Students' Experiences with the Science and Engineering Practices in a Workshop-Based Undergraduate Research Experience

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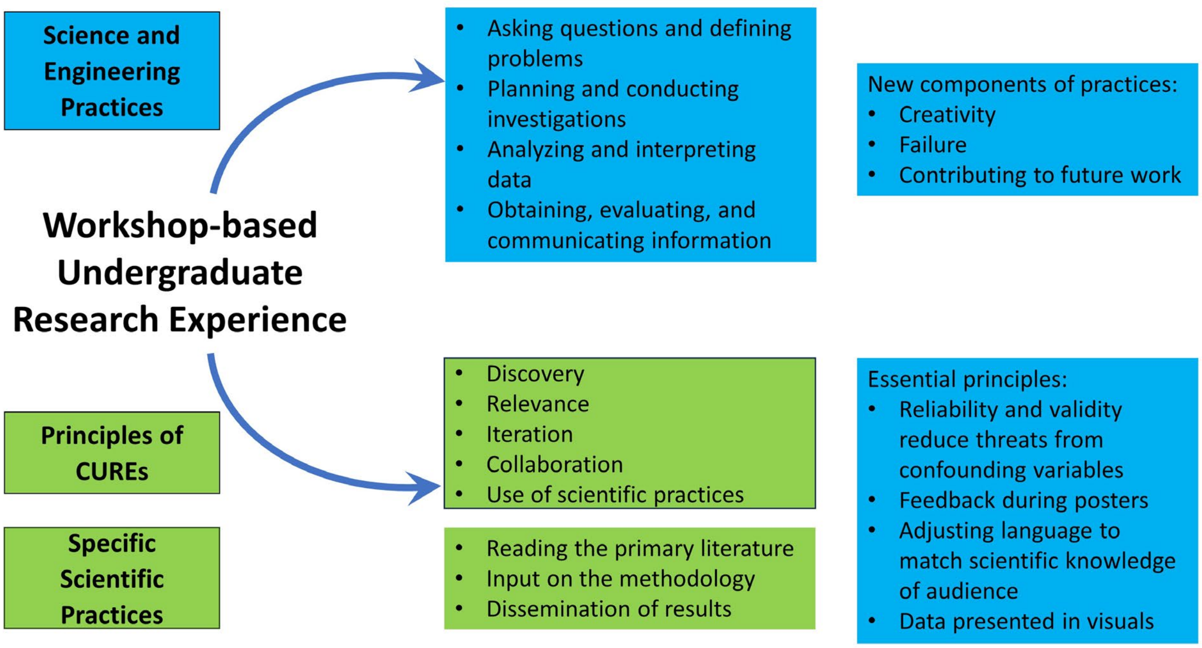
KEYWORDS

Biochemistry; Laboratory Instruction; Inquiry-Based/Discovery Learning; Proteins/Peptides; Meaningful Learning; Phenomenography; Situated Cognition; Science and Engineering Practices; Course-Based Undergraduate Research Experiences; Chemistry Education Research

ABSTRACT

This paper presents a phenomenographic investigation on students' experiences about research and poster presentations in a workshop-based undergraduate research experience with a focus on how the experience connects to the Science and Engineering Practices (SEPs) of the NRC *A Framework for K-12 Science Education* and the principles of CUREs. This provides insight into how these structured research experiences reflect particular SEPs and also elements of scientific practice that are not captured in the SEPs as they have been formulated previously. This work showcases the importance of future applications, failure, and creativity as additional science practices necessary for students to engage in authentic science. The SEPs and the additional elements of scientific practice are related to how students experience meaningful learning in the cognitive, psychomotor, and affective domains. Students highlighted the components of CUREs: importance of contributing relevant discoveries as a motivation for their research, the value of repetition and iteration in ensuring reliable and valid results, and the role of collaboration in seeing new perspectives and solving problems. As a result of presenting their results through a poster, students reported deeper understanding of their research topic, increased ability to articulate scientific concepts, and a better understanding of how to create a visually appealing poster. Students changed the vocabulary they used in their presentations to fit the knowledge level of their audience and highlighted their data in figures and explained other parts of their work in text. Moreover, they saw the poster as an outlet for their creativity.

GRAPHICAL ABSTRACT



INTRODUCTION

This article describes an examination of students' experiences in a workshop-based undergraduate research experience[1] with the lens of the Science and Engineering Practices (SEPs) of the National Research Council's *A Framework for K-12 Science Education*[2] ("NRC *Framework*") that constitutes a basis for the *Next Generation Science Standards* (NGSS).[3] Our previous work used the frameworks of meaningful learning, situated cognition, and phenomenography to create an outcome space across three cross-cutting themes to describe students' meaningful learning in a summer workshop based on the principles of course-based undergraduate research experiences (CUREs).[4] That analysis gave additional insight into how early research experiences may contribute to STEM retention and graduation.[5–10] In this study, we use the same methods with students from a subsequent implementation of the program. In addition to elaborating the previous outcome space, we also examine how experiences across the outcome space reflect and, as we will discuss, go beyond the SEPs. In this case, we are able to gain insight into how the students' participation in particular practices relates to their overall experience. We also note where specific elements of science practices that are not emphasized in the SEPs may be important.

THEORETICAL FRAMEWORKS

As discussed in the prior study, three frameworks have been used in our work: situated cognition, meaningful learning, and phenomenography. Here we recap those and then provide a description of the additional framework of SEPs that are the focus of the present study.

First, the framework of meaningful learning is used to structure our analysis of learning that occurs at the intersection of the cognitive (thinking), psychomotor (doing), and affective (feeling) domains.[11] In order for meaningful learning to occur, the learner must possess relevant prior knowledge, the new knowledge must be taught in such a way as to connect to their prior knowledge, and the learner must make a conscious effort to connect the new knowledge to their prior knowledge.[12]

Second, situated cognition describes how context influences learning.[13] In a structured research experience, this is done through scaffolding or problems that allow students to experience the messiness and uncertainty of real research instead of simply following a procedure in a lab manual.[13,14] Situated cognition is also the basis of key components of CUREs that differentiate them from traditional lab experiments: use of scientific practices, collaboration, iteration, discovery, and relevance.[15] This assumes, then, that CURE experiences align with the authentic practices of science. Recently, Buchanan and Fisher proposed that authentic scientific practices of CUREs may be further subdivided into: students select the hypothesis, students design the methodology, students review the primary literature, and students disseminate the results to determine which specific scientific practices are used in the CURE literature.[16]

Third, the *NRC Framework* notes the importance of seeing science as a multi-dimensional activity that combines disciplinary core ideas, cross-cutting concepts, and science and engineering practices.[3] The SEPs were developed to stress specific competencies that are important in both the conduct of science and in developing an understanding of science. The practices are asking questions and defining problems; developing and using models; planning and carrying out investigations; analyzing and interpreting data; using mathematics and computational thinking; constructing explanations and devising solutions; engaging in argument from evidence; and obtaining, evaluating, and communicating information. These are critical steps in constructing scientific knowledge and judging its usefulness in solving real world problems. Buchanan and Fisher also point to the need to examine CUREs for the presence of SEPs, which could strengthen claims about whether CUREs provide an authentic environment for the development of situated cognition about authentic science.[16] This will complement the recent paper in the *Journal* by Walker *et al.*[17] that examined CUREs from the framework of a Community of Practice, originally developed by Lave and Wenger.[18,19]

Finally, we continue to use phenomenography as the methodological framework as a way to describe participants' collective conceptions of a phenomenon.[20] This is done by creating categories of description that describe themes in an outcome space.[20] Phenomenographic outcome spaces may be organized as a developmental continuum ranging from simpler to more complex conceptions of a given phenomenon.[20–22] The present study describes a developmental outcome space that covers our three theoretical frameworks of meaningful learning, situated cognition, and the SEPs.

RESEARCH QUESTION

This article explores the research question: How are science practices, including those listed in the SEPs, present during the meaningful learning experienced by students in a workshop-based undergraduate research experience?

METHODS

DATA COLLECTION

We have previously described the overall structure of the CoLab program, a multi-week workshop for entering college students, that addressed topics ranging from the chemistry of fluorescent indicators to modeling extracellular electron transfer to, during the pandemic, modeling of inhibition of amylase by food-based molecules.[1] We further reported on student experiences to gain insight into their meaningful learning.[4] In the current study, we examine a group of students who participated in either six weeks of research (once a week) during the summer of 2022 or three days of research during January 2023 on a project related to cancer biochemistry: isolating and characterizing actin from tilapia following on previous work from Konno *et al.*[23] and others.[24–26] After a common set of experiences involving creation of acetone-dried microfibril (MF) powder and purification of pure actin from MF powder using ammonium sulfate, students were prompted to do research on the actin material. Some did research on "*in vitro*" studies using techniques including gel electrophoresis, size exclusion chromatography, fluorescence, and more. Other students did "*in silico*" studies using computer coding experiments centered on visualizing the interaction of actin with D-binding protein using *PyMOL*.[27] The program culminated with a poster presentation to faculty and other students not involved in the program in which students described their research (see the Supporting Information for more information on the structure of the summer 2022/January 2023 CoLab Program). In addition, this program was done in person, whereas the previous study reported on students who did their work at home.

Thirteen students (10 from the summer 2022 CoLab, 3 from January 2023) consented to participate in the study. Recruitment scripts and consent forms were approved by the university's Institutional Review Board (Study 2021-0457). All consenting students completed the Views of Nature of Science Form C (VNOS-C) survey and then participated in a semi-structured interview via Zoom.[28] We revised our previous protocol[4] for improved clarity based on student feedback and to ask about students' understanding of the steps involved in research, the importance of repetition and iteration within research, and the feedback that students received from others during the poster session, which is the focus of the current study (see Supporting Information). Another section of the interview made use of the affective word matrix from Galloway *et al.*[29] to probe students' affective experiences.

DATA ANALYSIS

Survey results were downloaded from Qualtrics.[30] Interview audio transcripts were downloaded from Zoom. The transcripts were read over by the first author and corrected for any spelling and/or grammar errors. Students' names were replaced with gender-neutral names as pseudonyms (see the Supporting Information for the full list of students).[31] These names were chosen as pseudonyms so that participants could not be identified by race or gender. All survey and interview data was then imported into MAXQDA 2020.[32] Any interesting information pertaining to students' views of what research is, the steps involved in research, students' gains from the poster presentation, and feedback received from the poster presentation was coded.[15] This was done in a manner that followed the outcome space of our previous work. The outcome space is structured as a matrix with cross-cutting themes intersecting with categories of description aligned with the framework of meaningful learning. In keeping with previous developmental outcome spaces presented in the CER literature, less desired perceptions are presented to the left and more desired perceptions are presented to the right.[4,22] Three categories of student experiences were identified from the phenomenographic analysis: the CoLab experience enhanced, impeded, or had no effect on students' meaningful learning.

In addition to using the previous outcome space structure, this new set of data was characterized with codes to reflect the SEPs as presented in the high school grade band for Appendix F of the *NGSS*. Coding was generally done at the level of the overall SEP but, for the practices of Planning and Carrying Out Investigations and Obtaining, Evaluating, and Communicating Information, we created sub-codes for data collection and designing investigations as well as literature review, looking at what's already been done, and dissemination of results, respectively, to underscore that there are different ways that these practices appeared in different parts of the workshop.[16] Coding occurred until saturation, meaning that no new codes were created from the data.[33] A second coder who was not involved in the CoLab Program also went through the transcripts and coded 15% of the data using the code book. Intercoder agreement was 75%. All discrepancies were resolved through discussion between the two coders until 100% intercoder reliability was reached. Similar codes were then grouped into themes through the process of thematic analysis.[34] These themes have already been previously described.[4]

In this article, we use this data and analysis to provide additional insight about two cross-cutting themes. This further enhances our previous analysis and provides a full set of examples across all categories of description that we previously presented. We then extend our analysis by connecting students' experiences within these two themes with the *Framework's* SEPs and, as will be discussed, additional practices that were important to the students.

RESULTS

Student experiences within the outcome space

Table 1 presents the results of our phenomenographic investigation of the students' experience, using the categories and two of the themes developed in our earlier work. We also provide illustrative definitions and quotes for each theme. As an initial indication of student experience in the program, we also used the affective terms tool of Galloway *et al.*[29] (see Supporting Information).

The broad categorization of the outcome space in this new implementation matches that of the earlier work. The exception is that, with a larger sample size, we were able to characterize a student experience of having no gains in deepening their understanding of research due to the CoLab or of their research topic as a result of presenting their poster. Students from the Summer 2022/January 2023 CoLab also provided additional insights into their understanding of the research process by going into more detail regarding the steps involved in research and why reliability and validity are key components of research. They additionally discussed how collaboration allows people to view a problem from multiple perspectives. With respect to the poster session, these students also fleshed out the outcome space by commenting on how they changed their vocabulary to suit their audience and the importance of using visuals to display their results.

Table 1 Meaningful Learning Outcome Space Results

Cross-cutting theme	Meaningful Learning was Impeded Due to CoLab		Meaningful Learning was Neither Impeded Nor Enhanced Due to CoLab		Meaningful Learning was Enhanced Due to CoLab	
	Definition	Quote	Definition	Quote	Definition	Quote
How students viewed their understanding of the research process	Students had a limited understanding of the research process and the shape it took in CoLab.	Gabriel: “Oh, I feel like it was pretty low understanding, like I get the basics of it [research], but not fully grasp it.” Interviewer: “Okay. And when you say you get the basics of it, could you go into a little bit more detail?” Gabriel: “Like I get that we were looking at actin and isolating the various parts of the molecule. And that's essentially all I got from it.”	Students already developed an understanding of the research process prior to participating in CoLab, and the experience did not change their understanding.	Santana: “I knew how to work in that environment so much better. I didn't feel? I mean, I feel like the CoLab helped me to just get more of an experience from like some of that stuff, and then, like doing it again, it's still a really good practice. So um, I guess, it was still a learning process that I’m involved in.”	The CoLab environment deepened student understanding of the research process by making them aware of previous steps they hadn’t considered, different modalities of doing science, and the importance of reliability, validity, and failure in doing research.	Quinn: “Um, well, I definitely got to learn about like the UIC lab, and like all the different instruments, and like the technology that they have, because it's like completely different than what I am used to in like a high school or elementary school laboratory. So being able to know, like the very, like we got to pipette. I got to learn like different skills in CoLab and like, understand, and how to use like various

						systems like the computer system that we used. So, hopefully, I'm assuming that I'm definitely going to need to know pipetting skills and stuff and like in other research laboratories. So that's definitely a good skill to like know how to do beforehand."
How students viewed the poster creation and presentation process	Students perceived they did not gain much from the poster session in terms of deepening their understanding of their research topic, improving their speaking skills, augmenting their visual presentation	Santana: "My understanding was I don't think I got out of it [the poster session] what it [my research] meant."	Students already had prior experience with the poster creation and presentation process and CoLab did not add anything new to the students' knowledge in this respect and/or students reported mixed benefits in terms of	Yael: "Uh, I guess my understanding is pretty good because in high school, I did it a lot. So, it was kind of similar to that, because I had to do it for one of the clubs I was in, and we had to read papers and then, like, put it like in an abstract basically, and	Students perceived value in the poster creation and presentation process in terms of deepening their understanding of their research topic, improving their speaking skills, augmenting their visual	Quinn: "After explaining it, like the same thing over and like several times to the people that wanted to come and read, it definitely helped me grasp a better idea of what I had had done than like that I previously had. So being able to explain

	skills, and receiving feedback on what they could improve on in the future.		deepening their understanding of their research topic, improving their speaking skills, augmenting their visual presentation skills, and receiving feedback on what they could improve on in the future.	we had to make it look nice. So that's [poster creation and presentation] pretty similar to that."	presentation skills, and receiving feedback on what they could improve on in the future.	it was like definitely a big part of like me understanding it because sorry. Um. Before it was just I had done the work. I had written it down, but then I was actually able to like, passionately explain it to some other person. So that was kind of nice."

How students experienced the SEPs in the context of the workshop research process

In addition to providing new insights on themes obtained before, our process examined how the students report engagement in the SEPs and other practices of research, connected to students' understanding of the research process and their views of the poster creation and presentation process. In the interview, students were asked "What is your understanding of how a researcher investigates a research question? Please describe the steps in the process." That data was coded for elements of SEPs. CoLab students had a good grasp on many steps in the research process following the program, which is a new understanding gained from the updated interview protocol that was not seen in the previous study. A noteworthy difference in the reported experiences of these students is the focused discussion of carrying out specific kinds of steps, including asking questions and defining problems, planning and design of investigations, data collection, and data analysis. These steps relate to the CURE component of the use of scientific practices. Figure 1 showcases the SEPs involved in the research process mentioned by students during the interview. Figure 2 details more specific steps that students saw involved within the SEPs.

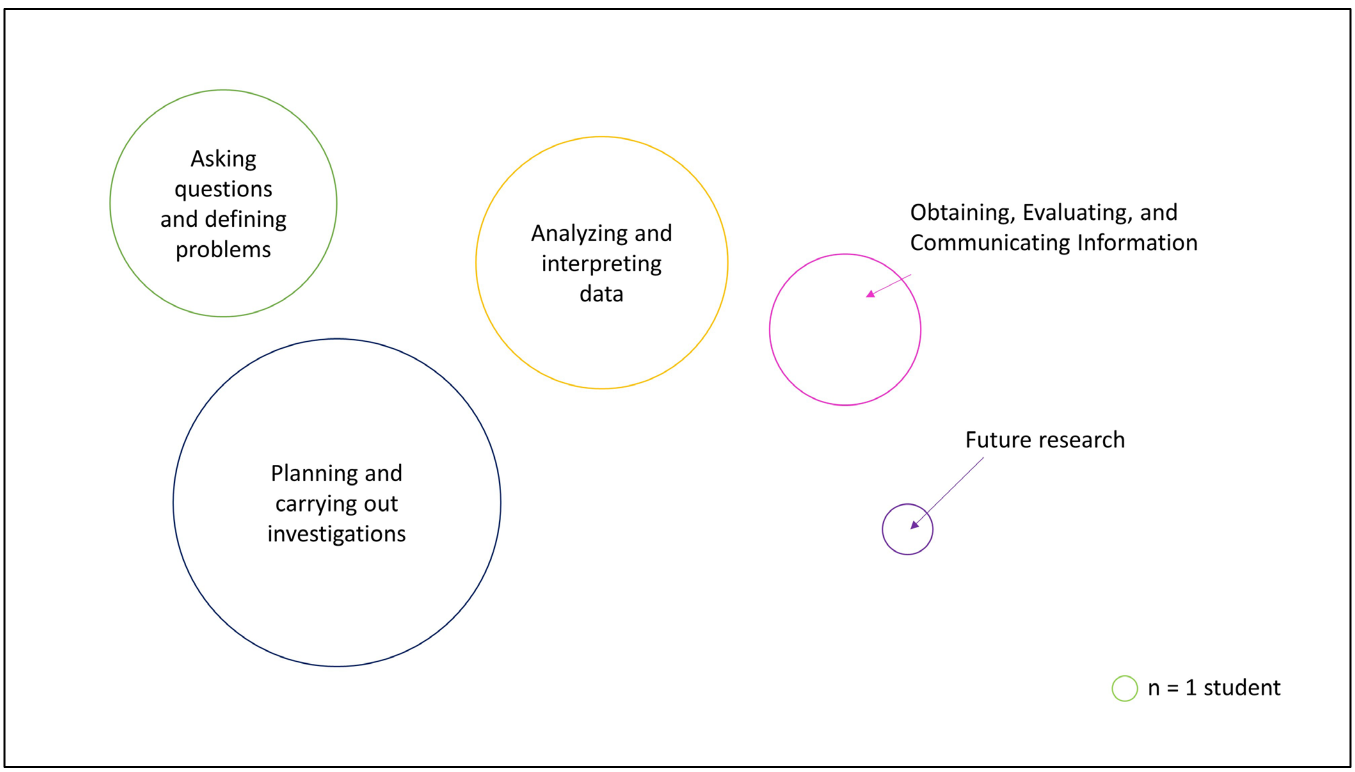


Figure 1. Science and engineering practices involved in the research process as described by students. The size of the circle indicates how many students mentioned a specific SEP during their semi-structured interview.

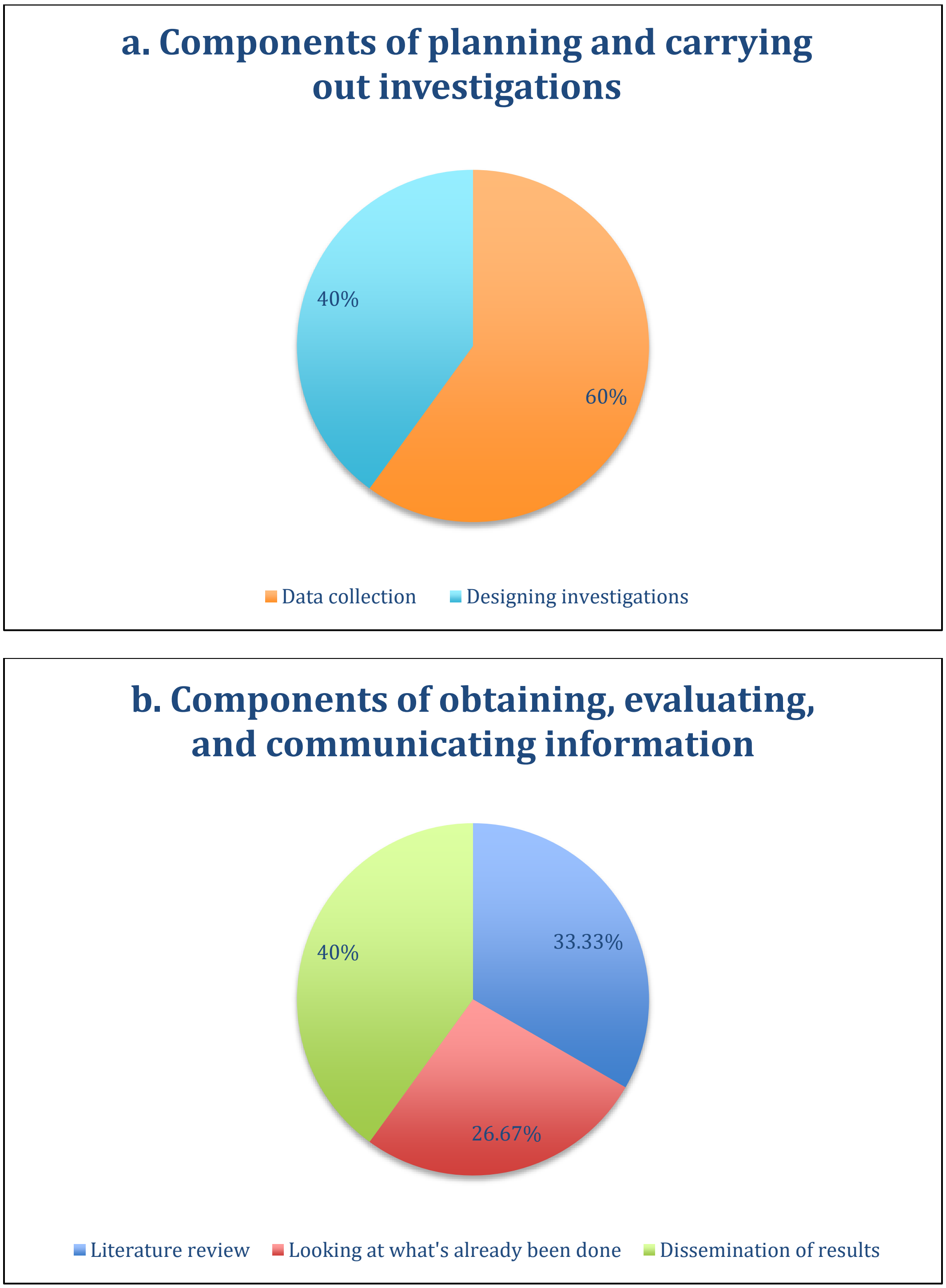


Figure 2. Steps in the research process as discussed by students within the SEPs of (a.) Planning and carrying out investigations and (b.) Obtaining, Evaluating, and Communicating Information. Pie charts display percentages of codes within each SEP.

The cross-cutting theme of the research process describes how students grappled with their understanding of the steps involved in research. Within this, we found several connections to the SEPs. The following student quote showcases an example of a student who mentioned the steps in the research process typically declared by other students in the program as well as the importance of looking at what's already been done:

> Wyatt: "So, I guess the first step for researchers is kind of finding a problem that they concern themselves with, something that interests them, and the next step would probably be to see what already exists on that topic, what research people have already done. And then, if they see that there is a gap somewhere in the research, or something that somebody hasn't really thought about yet, then they could use that and sort of make that their like primary focus and try to like fill in the gaps on what people don't know, and a lot of it I feel like is trial and error….at least, in the case of CoLab, we were trying to figure out how to make these reactions work, and people knew a little bit about them, people knew sort of what they were supposed to do, but nobody had ever actually gone through and done them over and over again to find what really works."

The above response highlights the SEPs of asking questions and defining problems, planning and design of investigations, and analyzing and interpreting data. CoLab students articulated that research begins with a question and one way to develop a question is by looking at the literature to see what's already been done and what's still not known. Then, researchers create methods to obtain data, for example experimentation, and this process may involve trial and error as steps are constantly repeated and iterated on. Once this is complete, researchers have to figure out claims supported by their data by making sense of the trends within their data set.

Students highlighted the significance of reliability and validity in ensuring that that the results they arrived at were consistent and truly measuring what they sought to measure. This is an important part of the SEP of Planning and Carrying Out Investigations. For example, this process involves accounting for extraneous variables to be able to arrive at causal statements:

> Haden: "So, something that was actually advised through this research that was done in the CoLab…sometimes there could be conditions that may cause the results to vary, and that is because you don't realize that there should something different impacting the results. So, this could be, for example, just using water without knowing the water could be impacting the

> experiment or its results in a different way from like, let's say water from another place. If you don't actually like, see if the water is the same being used. So overall just making sure that the results are consistent can help know if it's actually what you said for what you're experimenting on, it's actually the cause."

Another important part of Planning and Carrying Out Investigations is "testing solutions to problems." CoLab students needed to adjust their experimental conditions, whether that involved adjusting concentrations, pH, or temperature, among other factors. This is exemplified in the following student quote:

> Baylor: "Um, we followed, um, an experimental approach for what we did. We did the Bradford assay, and we modified it so that we could measure, uh, the absorbance. Um, but some of the quantities were either too large or too small for us to make sense of the data at the end. So, we had to adjust it as we went, which involved many trials….I believe it was one microliter um of what was it? Um, of fish pellets? Um, that amount was too small for us to take with the materials that we were using in the lab. So, we multiplied it by tenfold, for to some of them...that's done in labs often because we're limited to certain things, or we know that our numbers could be better if they were adjusted, or we don't know that, and we, we want to see different results."

While almost every student in the program benefited from gaining a deeper understanding of the steps involved in research as well as a first-hand experience with the messiness of doing actual research, two students already had prior knowledge of doing research, which meant that the CoLab did not change their understanding. One student reported not understanding what the research was about and described a very perfunctory overview of what research entails:

> Gabriel: "I view it as um, you would read up on scientific journals, peer-reviewed journals like, read those and then go out and do experiments. Yeah."

How students experienced SEPs in the context of the workshop poster creation and presentation process

This cross-cutting theme describes what students experienced in the process of creating and presenting a poster at the end of CoLab and also how they connected it to the SEPs of obtaining, evaluating, and communicating information and engaging in argument from evidence. In the interviews, students were asked about the poster process including with the question, "How would you describe your ability to communicate scientific concepts to others during the scientific poster session?" This elicited comments about both creating the posters and the experience of presenting the posters to others. An example of a student poster is shown in Figure 3.

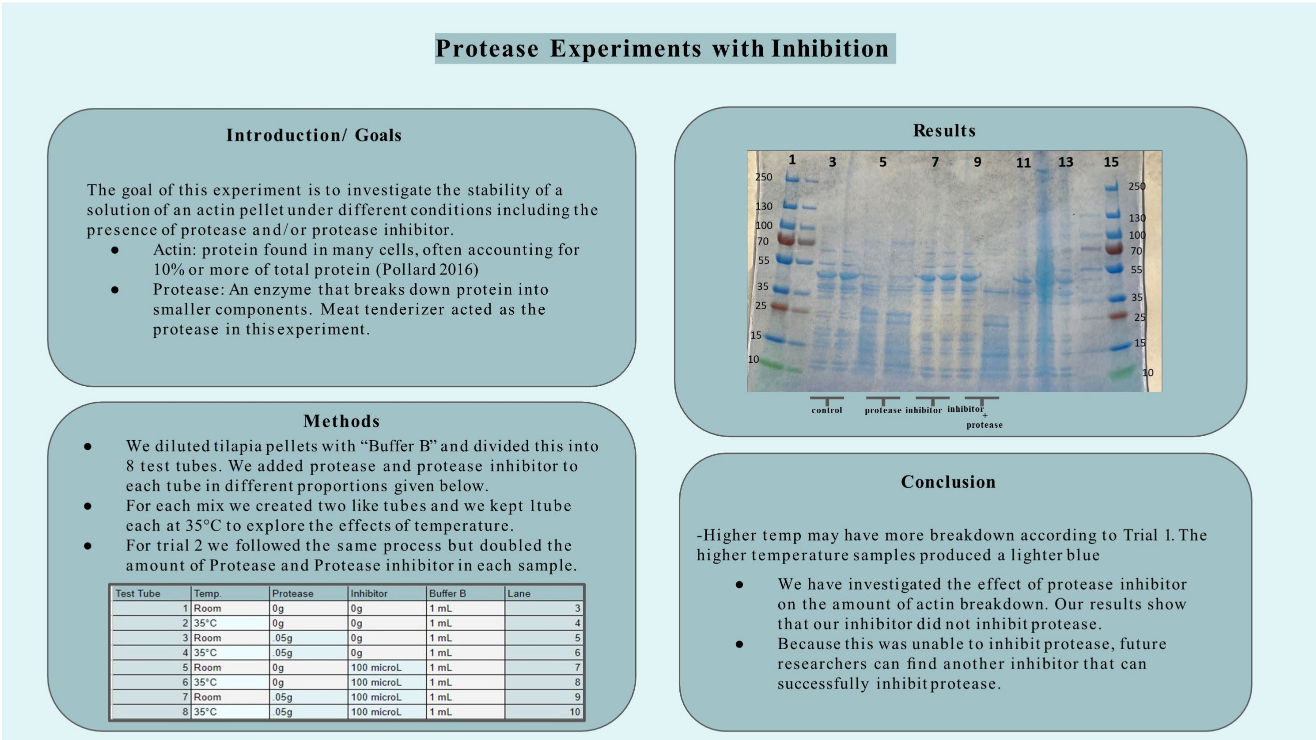


Figure 3. Example of a student poster from CoLab. All students were provided with a poster template with introduction/goals, methods, results, and conclusion sections that they were able to modify.

The vast majority of students discussed having a deeper understanding of their research topic as a result of the poster session. Some students stated that organizing all of the information together while making the poster deepened their understanding, whereas others attributed this deeper understanding to explaining their poster to others. This is shown in the following representative quote:

> Kadence: "After the poster session, I feel like I understood it way better than I did in the beginning, even though it was only like 3 days later. I do feel like there's still aspects that I need further clarification on. But I definitely feel that after the posters session it really helped, I don't know, it really clicked in my brain like what I'm doing, and its impact to like the research that we're part of."

Students also mentioned that they became better at using the appropriate language for their audience as the poster session progressed, which is a new insight gained from this group of students. They initially defaulted to using scientific jargon, but when they encountered people who were unfamiliar with their experiments, they improved at situating their explanation within the CoLab context by explaining concepts to a lay audience:

> Onyx: "Just put it into words that make sense that will stick in the brain that are accessible to all audiences."

Feedback was another aspect of the poster presentation that frequently appeared in interviews with the students. This feedback was always positive – not a single student mentioned that they experienced any negative feedback. Feedback ranged from future directions the students could take with their research to explaining things more clearly to the students to commenting about the poster being clear and visually appealing. The feedback that students received also allowed them to think about their research in ways they hadn't previously considered, to become more confident in their knowledge, and to construct arguments based on their collected data, which ties into the SEP of Engaging in Argument from Evidence. For example, students thought about how their research may be relevant to the broader scientific community:

> Wyatt: "I think at the poster section. Um. One of the first questions we got was 'Alright, but how did it? How does this tie into cancer research?' And at first I kind of had no idea. Um, I never, I didn't really even think of that. But somebody else in a different group, I think, said something along the lines of like 'Well, if we can, you know, build back muscle tissue, using thicker actin, if we could put this synthetically into people's muscles, then maybe it could help like prevent cancer or something.' And so we went online, and we searched it up, and our sort of thought process was, well, after chemo, people's muscles can be really like deteriorated and weak, so maybe we can use this as a treatment option, and, I think, somebody else who came to our table, also said something that, like maybe strengthening the actin, can help, you know, prevent or weed out cancer cells, and you know their cells are really weak, but the ones around them are strong."

Through communicating their knowledge with others, students engaged in creating new knowledge that is relevant to the broader scientific community, thus engaging in authentic scientific practices.

Beyond the Accepted SEP Elements

In our coding for what practices students reported in the context of the research, we noted three additional elements of scientific practice that are not, in our reading, clearly present in the SEPs, either as presented in the *NGSS* or as initially discussed in the NRC *Framework*. These are *connections to future research, failure,* and *creativity*. Here we present how students experienced those and then, in our discussion, we consider how these may be evidence for additional practices not covered in the *Framework*.

Several students highlighted that research involved *connecting to future research*, including new knowledge that could benefit the scientific community as a major distinction between the CoLab and previous labs they had completed in high school. This aspect of the CoLab also showcases student input into the research methodology that was not present in their earlier schoolwork. The following quote shows the perceived value across the cognitive, psychomotor, and affective domains to students of not knowing the result of an experiment beforehand and also needing to revise it:

> Yael: "Yeah. Well, like it was my first time in a lab setting that wasn't for like a school lab. So you didn't have like expected results. You're supposed to get something new. So it was interesting."
> Interviewer: "Okay. So could you elaborate a little bit on that last thing that you didn't have expected results?"
> Yael: "In like a school lab there's results like you have to get, or else you get points off. You know what I thought was interesting that we went into it, and we had to revise, and everything most times. But the school one, it's set exactly what you're doing. There was no like room to make a difference."

Students also appreciated their work as it tied into the larger question of cancer biochemistry:

> Marin: "…I know like what we were doing, it was somewhat related to cancer research because I think that the actin pellet, my understanding is that actin is a protein that, it's just found in like a lot of cells and specifically muscle cells, and that it helps with like mobility and structure of a cell. And I think that scientists are like hypothesizing now that actin can actually help cancer cells spread out from a tumor by like providing them with mobility. So that was interesting because it could someone correlate to cancer research, or something I like might want to do in the future and do more like experiments with like protease inhibition."

The *Framework*'s concept of science recognizes that science is important in addressing authentic problems and, of course, developing new knowledge. But, as these quotations indicate, for these students there is a close connection of research, applications to increasing scientific knowledge, and the relation to important problems which underscores potential avenue for future research that is relevant to the scientific community in a way that is not presented as a part of scientific practice in the *Framework* or is articulated in the listings of SEPs within *NGSS Appendix F,* even in the SEP of Obtaining, Evaluating, and Communicating Information.

Many students reported on their work towards reliability and validity, which in itself fits within the SEP of Planning and Carrying Investigations, which includes, in the high school grade band, one element (from NGSS Appendix F) of that practice is to "Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly." However, for many students there was a particularly important element of engaging with *failure* of some sort during their work that goes beyond that element of the SEP.

In this setting, most students were not afraid of failure and recognized it as integral to the research process. They worked together with each other in their groups and when they did not know how to proceed with something themselves, the students sought out additional assistance from the professor in charge of the program, the graduate teaching assistants, or other professors who stopped by during the course of the program as shown in the following quotes:

> Onyx: "Yeah, so I think that the first day that we were actually working on our experiments, for some reason, my group members did not get the kinds of fluorescence readings we should have been getting based on the amount of actin that was within each of our samples, there was no correlation when there should have been, so we took a lot of time to try to figure that out by lowering the amount of dye, and eventually, by lowering the amount of dye that we were using in our samples so that we could get readings that correlated with the amount of actin in our samples. So, I think, in short, when something didn't go well in CoLab, my group mates and I, we spent time looking at what we're doing in the procedure. Look at what was the problem, see if there was a link, and look at the procedure again and try to fix it a bit, not tweak it dramatically, to get better results."

Students' experiences with failure were also noted in the affective words they chose to reflect their experiences in the CoLab (see Figure S1). As was noted in our analysis of their responses to the affective word matrix from Galloway *et al.*, many students described becoming less intimidated, nervous, and anxious as the CoLab progressed, and they became more comfortable with their peers and the lab techniques used. Towards the end of the program, their confidence increased, particularly during the poster presentation.

We saw that students described what may be an additional element of scientific practice not included in the SEPs during the poster creation and presentation process: *creativity*. Students mentioned that creativity is necessary in terms of conducting science, and they related this to the choices they made in deciding how to carry out procedures and creating their posters. Students stated that the iterative research process with greater control over the procedure allowed them to showcase their creativity:

> Quinn: "So the way I saw CoLab was that I got to meet new people, and it was all completely new for me. So, being able to like create my own like instructions rather than like a teacher giving it to me allowed me to show my creativity."

Students expressed that the posters were an outlet for their creativity in terms of design and showing their knowledge to others:

> Kadence: "Yes, in a way, I did feel creative because, especially towards the end, when we were making the posters…I know there was like a kind of like a format of how we're supposed to have our poster. But we still had creative freedom, and I felt like being able to design the poster and show what I've done over the past few days. It was a way for me to show my creativity in that way."

Students engaged with elements of scientific practice that went beyond those elaborated as elements in the SEPs. They underscored the importance of doing future research, which connects to the authenticity of science in solving real world solutions. They engaged with failure to persevere through challenging situations and learn from them. Creativity allowed students to put their own spin on their data when deciding how to modify procedures and how to present their data on their posters.

DISCUSSION

The previous section provides valuable insight into the meaningful learning experiences of students in the CoLab program as connected to the SEPs of the NRC *Framework* and the *NGSS*. These findings will be discussed within the frameworks previously discussed and are graphically depicted in Figure 4.

New insights

- Students mention the SEPs of asking questions and defining problems, planning and carrying out investigations, data analysis and interpretation, and obtaining, evaluating, and communicating information when discussing research process.
- Components of CUREs are important in learning about research and make it feel more authentic.
- Specific scientific practices used by students: Reading the primary literature, input on the methodology, dissemination of results.
- Science practices mentioned by students not present in SEPs: future research, failure, creativity.
- Use of appropriate scientific language depends on poster audience.
- Poster visuals focus on showing data.
- Poster presentation feedback was helpful for all students.

Figure 4 New insights gained from the summer 2022/January 2023 CoLab: Students describe several of the science and engineering practices as being involved in research, and they experience these practices alongside the components of CUREs as contributing to making the research environment feel more authentic.

We have documented in our results that students expressed examples of the five major components of CUREs: collaboration, iteration, discovery, relevance, and use of scientific practices[15] in their own work. They highlighted the importance of collaboration to see a situation from multiple perspectives and to overcome challenges, which showcases important gains in all three domains of meaningful learning. The communication aspect of working in groups was also much improved in this cohort compared to the previous cohort. This may be because this CoLab occurred in person, whereas the previous CoLab was online or at-home due to COVID-19 restrictions. The CoLab students also underscored the significance of iteration in producing data that is reliable and valid. Simply conducting an experiment once does not paint a complete picture as outliers may affect the result. They also highlighted that iteration is important in overcoming failure by carefully considering what factors led to an undesired result in the lab and how to modify an experiment to produce usable results. Students additionally took pride in contributing new knowledge to the science community to the larger question of cancer biochemistry, which they contrasted with their past experiences in traditional labs where they simply followed procedures in lab manuals to arrive at a known result.[35,36] This aspect of relevant discovery has been linked to making students more likely to state that they engaged in scientific research compared to students taking a traditional "cookbook" lab course.[37]

We found several instances where students discussed a particular element of a scientific practice that, in our understanding, is not covered in the *Framework's* formulation of the SEPs. Several students highlighted connections to *future research* as a step in the research process, which is not mentioned in the K-12 investigation and assessments emphasized by the *Framework*. Often, real research will be iterated upon as new information is learned and procedures for data collection and data analysis are adjusted accordingly. Interestingly, this aligns with an observation made by Russell and Weaver in an early paper on student experiences in a traditional CURE: the ability to consider questions such as "what could be done next?"[38] This is another component of learning in CUREs: Thinking of new directions to take research, which is an aspect of science often considered by actual practitioners in a given field. Our results also show that the practice element of connecting to future research connects to the CURE components of discovery and relevance as students considered ways in which their work in CoLab tied into the larger question of cancer biochemistry and what additional work could be done.

Failure is an additional element of scientific practice that is not emphasized in the SEPs that students mentioned in their responses. When things did not work out, students iterated on their procedures to change the reaction conditions to achieve a desired result or asked for help. While this does overlap with iteration as it is currently discussed in the SEP of Planning and Conducting Investigations, the experience of some students went further as some of them encountered situations where, as they are told by the program leaders, "The right answer is that it does not work." In this setting, though, this did not lead to negative affective experience, perhaps because the program situated the potential for such failure as an expected part of authentic research.[39,40] When things did not work out, they were not generally frustrated by the failure (see Figure S1) but persevered in altering their experimental conditions to produce usable results. This points towards the concept of growth mindset being important for students in conducting research: When things do not work out, one must realize they can grow in their knowledge through setbacks and persevering in the face of hardship.[41–43] It has been noted that failure in CUREs allows students to think deeper about why their results were unexpected or contradictory.[44] Moreover, previous work in the context of a CURE demonstrated that over 50% of students considered failure to contribute to the authenticity of their research experience.[45] Similar results were found in a Research Experiences for Undergraduates Program.[46] This was manifested in the CoLab through students adjusting their experimental conditions to arrive at desired results.

Creativity is a science practice that lies at the heart of ingenuity in science and has additionally been recognized as an important part of nature of science.[47,48] Students expressed creativity as an important science practice in their work. Iterating on procedures and creating as well as presenting their posters were the primary outlets for this creativity. Creativity goes hand-in-hand with ownership as creative endeavors can promote students' agency, excitement, personal scientific achievement, and help foster connections between their work in the lab and real-world applications.[49,50] Prior research shows that creativity is augmented when individuals are intrinsically motivated.[51] Indeed, the *Framework* notes that the "actual doing of science" provides insights that "help them recognize that the work of scientists and engineers is a creative endeavor—one that has deeply affected the world they live in." And, yet, the word "creative" is itself completely absent from both Chapter 3 of the *Framework* and, except for the quotation just provided, from Appendix F of the NGSS.

The new results deepen our understanding of how the CoLab environment could support meaningful learning across the psychomotor, cognitive, and affective domains. Meaningful learning was situated in the context of students having positive affective experiences in a research setting by contributing new knowledge through carrying out actual scientific procedures that scientists use on a daily basis, such as fluorescence measurements, and synthesizing what they learned to create and present their posters. As the quotation from Kadence earlier exemplified, we noted that students expressed satisfaction (affective domain) with their experience, often also describing how they came to learn more about research, about the topic of actin biochemistry (cognitive domain) through the process of producing a poster (psychomotor domain). Prior knowledge was also used by students to devise new ways of achieving their desired results when procedures needed to be iterated on.

Our results also document how certain SEPs are found in the way that CoLab students articulated steps in the research process. We documented four SEPs in particular: asking questions and defining problems, planning and carrying out investigations, analyzing and interpreting data, and obtaining, evaluating, and communicating information (see Figure 1). We were also able to analyze how the SEPs operated at a finer grain size (see Figure 2). For instance, students differentiated between designing investigations and data collection as part of planning and carrying out investigations. Not as many students pointed out the importance of literature review and dissemination of results, which may be due to these aspects of research being new to students, and the CoLab being the first place where many of them received exposure to these steps in research. Because of the short time scale of the CoLab, students did not get the chance to plan additional steps to further their research. But they did know that their results would be directly used as the basis for later implementations of the program. In the future, it is important to stress to students that research is often an ongoing process that may not end for an extended period of time.[52]

Students discussed the role of the poster presentation in deepening their understanding of their research topic, improving their oral communication skills, and augmenting their visual presentation capabilities. Prior studies have shown that use of posters can improve oral and visual presentation skills[53,54] and understanding of a research topic[55–58], but, to our knowledge, this is the first to show such gains in a workshop-based undergraduate research experience. Compiling all the information they had learned throughout the CoLab experience allowed students to think about what they had done and why. Students reported struggling with initially presenting the poster orally, but they became more confident in their abilities as the presentation proceeded. Several students credited the poster presentation template that was provided to them as a useful tool in making sure their poster was appealing to look at and not text heavy. Students also expressed creativity in being able to create their poster. This aspect of creativity has been reported in other studies using posters.[59] Students displayed creativity concepts of fluency, flexibility, and elaboration in their work through conceiving new ideas of how to measure something if their initial idea did not work out, concocting different conditions when iterating on procedures, and detailing their experimental process visually and orally to others through their posters.[48,60] Almost all students reported receiving positive feedback from other students on campus as well as professors on their poster. This feedback resulted in positive cognitive, psychomotor, and affective outcomes for the students as they became more knowledgeable and confident about their topic through conversations with expert professors and thinking and discussing about their research in ways they hadn't before.

This experience also inspired some students to continue further with discussing their research by presenting their findings at a scientific conference, highlighting the scientific practice of dissemination of results, and further gains in all three domains of meaningful learning as students became more proficient at understanding their research, explaining their findings to others, and feeling more confident in doing so. This study thus underscores the importance of dissemination of results, a scientific practice that is present in less than 40% of chemistry CUREs[61], which we argue is a key component of authentic science and immersing students deeper into future science careers as demonstrated by students who took the initiative to further present their work at a scientific conference.

In our previously published work, we have seen that students enrolled in the CoLab Program have much higher rates of graduation (86%, 82% in STEM) than the graduation rate of the university as a whole (62%).[1] We have begun to unpack the factors that contribute to these positive educational outcomes. Clearly, the presence of the Science and Engineering Practices, other elements of scientific practice, namely future research, failure, and creativity, and the components of CUREs contribute to making the CoLab feel like an authentic science environment that is different from the verification labs that students are used to. Presenting their work at the poster session also gives students the confidence and motivation they need to further engage with the broader scientific community by showcasing their work at a scientific conference.

CONCLUSIONS

This study provides new insight into elements of scientific practice not mentioned by the NGSS framework, namely future research, failure, and creativity, that contribute to making a science experience authentic. There are two likely reasons for this. First, the *Framework* designers had a focus on K-12 science education, a place where open-ended research-related work is uncommon.[62] Including those elements as part of *post-secondary* multi-dimensional learning designs may be appropriate elaborations of the SEPs. We therefore propose that "contributing to future research" should be included as an element of the practice of Obtaining, Evaluating, and Communicating Information in such settings. We also suggest that "failure," or something equivalent to it, needs to be formulated as an element (or part of an element) in a proper understanding of the SEP of Planning and Carrying Out Investigations. Finally, we are left with the surprising, to us, apparent neglect of the notion of "creativity" in the practices (again, referring specifically to Chapter 3 of the *Framework* and Appendix F of the NGSS). Certainly, the idea of creativity is present as part of the disciplinary core ideas for engineering, technology, and applications of science. The *Framework's* discussion of ETS1.B, "Developing Possible Solutions" begins with the observation "The creative process of developing a new design to solve a problem is a central element of engineering." However, similar creativity is certainly present in other science as well and should be considered as part of the SEPs. Certainly, our data points to its potential importance as an element of the SEP of Obtaining, Evaluating, and Communicating Information. But it almost certainly belongs in the context of Planning and Carrying Out Investigations and, perhaps, Analyzing and Interpreting Data and Developing Explanations and Designing Solutions.

Our work offers a complementary approach to understanding CUREs through the use of established practice frameworks to that employed by Walker *et al.*[17], who examined CUREs relative to the Community of Practice framework presented by Lave and Wenger.[18] We are examining CURES relative to SEPs. They used focus groups as a source of data for student experiences and analyzed them with respect to the framework of a Community of Practice as formulated by Lave and Wenger. Their thematic analysis of the data highlighted three components that aligned with the idea that a CURE is a site of a legitimate CoP: "working toward a common goal, addressing obstacles, and developing a deeper understanding of the science content." Our analysis, focusing on an SEP framework, also highlights how deeper understanding is developed, likely because the SEPs, such as Planning and Carrying Out Investigations and Obtaining, Evaluating, and Communicating Information, are used within the research and poster creation process, supporting the multidimensional learning goals of the NRC Framework. And the CoP notion of a "common goal" aligns with the additional practice element of *contributing to future research* which students collaboratively worked towards, while "addressing obstacles" in the CoP setting connects to the notions of iteration and even failure that are experienced by students in the CoLab.

Additionally, this study extends previous work on students' meaningful learning experiences in the CoLab program by underscoring the steps that students understand in the research process and their connection to the SEPs, the significance of needing valid and reliable results, students adjusting their scientific language based on the knowledge level of their audience, and the impact that feedback had on students presenting posters. Several steps in research are discussed by most students, but the value of literature review and dissemination of results as well as thinking about future research must be made clearer to students in the future. Moreover, having audience members comment on students' work in the final culminating experience in a CURE or summer bridge program may foster students' positive feelings. This was reflected in some students choosing to present their results at a scientific conference following the CoLab Program. This better understanding of research and contributing to the science community as well as a positive culminating experience may contribute to students' desire to remain in STEM. Providing such experiences to students early on in their undergraduate studies is particularly important because most attrition from STEM majors occurs in the first two years of study.[8,9]

By showcasing the specific science practices that students used in their CoLab research, this article answers the call by Buchanan and Fisher to more clearly portray the types of scientific practices used in CUREs and other similar research experiences.[16] Students not only collected and analyzed data using apparatuses and software used by actual scientists, but they also had creative input on their methodology through iterating on reported procedures in the literature, reading that primary literature, and disseminating their results through a poster presentation and sometimes even an additional scientific conference. These results are in line with previous literature that shows that even short term CUREs can have an impact on students' gains in discovery, collaboration, and use of scientific practices.[63] The results presented here also display that a short research experience can have an impact on students appreciating iteration in research through making results more valid and reliable as well as persevering through failure to eventually achieve a desired result.

LIMITATIONS

This study occurred at a single institution; therefore, results may not be generalizable to other institutions. Additionally, students self-selected into this program, which presents a potential confounding variable as these students may be more motivated than typical students. On the other hand, we note that the program draws from many different majors, including those such as computer science, that might not be well-disposed to the actin biochemistry work of this CoLab implementation. The positionality of the authors is another limitation. The authors were involved with the program, but it was made clear throughout the program that choosing to consent or not consent to participate in the research would have no effect on students' standing in the program or the university. Intercoder reliability was conducted with someone not involved in the CoLab Program to provide an outside voice free of potential bias in interpreting the codes. It should be noted that this process may impart some biases of the CoLab coder onto the external coder. Another limitation of the current study is that the summer 2022 and January 2023 CoLab occurred on different time scales (6 weeks vs. 3 days), which impacted how much the January 2023 students could learn about the research process and poster creation and presentation process. The results of this study may not generalize to students in a traditional CURE as CoLab students are not graded and the CoLab occurs on a condensed time scale compared to a traditional CURE.

FUTURE DIRECTIONS

Students' responses to the VNOS-C survey[47] will be connected to their sense of belonging and science identity as described in the survey and interview results. Additionally, a one-year follow-up survey and interview will provide longitudinal data for these students. This supports the call for more longitudinal data to be collected about participation in CUREs and other similar research experiences.[15] Students who participate in the summer 2023 version of the CoLab will be paired with control group students who are enrolled in a traditional general chemistry course via propensity score matching to gauge the impact of the CoLab program.[64]

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ASSOCIATED CONTENT

Supporting Information

Student Demographic Information, Coding Data, Interview Questions, Schedule Overview of CoLab Program, Analysis of affective learning within the program

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ACKNOWLEDGMENTS

The STEM Initiative at UIC is supported through the Office of the Provost. The CoLab builds on particular work done with the support of the Chemistry Division of the NSF (NSF-CHE-0418902) and an NSF STEP grant (NSF-DUE-0525582). Some students are also participants in programs supported by the university or through an NSF S-STEM grant (NSF-DUE-1929722) and an NIH Bridges to the Baccalaureate grant (T34-GM142627). We thank Drs. Paul Grippo of the UIC Cancer Center and Peter Grudzien of Malcolm X College for support of some of the research work, including identifying the cancer biochemistry theme of the project. Student data was collected with the approval of the UIC Institutional Review Board, Protocol # 2021-0457.

The authors would additionally like to thank Robert Milligan for insights provided into earlier versions of this work.

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