dinesh’s group took cues from the research going on just down the hall when he explained “It was based on [the instructor’s] work and we looked at that and saw it was successful and thought, okay, we’ll use that.” In a reflection, one student pointed out that the catalyst selection process “required extensive literature research and interpretation.” Across these examples, the students made decisions based not on textbooks but on published and in-progress research.

This deep dive into research also prompted many to realize that just because something is published does not mean that it is reproducible. In a written reflection, one student described the experience as “I have learned that just because it has been publicized [sic] it does not mean it can be replicated or that all the assumptions are correct and applicable.” Similarly, in the laboratory, one student commented to their teammate while looking at the results, “Well, that is not what the paper said. Well then.” In this way, the students engaged not only as consumers of research literature but critically, taking up more agentive roles in questioning that same literature.

Students’ engagement with the research process even resulted in many of them wanting to be more involved.[43] One student cited a constraint of the experiment as “We didn’t get to control the entire process, such as setting up the experiment.” Several wanted to be more deeply involved in the synthesis of catalysts and play a direct role in the actual creation of their materials. For instance, Mateo suggested a change to the lab could be “getting to see how that catalyst was made, because the big part of [the experiment] was picking the catalyst and then it just kind of just showed up out of nowhere, which, you know, it was made, it was made here.” This demonstrates a recognition that the things they are doing in the lab are not happening in a vacuum but as part of a larger system that they could engage in.

In articulating their roles, we again notice the focal students shared agency with their peers, using the first-person plural pronoun “we,” while also using third-person subjects that attributed agency to the body of published research (“There”), the researchers (“he,” “they”)—including their instructors, and to the catalysts themselves (“That one,” “the catalysts,” Figure 6). This helps us understand consequential agency not as individualistic but as negotiated, shared, and tied to the situation. Rather than aiming to offer students the most open-

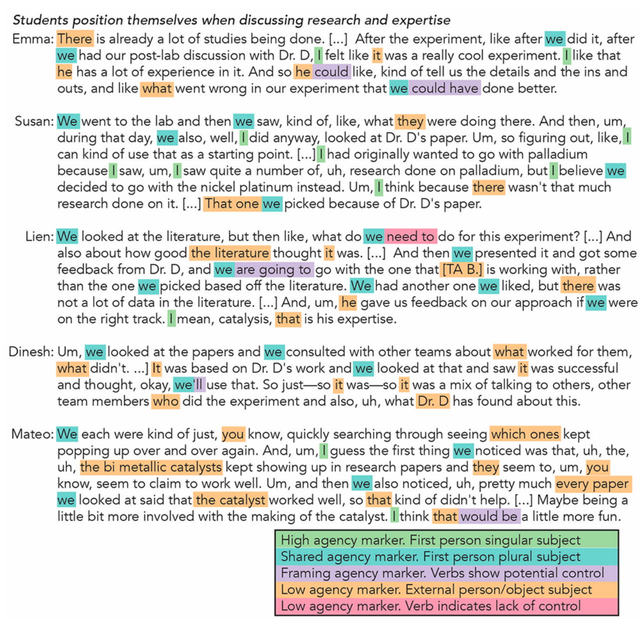

Figure 6. When discussing their roles in relation to research and expertise, students commonly shared agency with teammates and distributed agency to the research literature. Several expressed tentativeness, as they considered other possibilities for their research.

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ended opportunity structure and free will, our results suggest that comparatively constrained decisions—researching and choosing a particular catalyst and a few parameters (e.g., temperature and flow rate)—created an opportunity structure that invited consequential agency. Considered from the lens of learning as legitimate peripheral practice, such decisions bring students from peripheral into more central positions.[43]

LIMITATIONS

There are several limitations of this work. Chief among these is our singular and distinctive setting. Focusing on just one course in one institution allowed us access based on our rapport with the students and depth of understanding that supported trustworthy and credible results. Yet, our restricted focus may limit transferability in specific ways. The particular course and CURE relied on the expertise of the instructors and access to specialized equipment. As a one-credit, senior-level course, this course required a proportionally high number of contact hours from the instructional team, which may not always be feasible, and the outcomes may differ for the lower division or graduate courses. In addition, as a Hispanic-serving institution, our student population is unlike a majority of research universities; in recruiting focal students, we found nontraditionally aged students more willing; and our department, in part because of a concerted effort to use teaching innovations, includes many more students from groups minoritized in STEM compared to many programs. While we valued the opportunity to investigate the impacts of our approach on such students, it is possible that their engagement was inextricably connected to these other characteristics. Our analytical approach does not include a focus on linguistic differences that may be due to learning English as a second language; it is possible that those who learned English as a second language could use modal verbs to match their native language norms. However, all but one of our case study participants were native English speakers or raised as bilingual speakers with English as their home language.

IMPLICATIONS AND FUTURE DIRECTIONS

Using the methodology of case study to understand students' first experiences with a CURE, we found that students' prior experiences with cookbook-style experiments shaped their expectations, evidenced by requests for typical supports that would have misaligned with the CURE. An implication of this finding is that instructors can anticipate those expectations and support student participation in the CURE in several ways: First, they can explicitly explain how the CURE differs from past experiences, drawing attention to the fact that the outcome is not known, that there are multiple acceptable ways to design the experiment, and that even "failed" experimental outcomes can be valid research. Second, they can support students to negotiate the uncertainty of the CURE by specifically modeling that uncertainty and failure are endemic to research. Third, instructors can engage students collaboratively and legitimately, leaving consequential agency with the students, such as by asking students about their reasoning rather than directly answering their questions.

We also found that students recognized that the CURE context offered support, that help-seeking was itself a form of agency, and that failure is endemic to research rather than an indication of self-worth. Students positioned themselves as legitimate and capable research collaborators. Participating in the exploration process was deeply rewarding for students, many of whom either did not have the opportunity to participate in research outside of class, or used their experiences outside of class to inform their assessments of this course. Future studies may address the limitations of our work by contrasting our interpretations with their own and especially in light of the ways instructors aim to offer an opportunity structure that students perceive of as inviting their agency. Of particular interest that studies might contrast students' recall and assessments of the consequentiality of their decisions immediately after making them, and after a time delay, as was the case in our study; such studies may reveal additional impacts of immediate reflection upon their later recall of decisions, in line with research on distributed practice and spaced recall. Future studies might investigate whether CUREs set earlier in degree programs prompt similar expectations for well-structured problems. Our approach of using a discourse toolkit and highlighting subjects and modal verbs that are markers of agency in the transcript can be adapted for other studies using similar techniques. Additional studies are also needed to investigate differences in discourse that might be systematically present for non-native English speakers.

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Notes

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