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Promoting Chemical Engineering Identity through Student Agency and Experiment Relevance

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Abstract

Although laboratory courses are undeniably important in the education of chemical engineers, many experiments are prescribed, leaving students minimal decision-making opportunities. To understand the impact that making consequential decisions has on student learning and development, we explore students' perceptions of different aspects of laboratory experiments. Specifically, we investigated students' agency in four domains—(1) experimental design prior to doing the laboratory experiment; (2) data collection and documentation during experiments; (3) data analysis and interpretation; and (4) communication of purpose, methods, and conclusions—contributes to students' development. We conjectured that having agency in Domains 1 and 3 may matter more than Domain 2.

We used a survey to measure consequential agency in all four domains, as well as engineering identity, relevance, and persistence intentions. Students at two research universities completed the survey as part of their post-lab activities (N = 74). We conducted exploratory factor analysis and found support for our survey. Based on this, we proceeded with sequential regression modeling.

We found persistence intentions were positively, significantly predicted by engineering identity. In turn, engineering identity was positively, significantly predicted by relevance and data analysis and interpretation consequentiality (Domain 3), and negatively, significantly predicted by consequentiality during the experiment (Domain 2). This suggests having agency over tasks like analyzing data and interpreting results contributes to students' identities as engineers more than other domains.

Introduction and research purpose

Laboratory courses play a central role in chemical engineering education. However, at many institutions, experiments are prescribed, leaving students minimal decision-making opportunities. Our approach to promote student engagement and belonging in engineering is to investigate the role of consequential agency in laboratory experiments. To determine the effect agency has on students, we explore how different aspects of laboratory experiments contribute to students' development through a survey used to measure consequential agency as well as engineering identity, relevance, and persistence intentions.

The goal of the project is to extend theory about agency in learning and the development of professional identity in upper division chemical engineering laboratory courses. Specifically, we investigate how agency in four domains—(1) experimental design prior to doing the laboratory experiment; (2) data collection and documentation during experiments; (3) data analysis and interpretation; and (4) communication of purpose, methods, and conclusions—contributes to students' development. We conjecture that students having agency in planning the experimental design (Domain 1) and in analysis of data (Domain 3) may matter more than having agency while performing the experiment (Domain 2).

Background

Students' prior experiences in introductory chemistry courses, where cookbook style laboratory experiments are commonplace, can shape their expectations about upper division chemical engineering laboratory courses [1]. In such courses, students commonly have agency only over domain (2) data collection and documentation during experiments, as the experiment is designed for them, a specific analytical approach and known interpretation are expected, and even the communication of the experimental methods and results follow a template.

Chemical engineering faculty have long been investigating ways to support students to engage in laboratory courses in ways that transcend the cookbook approach [2], providing students with agency over all four domains: (1) experimental design prior to doing the laboratory experiment; (2) data collection and documentation during experiments; (3) data analysis and interpretation; and (4) communication of purpose, methods, and conclusions—contributes to students' development. This is in part prompted by accreditation criteria that emphasize the role of the student in not just conducting, but also planning or developing experiments, analysis, and interpretations [3].

Indeed, recent publications in chemical engineering education highlight a breadth of studies investigating ways to provide more opportunities for students to access such experiences, from using data science tutorials that make it possible for more students to participate in authentic laboratory research [4] to creating laboratory experiments where students have increased opportunities to make decisions about how to analyze data (Domain 3) [5]. For instance, as a guided-inquiry approach Elkhatat and Al-Muhtaseb [5] used a MATLAB-aided learning package in a unit ops laboratory in which students compared experimental and simulated results, making decisions about this comparison (Domain 3).

Many such approaches emphasize using inquiry in some format, such as guided inquiry, discovery, or problem-based learning. Not only do such approaches support conceptual learning, they can also increase students' self-efficacy [6-8]. This is in part because opportunities to conduct authentic experimental practices, like troubleshooting, provide a chance for students to test not only the experimental conditions, but also their own understanding and expectations. For instance, Crockett, et al. [8] studied the link between troubleshooting and experimental self-efficacy for undergraduates in a senior chemical engineering laboratory course (Domain 2). They administered a self-efficacy survey [7] and found that students ranked their self-efficacy as high. However, the authors did not find a correlation between self-efficacy and exam grades. While the authors attributed this to a small sample size, both troubleshooting and the measure of self-efficacy primarily focused on data collection and documentation during experiments (Domain 2).

We wonder if high self-efficacy related to Domain 2 might be a weaker correlate of learning than other domains, in part because students may experience what scholars have named "deceptive clarity," a phenomenon in which students underestimate how complex something is based on having completed a simplified version of the task [9]. The activities associated with collecting data and monitoring during the experiment are somewhat more straightforward compared to activities in the other domains. Indeed, a cognitive analysis of the tasks related to experiments identified many tasks associated with Domains 1, 3, & 4, but only one ("collecting experimental data") associated with Domain 2 [10]. In addition, analysis of curricula suggest that students less commonly have opportunities to make decisions related to Domain 1, especially setting research goals, designing experiments, and designing and evaluating the experimental apparatus, while they have abundant opportunities to collect data (Domain 2), analyze it (Domain 3), and communicate their experiments (Domain 4)[11]. As a result, scholars have raised concerns about how prepared students might be for conducting research, if they have few opportunities to practice the tasks associated with Domain 1 [10, 11].

Some laboratory experiences do engage students in all four domains. This is true in many course-based research experiences and in designs that allow students to find and propose an experimental design. For instance, [12] reported on a learning experience within a physical chemistry curriculum designed to promote skills like planning work (Domain 1), obtaining information (Domain 2), processing and organizing data (Domain 3), and communicating (Domain 4). Students reviewed physical chemistry experiments published in a journal, then wrote NSF-style proposals to plan and justify their proposed experiment, which they then conducted and presented their results. On end-of-course evaluations, students reported that the experience seemed authentic and especially helped them learn to plan, organize, and prioritize work.

We argue, from the lens of desirable difficulties [9], that having students participate in laboratory tasks in low agency ways—e.g., carrying out an experimental or analytical procedure by following directions, writing directed by a detailed report template—might not prepare them to engage in these activities independently. We theorize this with the notion of agency. Classical definitions of agency differentiate it from free will, noting that humans make decisions that are constrained in various and often enduring ways [13-15].

In our past work on agency and learning, we highlighted that agency is contextual [16-19]. This is the case with many psychosocial constructs; for instance, one's interest in, motivation for, and self-efficacy related to a topic like painting might not be predictive for other topics, like soccer or catalysis. In the case of agency, however, contextualization is not to a broad field, but rather to the consequentiality of the decision. Laboratory experiments are an excellent illustration of this phenomenon: making decisions related to how often to sample data and how to document an experimental apparatus (Domain 2) are less consequential, for instance, than setting an experimental aim and designing an experiment to address that aim (Domain 1). Likewise, within domains, there are more and less consequential variants. For example, choosing how to go about analyzing data is more consequential than simply following analysis directions (Domain 3), and choosing an audience and what and how to communicate to them is more consequential than following a template on how to write a technical report (Domain 4).

Methods

Study design

To address the study aims, we first conducted a validation study of our survey, then conducted regression modelling. We adapted a survey we previously developed to measure consequential agency in laboratory experiments to focus on all four domains, as well as engineering identity, relevance, and persistence intentions. We systematically developed the survey across three studies following research guidance [20, 21]. Importantly, when measuring a construct (e.g., identity, self-efficacy, agency), multiple questions are needed to approximate it, as a single question does not provide an adequate measure of that construct [20, 21]. Exploratory factor analysis (EFA) was used to verify that questions intended to measure a construct do cluster together. Once validity procedures for the survey were completed (e.g., exploratory factor analysis), we sought to investigate trends in the data. Specifically, we conducted regression modelling to explain variance in persistence intention scores.

Participants and setting

Chemical engineering undergraduate students at two research universities (North University & Southwest University, pseudonyms) completed the survey as part of their post-lab activities (N = 74). Students were enrolled in spring, junior- and senior-level laboratory courses (Table 1).

Table 1. Description of courses

Course and institution	***Topics***
Senior-level, 3-credit 2nd in a 2-semester sequence, North University	Unit operations; 4 experiments (a heat exchanger experiment, fluid flow and friction, a continuous stirred tank reactor (CSTR) experiment, and an enzyme reaction kinetics experiment).
Junior-level, 1-credit 2nd in a 4-semester sequence, Southwest University	Transport phenomenon; 3 experiments (investigating how pipe length impacts efflux from a tank, how types of wood impact conductive heat transfer, and how fittings and pipes impact frictional pressure loss).
Senior-level, 1-credit 4th in a 4-semester sequence, Southwest University	Kinetics and process control; 2 experiments (investigating different catalysts used in the selective hydrogenation of ethane, and determining and comparing tuning parameters for a level controller on a water tank)

Data collection and analysis

In our prior work, we adapted a measure of framing agency that was used to measure students' agency in engineering design courses [22, 23]. We initially adapted this survey to focus on experimental design. However, because the framing agency survey measures four dimensions of agency, we recognized that a long survey with questions for all four dimensions of agency for each laboratory domain could result in survey fatigue. We therefore used a multi-step process. First, we selected two domains (Domain 1: experimental design; Domain 4: communication) and adapted all items from the original survey for these domains [17, 19]. This allowed us to identify the agency dimensions relevant in the laboratory context—specifically, consequentiality of decisions and sense of responsibility. As the next step, in the current study we report on a version of the survey that covers all four experimental domains (Table 2), as well as items that measure perceived relevance to professional work, engineering identity, and persistence intentions [24, 25]. The survey also collected demographic information (gender, race/ethnicity, age, veteran and college generation status, home language, community context) using inclusive wording [26].

Table 2. Survey questions

Questions by construct
Consequentiality of Domain 1) Experimental design prior to doing the laboratory experiment; Describe one decision that you made in the PLANNING or DESIGNING this experiment that stands out for you. Considering the decision you described, how important or unimportant was: (7-point Very unimportant / Very Important scale) • the decision? • the impact of that decision on your experiment?
Consequentiality of Domain 2) data collection and documentation during experiments Describe one decision that you made DURING THE EXPERIMENT, such as related to data collection or a change to the experiment, that stands out for you. Considering the decision you described, how important or unimportant was: (7-point Very unimportant / Very Important scale) • the decision? • the impact of that decision on your experiment?
Consequentiality of Domain 3) data analysis and interpretation Describe one decision that you made related to ANALYSIS OR INTERPRETATION of your data, that stands out for you. Considering the decision you described, how important or unimportant was: (7-point Very unimportant / Very Important scale) • the decision? • the impact of that decision on your experiment?
Consequentiality of Domain 4) communication of purpose, methods, and conclusions Describe one decision that you made related to COMMUNICATING your experiment, such as in a technical report or presentation, that stands out for you. Considering the decision you described, how important or unimportant was: (7-point Very unimportant / Very Important scale) • the decision? • the impact of that decision on your experiment?
Responsibility: How responsible or not responsible did you feel for making decisions about: (7-point Very not responsible/Very responsible scale) • your experiment? • the outcomes of your experiment? • reporting your experiment?
Relevance: How similar or dissimilar: (7-point Very dissimilar / Very similar scale) • was your communication of your experiment to how chemical engineers report their work? • were the skills you used in the experiment to those used in chemical engineering? • was the experiment to the work of chemical engineers?
Engineering identity How true or untrue is each statement below of you? (7-point Very untrue of me / Very true of me scale) • My classmates see me as an engineering person • My engineering instructors see me as an engineering person • I feel like I belong in engineering

Persistence intentions (7-point Strongly disagree to Strongly agree) I intend to • pursue a career in engineering in the future. • work in engineering for at least 3 years in the future—as a professional engineer, a graduate student, and/or researcher.
Demographics • Growing up, what language or languages were spoken in your home? (Only/mostly a language or languages other than English; Another language or languages AND English; Only/mostly English) • What is your age? (17 or younger; 18-24; 25-30; 31 or older) • Which best describes where you lived while attending high school (or similar)? (Tribal reservation; Rural; Small town; Urban) • What is your gender identity? (Non-binary; Woman; Man) • How do you identify? Choose all that apply (American Indian or Alaska Native, Native American, Indigenous to Turtle Island, or First Nations; Native Hawaiian or other Pacific Islander; African, African American, or Black; Hispanic, Latino/a/x/é, Mexican, Mexican American, Chicano/a/x/é, Cuban, or Puerto Rican; Arab or Middle Eastern; Asian or Asian American; White) • Are you a first generation college student? (No; Yes) • Are you now or have you ever served on active duty with the U.S. Armed Forces, Military Reserves, or National Guard? (No; Yes)

We used SPSS version 28.0.0.0. We conducted exploratory factor analysis (EFA) to assess whether the adapted survey items measured the intended dimensions. EFA is a statistical method that is used to examine how responses to survey questions cluster together, meaning they measure the same underlying latent factor [27]. Studies investigating the validity of data provided by surveys use this approach to evaluate whether the survey measures what it purports to measure. EFA procedures include established metrics for determining whether items adequate group together and whether to remove an item that groups with multiple factors or that too weakly groups with a factor [27]. While there are decisions—extraction method, rotation method—to make in EFA, within the social and behavioral sciences, there is abundant guidance about these decisions.

We used principal axis factoring as our extraction method because it is effective with data that have a non-normal distribution [28], and such distributions are to be expected with survey data. We chose a promax rotation, which is an oblique method favored in social, behavioral, and educational settings where factors are expected to be correlated with one another [29, 30]. To determine whether our data were appropriate for EFA, we used two typical metrics. The Kaiser-Meyer-Olkin (KMO) measure estimates the adequacy of the sample size, with values below .6 indicating that the sample size is not adequate [31, 32]. Next, Bartlett's test of sphericity should be significant [33]. We found KMOs ranging from 0.56 to .68 and Bartlett's test of sphericity was consistently significant, $p < .001$. This indicates that our sample is somewhat underpowered and risks not recovering all factors. As a result, although we proceeded with EFA, we recognize this as a limitation to be addressed in future studies, and to diminish the issue, we selectively tested a subset of items sequentially. Following typical procedures, we retained those items that did not cross-load on multiple factors and that had loading above an absolute value of 0.4 [34, 35], and we retained factors that had a Cronbach's alpha ≥ .70 [28, 30, 36, 37].

Based on the EFA results, we created variables representing the average scores of the individual items comprising each factor: consequentiality by domain, responsibility, relevance, and engineering identity. We also created a score based on students' membership in privileged and minoritized demographic groups. We assigned one point for membership in each of the following privileged groups: English speaking in the home; traditional college age; from a small town or urban setting; man; Arab, Asian, or white; and continuing generation in college. We divided the resulting score by six to calculate the percent of privileged groups each student belonged to.

Results

Using a sequence of EFA models, we found support for our survey. For instance, we found that questions intended to measure consequential agency in each of the four domains clustered as expected (Table 3).

Table 3. EFA results, showing how each item loads on a factor (>.4 is highlighted), with four latent factors recovered. Loading indicates that the items cluster together to measure the same underlying (latent) construct. Factors are normally retained if they have a Cronbach's alpha ≥ .70. Means and standard deviations are reported for the responses.

Item prompt	*Factor Loading*				*Mean (SD)*
Factors:	1	2	3	4	
Factor 1: Consequential agency in Domain 1: Experimental design prior to doing the laboratory experiment ***(α = 0.70)***					
How important or unimportant was the decision?	0.76	-0.05	0.15	0.10	5.75 (1.23)
How important or unimportant was the impact of that decision on your experiment?	0.78	0.05	-0.15	-0.08	5.57 (1.46)
Factor 2: Consequential agency in Domain 2: Data collection and documentation during experiments ***(α = 0.81)***					
How important or unimportant was the decision?	0.07	0.82	0.08	-0.03	5.73 (1.04)
How important or unimportant was the impact of that decision on your experiment?	-0.05	0.83	-0.06	0.03	5.78 (1.27)
Factor 3: Consequential agency in Domain 3: Data analysis and interpretation ***(α = 0.87)***					
How important or unimportant was the decision?	-0.07	0.06	0.76	0.12	5.67 (1.14)
How important or unimportant was the impact of that decision on your experiment?	0.02	-0.04	1.01	-0.10	5.86 (1.13)
Factor 4: Consequential agency in Domain 4: Communication of purpose, methods, and conclusions ***(α = 0.90)***					
How important or unimportant was the decision?	-0.05	0.03	-0.02	0.91	5.41 (1.02)

How important or unimportant was the impact of that decision on your experiment?	0.06	-0.03	0.01	0.89	5.73 (1.04)

In other models, we found that questions grouped together as intended for other study constructs: overall responsibility for decisions; relevance; engineering identity; and persistence intentions.

We then used sequential regression modeling in order to investigate trends in the data. We used a stepwise approach, investigating a series of models. Specifically, we sought to model variance in persistence intentions as well as engineering identity. Across these models, significant variance was not explained by overall responsibility for decisions, individual demographic variables, or the percent privileged. We report parsimonious models below (Tables 4 & 5).

We found that persistence intentions were positively, significantly predicted by engineering identity, $F(68, 2) = 5.14$, $r^2 = .12$ (Table 4).

Table 4. Regression model of persistence intentions

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
Constant	2.96	0.96		3.08	0.003
Engineering identity	0.53	0.17	0.36	3.21	0.002

Next, we modeled variance in engineering identity (Table 5). We found that engineering identity was positively, significantly predicted by relevance and data analysis and interpretation consequentiality (Domain 3), and negatively, significantly predicted by consequentiality during the experiment (Domain 2), $F(58, 5) = 4.03$, $r^2 = .129$. Neither consequential agency in Domains 1 nor 4 explained significant variance, either in the model reported below or in other models.

Table 5. Regression model of engineering identity

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
(Constant)	2.65	0.88		3.00	0.00
Relevance	0.32	0.14	0.29	2.35	0.02
Domain 1 Consequentiality	0.10	0.09	0.14	1.11	0.27
Domain 2 Consequentiality	-0.20	0.09	-0.29	-2.19	0.03
Domain 3 Consequentiality	0.21	0.11	0.26	1.87	0.07
Domain 4 Consequentiality	0.11	0.12	0.13	0.93	0.36

Discussion

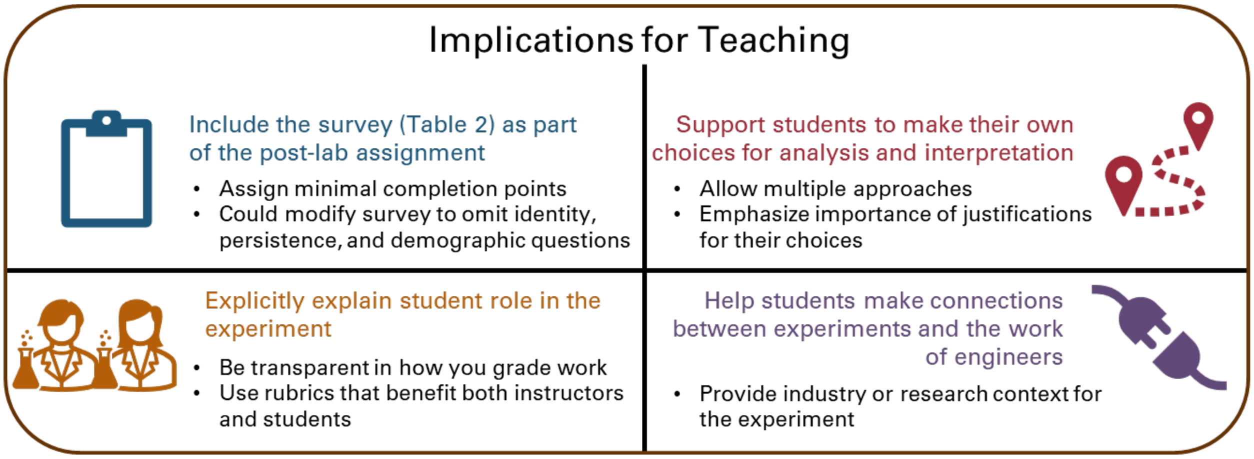
In this study, we sought to further develop a survey to measure consequential agency in four domains in the context of laboratory experiments—(1) experimental design prior to doing the laboratory experiment; (2) data collection and documentation during experiments; (3) data analysis and interpretation; and (4) communication of purpose, methods, and conclusions. We then sought to investigate the impact of having consequential agency in each domain, along with perceptions of relevance, on student development. We discuss these in turn and share implications, summarized in Figure 1.

First, overall we found preliminary support for our survey. However, due to sample size limitations, additional work is needed. Future studies, ideally involving multiple sites, can add greater confidence that the survey measures what it purports to. Despite this, the survey development process, detailed here and in our prior studies [17, 19], supports the use of the survey for both research and instructional purposes. While faculty should affirm the factor structure, as is the case for any use of a survey in a new setting, the survey detailed in Table 2 can be used with any laboratory experiment. If length is a concern, faculty can omit the questions on overall responsibility, identity, persistence and demographics. We have found some value in including the survey as part of the normal post-laboratory assignments, as the questions about relevance and consequential agency jointly provide an opportunity for students to reflect on their experience and provide additional insight for faculty about how students perceive the laboratory experiment. As such, we encourage faculty to assign minimal completion points (not extra credit), in line with an activity that takes around 10 minutes to complete. Research emphasizes the value of reflecting on experience, as this helps cement and organize learning [38]. In addition, faculty may benefit from gaining insight into students' perceptions about their roles in each aspect of the experiment. This matters because, even when we design a laboratory experiment to be highly authentic, as in the case of course-based undergraduate research, students' repeated exposure to cookbook style labs can prevent them from recognizing and taking up agentive roles [1, 39]. Minor changes in how faculty introduce an experiment (i.e., explicitly telling students what their role is), and being transparent in how they grade student work (i.e., making clear that alignment across experimental aims and methods and being able to account for results is more important than other outcomes common in early chemistry laboratory settings, like percent yield).

Second, our regression modeling found support for a positive relationship between engineering identity and persistence intentions. This aligns with other research in engineering education [40-42]. While many studies have investigated this relationship, far fewer have examined the instructional practices and learning experiences that contribute to engineering identity, and therefore, persistence, although research has affirmed that providing more authentic design experiences, relevant to students' futures as engineers, contributes to their identities and persistence intentions [43].

We found that students having agency over tasks like analyzing data and interpreting results (Domain 3) contributes to students' identities as engineers more than other domains. Likewise, tasks that seem relevant—meaning, similar to the work of chemical engineers—provide a more potent experience for students' developing identities as engineering. Our results, while tentative, suggest faculty seeking to make changes to their laboratory courses can focus efforts on supporting students to make their own choices related to analysis and interpretation, and on helping students understand the connections between the experiments and the work of chemical engineers. However, a key limitation should be noted, as it suggests the need for additional research. Comparatively few students reported high agency experiences in Domain 1. As a result, our findings that consequentiality in Domain 1 did not explain variance in engineering identity may be an artifact of more limited variance in scores on Domain 1. Given that this is the domain students are least likely to have agency over [10, 11], our ongoing studies strategically seek to identify such instances to ensure we can adequately model the impacts of each domain.

Figure 1. Implications for teaching



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