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Consequential Agency in Chemical Engineering Laboratory Experiments

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Abstract: Despite being at the center of undergraduate engineering education, laboratory experiments have remained unchanged for decades, resulting in assignments lacking in opportunities for students to learn and grow. We used a survey to measure students' sense of agency in prototypical design and laboratory courses at research universities. We found students in laboratory courses at both levels experienced significantly lower framing agency than their peers in senior design, and that even those engaged in authentic course-based research did not perceive the experiments as more agentive or authentic. We infer students drew upon abundant low-agency experiences in laboratory experiments; maximizing learning in laboratory courses may hinge on clearer communication about authentic experiments or systematic redesign of earlier courses.

Purpose

While understandings of theory and ability to solve complex engineering problems on paper take up much of students' time, their time in laboratory courses and design projects offers the opportunity to test these ideas firsthand and direct their own investigations and problem framing and solving processes. Laboratory experiments in particular vary in offering students opportunities to make decisions about what question to pose, how to design an experiment, how to collect and analyze data, and how and with whom to share results. Upper division engineering laboratory experiments are typically more complex—and sometimes more authentic, involving students in aspects of faculty research—than those encountered in their supporting, introductory science classes, which tend to be cookbook in nature (Hauwiller et al., 2019). Yet, those foundational experiences may shape students' perceptions of the laboratory courses as being an opportunity to demonstrate their capacity to deliver the known answer, rather than participating in a discovery process (Chen et al., 2016).

We sought to understand how students perceived their agency in upper division chemical engineering laboratory courses. Specifically, we investigated students' agency in two domains: (1) experiment and analysis and (2) communication of their work. We compare this to students' framing agency—their capacity to make decisions consequential to the framing of design problems—to evaluate their perceptions of consequentiality within laboratory experiments. Making all such experiments high-agency is not feasible due to the high enrollment of these courses, as well as the specialized equipment and potentially hazardous nature of experiments. Understanding more about how students perceive their agency could provide insight about comparatively simple changes that encourage students to take more agentive roles. We sought to answer three research questions:

1. To what extent are students' perceptions of their agency similar across classical engineering design and experimental design contexts?
2. To what extent do students view their experiments as authentic to chemical engineering practice?
3. To what extent do students' perceptions of their agency differ across the two domains of (a) design of experimentation and analysis and (b) communication of results and across more and less authentic laboratory experiment contexts?

Theoretical framework

We frame our study by considering research on student agency across the learning contexts of prototypical design, experimental design, and communication. Across these, we consider the influence of authenticity, defined as having 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" (Strobel et al., 2013, p. 151).

What is framing agency?

Design problems are ill-structured, meaning these problems have more than one solution and path to solution, as opposed to a single answer (Jonassen, 2000). Designers direct the process of framing and reframing problems (Runco & Nemiro, 1994). This ability is consequential as the framing determines the ultimate choices and outcomes a designer can make. The empowerment to make such decisions is a specialized form of agency, termed framing agency (Svihla et al., 2019, 2021). The bounds on agency can be thought of as set by the opportunity

structure (Narayan & Petesch, 2007), which shapes not only which and if decisions can be made, but the consequentiality of those decisions. For instance, traditional, well-structured classroom problems that have a single right answer limit the opportunity structure and students make few or no consequential decisions. In contrast, design problems, especially authentic problems sourced outside of school contexts, offer significant opportunity structure, allowing students to decide how to frame problems and proceed in their work. Designers make decisions about what they need to know, which in turn leads to learning, such as from consulting stakeholders (Basadur et al., 1982).

How does framing agency relate to laboratory experiments?

Laboratory experiments vary from authentic experiments conducted as part of research to cookbook-style experiences that are highly prescriptive, with a limited opportunity structure (Mohrig, 2004). As students advance in their programs of study, labs become more complex, meaning the number of variables and the relationships between variable increases (Jonassen, 2000). While this opens the opportunity structure somewhat as students make choices about which variables to control or vary, the problems typically remain well-structured, with the answer known ahead of time. In contrast, ill-structured experiments that engage students in discovery can support learning about the relationships between variables and the design of experiments (Flora & Cooper, 2005). Such problems may even be part of authentic research process, such as when faculty bring their research into the classroom through course-based undergraduate research experiences (Chase et al., 2016). More authentic problems should support greater agency. However, the preponderance of experience with well-structured problems could sabotage the sense of authenticity for students.

Making experiments fully authentic – meaning, based in problems that exist externally (Strobel et al., 2013) – is unrealistic in terms of time, cost, and capacity, including the acknowledgment that ill-structured problems are difficult to propose, implement, support, and evaluate, evidenced by the limited uptake of such approaches. And, more authentic tasks can also limit participation, as students may report low agency if they perceive the requisite decisions as beyond their reach (Hagvall Svensson et al., 2021). Thus, there is a need for investigations into ways to enhance agency in ways that is impactful for student learning and development yet feasible for faculty to manage.

How does framing agency relate to communication?

Writing tasks, encountered in both laboratory and design courses, also fall on a continuum from well- to ill-structured. The lab report is a quintessential form that narrows the opportunity structure, sometimes down to the sentence (Hicks & Bevsek, 2012). These reports can reinforce the idea that work is judged for accuracy, rather than authentically communicating new knowledge to an audience (Abidin et al., 2013). Yet, authentic technical communication, even when fit into genre and journal expectations, can be an ill-structured, iterative process much like design (Howell, 2015), in that authors define stakeholders (audience), purpose, and make decisions to reach those goals (Sharples, 1998). While more authentic forms of communication may enhance the consequentiality of students' agency, their expectations about lab reports may reduce the opportunity structure.

Methodology

We conducted comparative analysis of agency in design versus laboratory courses in engineering. This involved analysis of post-instructional surveys completed by students. We additionally had insight into course instruction via participant observation of the courses (Atkinson & Hammersley, 1994).

Participants and setting

We collected data in senior design courses (n=109) and in two laboratory courses (n=31 in the junior course; n=31 in the senior course). The senior design courses partially met the definition of authenticity, in that students selected projects that had originally been sourced in the world, but that had been reformulated as instructional projects (they included a client but were narrowed in scope by the instructor, or they lacked a client but were based in a prior authentic project).

The junior laboratory experiment asked students to evaluate and then calculate the friction and corresponding pressure drop of water flowing through pipes with different fittings and bends during turbulent flow. Students measured the pressure of water at the beginning and end of two (out of ten) different pipes of different lengths, and—combining their information with that of four other groups to form a complete data set—calculated information about how the bends, length, and fittings of the pipes differently affected the pressure drop and the relative friction. They were scaffolded on how to conduct analysis with an Excel worksheet and on how to communicate their results with a presentation outline. Each group created a 20-minute presentation detailing their findings.

The senior laboratory experiment focused on selective hydrogenization of acetylene into ethylene while minimizing the conversion of ethylene into ethane to be used later to create the plastic polyethylene. The catalysts used by each group was one of several catalysts synthesized in a research laboratory at the university and are part of a larger research study attempting to develop new catalysts to maximize the ability to create polyethylene. Students ran optimization experiments on their unique catalysts by determining the selectivity of converting acetylene to ethylene without converting ethylene to ethane by varying the proportions of starting gases, the flow rate, and the temperature. Students then calculated the kinetics of each reaction and evaluated the effectiveness of their own catalysts. Students worked in groups of five. They individually wrote a short technical report on their findings modeled after a short technical journal article. After peer review, the students in each group combined their individual reports into a single report.

Data collection and analysis

We used two versions of the framing agency survey (Table 1), a survey which has previously undergone validation procedures. In the design course, we used the original framing agency survey, which includes 18 items covering six factors—individual consequentiality; shared consequentiality; learning as consequentiality; constrainedness; shared tentativeness/ill-structuredness; and individual tentativeness / ill-structuredness (Svihla et al., 2020). We adapted questions to the context of experimental design and laboratory decision making within the original factors (Table 1). In addition, we added two questions about authenticity, in which students reported the likelihood their results would be used to inform future research or be shared with others outside the course, in a research lab, a publication, or similar.

We calculated descriptive statistics and used independent samples t-tests with effect sizes to selectively make comparisons between the two laboratory courses, and between design and laboratory courses. We used repeated measures two-way ANOVA to evaluate differences between the laboratory courses and domains (experimental design versus communication).

Table 1

Framing agency survey. All questions on a 7-point bipolar scale, with poles named in question stem.

Factor: Individual Consequentiality. [contextualized to design / contextualized to experimental design]
How responsible or not responsible did you feel for the outcomes of the [*design project/experiment*]?
Considering the (individual) decision you described, how important or unimportant was the decision?
Considering the (individual) decision you described, how important or unimportant was the impact of that decision on your [*design process / experimental design and interpretation of results; final presentation/report*]?
How responsible or not responsible did you feel for making decisions personally?
How responsible or not responsible did you feel for coming up with your own ways to make progress on the [*design project / experimental design and interpretation of results; the preparation of the presentation/report*]?
Factor: Shared Consequentiality
Considering the (team) decision you described, how important or unimportant was the impact of that decision on your [*design process / experimental design and interpretation of results; final presentation/report*]?
Considering the (team) decision you described, how important or unimportant was the decision?
Factor: Learning as Consequentiality
How much or little did you learn as a result of decisions about the [*design problem / experimental design and interpretation of results; presentation/report preparation*] a teammate made?
How much or little did you learn as a result of decisions about the [*design problem / experimental design and interpretation of results; presentation/report preparation*] you personally made?
Factor: Constrainedness
Considering these constraints, how free or restricted did your teammates seem when making decisions?
Considering these constraints, how free or restricted did you feel when making decisions yourself?
How free or limiting did the [*design problem / experiment*] seem to be?

Factor: Shared tentativeness / Ill-structuredness
How certain or uncertain do you feel that you have to [*solve the problem / carry out the experiment*] as given to you?*
How certain or uncertain do you feel that [*your design project has a single right solution / there is a single right way to conduct the experimental design and interpretation of results*]?*
How certain or uncertain do you feel that you have to just [*develop what was asked of you / collect data as you were asked to*]?*
How certain or uncertain do you feel that you know the optimal [*solution / experimental design and interpretation of results*]?*
Factor: Individual tentativeness / ill-structuredness
How certain or uncertain do you feel that you understand the [*design problem / experimental design*]?
Considering your [*design project / the experiment*], did you have many or few opportunities to make decisions as a team related to your [*design project / experimental design and interpretation of results*]?

*Reverse scored items

Results

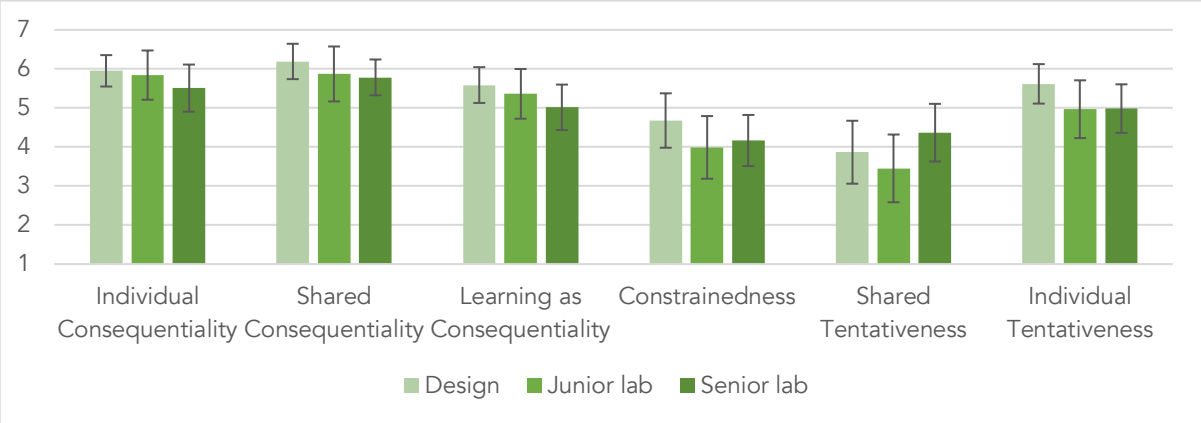
We organize the results by research question.

To what extent are students' perceptions of their agency similar across classical engineering design and experimental design contexts?

Overall, we found design students experienced higher levels of agency across all factors (Figure 1, Table 2). One exception was the senior lab which reported higher shared tentativeness on average. Responses range from 1, which is the lowest or most negative, to seven, which is highest or most positive). Scales differ by question.

Figure 1

Average scores by course on each factor. Refer to table 1 for definitions of Likert scales, as items are bipolar and construct-specific, and poles are named within the question stem.



Students enrolled in design courses reported significantly higher learning consequentiality than those in laboratory classes, $t(169) = 2.40$, $p = 0.017$, $g = 0.38$, a medium effect size. This suggests the kinds of decisions made in the former resulted in more learning opportunities about framing problems. Students enrolled in design courses reported significantly higher individual tentativeness than those in laboratory classes, $t(169) = 3.50$, $p < 0.001$, $g = 0.56$, a medium effect size. This suggests students in the design courses tended to believe there was not a single correct answer to the problem. Students enrolled in design courses reported significantly lower constrainedness than those in laboratory classes, $t(169) = 2.66$, $p = 0.009$, $g = .42$, a medium effect size. This indicates students in laboratory courses felt more limited by the structure of the problem than in design courses. These results indicate that students in laboratory courses experienced less agency than their peers in design courses.

Table 2
Descriptive statistics. All measures on a 7-point scale

Factor	Design courses (n=109) Mean (SD)	Junior Lab (n=31) Mean (SD)	Senior Lab (n=31) Mean (SD)
Individual Consequentiality	5.95 (0.81)	5.84 (1.26)	5.51 (1.21)
Shared Consequentiality	6.19 (0.91)	5.87 (1.41)	5.78 (0.92)
Learning as Consequentiality	5.59 (0.92)	5.36 (1.27)	5.02 (1.16)
Constrainedness	4.68 (1.39)	3.99 (1.61)	4.17 (1.31)
Shared tentativeness / Ill-structuredness	3.87 (1.61)	3.45 (1.74)	4.37 (1.48)
Individual tentativeness / ill-structuredness	5.62 (1.01)	4.97 (1.48)	4.98 (1.24)

To what extent do students view their experiments as authentic to chemical engineering practice?

The second research question compared the inauthentic junior experiment to the senior experiment, which was part of faculty research. Overall, students reported relatively low authenticity. Students in the junior course reported somewhat lower authenticity ($M = 3.06$; $SD = 1.87$) than seniors ($M = 3.67$; $SD = 1.65$), but this difference was not significant, $t(78) = -1.33$, $p > 0.1$, $g = .34$, a medium size effect. This indicates that even experiments designed to be authentic do not necessarily translate to perceived authenticity.

To what extent do students' perceptions of their agency differ across the two domains of (a) design of experimentation and analysis and (b) communication of results and across more and less authentic laboratory experiment contexts?

We found no significant interaction effect and no difference between courses. This corresponds to students' reported sense of authenticity. Students reported significantly higher agency in the domain of communication than in experimental design, $t(62) = 2.82$, $p = .0064$, $g = .36$ for a medium effect size, indicating perceptions of agency vary across domains (Table 3).

Table 3
Repeated measures ANOVA of agency in two domains (experimental design and communication) between junior and senior courses

Source of variance	*df*	*Sum of Squares*	*Mean Square*	*F*	*p*
Between subject effect	**61**	**78.23**			
Junior v. senior (A)	1	3.28	3.28	2.62	0.11
Error	60	74.95	1.25		
Within subjects	**62**	**20.52**			
Experimental design v. communication (B)	1	2.37	2.37	8.29	0.0055*
A*B	1	0.97	0.97	3.39	0.071
Error	60	17.17	0.29		

Discussion

Framing agency in laboratory and design courses

Students in capstone design report greater agency overall. This is unsurprising as students in design must make decisions about elements such as the scope of the problem and where to source information, which is consistent with greater opportunity structure (Narayan & Petesch, 2007). While the laboratory courses varied in the number of available consequential decisions, constraints like procedure and time limited the students' abilities to frame the problems for themselves. Because of these limitations, students do not have as much space to reframe the problems win whichever ways they see fit, making the problem more well-structured than design problems

(Jonassen, 2000). We can also see that the option to make decisions doesn't necessarily translate to empowerment to make decisions, which is the key component of framing agency (Svihla et al., 2019, 2021). Students in junior and senior labs have completed many well-structured experiments previously in their coursework, and this may have shaped their expectations about these labs.

Framing agency in experimental design

While the intended opportunity structure of the junior and senior labs differed, we found no significant difference between junior and senior students' overall perceptions of their agency. Even though the senior students had many more consequential choices (particularly when it came to design of experiments), this did not translate into sense of consequential agency. We consider the contextual factors that may have contributed to this.

First, felt time constraints meant that students in both the junior and senior courses had limited opportunity to reframe the problem presented to them or even to revise their method of solving it. However, students in the senior course did revise the parameters they used for data collection in response to unsuccessful results or additional information. Students had to frame the ways in which they interpreted their data and used it to make decisions moving forward by balancing variables and deciding their relevant importance. This is the type of framing through making decisions about importance and outcomes we would expect to be demonstrated in students' reports of their agency.

Second, we found that students perceived both the junior and senior laboratory experiments as inauthentic. Research suggests that taking part in authentic research can be sufficient to bring greater impacts to students (Chase et al., 2016). However, our findings indicate that the mere presence of authenticity was sufficient to convince students of their own agency. Students struggle to view assignments in their class as part of authentic research, given the many experiments they have done where the answer has been known for decades (Mohrig, 2004).

Framing agency in communications

Previous experience with lab reports as a genre may limit students' perceptions about the types of choices they may make (Hicks & Bevsek, 2012), with an emphasis on making the "correct" choices in their communication rather than communicating to an audience. In both the junior and senior laboratory courses, instructors emphasized that students needed to consider audience expectations. Students in both courses were asked to evaluate the specific target of their communication as well as choices that they should make to better meet the needs of that audience. While the communication was not authentic, meaning, students did not actually communicate their results to an audience outside the classroom, students still made genre considerations and framed the ways they wanted to present their results with the audience in mind (Sharples, 1998).

Students reported greater consequentiality in the communications of their results over the experimental design itself. It is much more feasible for instructors to support students to make decisions in their communications where there are no concerns about things like resources or safety. In addition, the line between decisions students make in the communication and the impact on the final product is much clearer, leading students to better understand the ways that their decisions are consequential.

Fostering framing agency to support professional identity formation

Having opportunities to make consequential decisions appears to support the development of engineering identity (Du & Naji, 2021; Godwin et al., 2013, 2016; Morelock, 2017). Indeed, engineering practices that depend on such decisions—analyzing data and designing—contribute to students' identities as engineers (Choe et al., 2019; Meyers et al., 2012). This is in part because, fundamentally, professionals have the capacity to make consequential decisions, and displays of doing so position one as belonging (Holland et al., 1998; Tonso, 2014). From this perspective, engineering identity is also double-sided, meaning the individual positions themself as an engineer, and they are recognized by others as belonging in engineering. Opportunities that foster consequential agency in line with what professionals do simulates professional practice, and this is one of the few forms of interventions shown to enhance professional identity formation (Morelock, 2017). In contrast, a preponderance of experiences with low-agency tasks can signal to students that engineers are skilled technical problem solvers who possess little agency (Chua & Cagle, 2017; Kirn & Benson, 2018). Thus, framing agency may shed light onto learning experiences that offer the kind opportunity structure needed to develop professional identity. While instructors may intend to offer ill-structure, students may not perceive this as consequential, instead treating it as just another chance to demonstrate the accuracy of their knowledge.

Conclusions

We found students in design courses reported greater framing agency, compared to laboratory courses. This highlights the importance such courses have in students' preparation. We contrasted laboratory experiments with high or low authenticity. We found no differences between perceived authenticity or agency. This contrasts with research suggesting course-based research experiences seem more valuable to students (Auchincloss et al., 2014). We interpret this finding as revealing the challenge of overcoming students' expectations about such experiences. In future, we plan to investigate ways to make the authenticity more apparent to students. Students in both laboratory courses reported higher agency related to communication, compared to experimental design. Future studies will investigate ways to enhance agency related to experimental design, while retaining the feasibility.

Limitations and implications

The study comes with limitations, including a relatively small sample size and relying on self-reported data. The methods did not include a means to control or randomize participants, and all data from laboratory courses comes from a single institution. Further steps include collecting data from additional laboratory courses, including at institutions with different contexts.

Our findings suggest that more needs to be done to support students' perceptions of their agency beyond simply providing them with opportunities to frame problems. However, the endeavor of supporting students' agency and interaction with realistic complex problems is vitally important to their understanding both of what engineers do and how they develop identities as engineers. Writing can be a potential avenue to feasibly enhance agency.

Our results more broadly inform the ways that agency and perceptions of agency are related in students. Perceptions of agency can be informed by the problems at hand but can also be influenced by other external factors like prior experiences and time pressure. Ideas about authenticity and ill-structuredness can inform each other, with students viewing their task with less agency, but also less belief about the authenticity (even when the problem is very authentic).

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