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Consequential Agency in Chemical Engineering Laboratory Courses

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Abstract

In contrast to the dynamic treatment of other aspects of the curriculum, and despite being at the center of chemical engineering education, laboratory experiments have remained largely unchanged for decades. To characterize the potential impact changes to laboratory courses could have, we explored student perceptions across a department and characterized the kinds of opportunities students have to use their agency in these courses across universities. We used a survey to measure students' sense of agency across several laboratory courses in a chemical engineering department. We found students in laboratory courses across the chemical engineering laboratory sequence, including those engaged in authentic course-based research did not perceive the experiments as agentive or authentic. We infer students draw upon abundant low-agency experiences in laboratory experiments. We report on the agency that instructors report students possessing across two chemical engineering departments to understand variation across institutions. 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 the ability to solve complex engineering problems on paper take up much of students' time, their time in laboratory courses offer the opportunity to test these ideas firsthand. Laboratory experiments vary in offering students opportunities to make decisions [1], such as 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 courses, which tend to be cookbook in nature [2]. Yet, those foundational experiences may shape students' perceptions of the laboratory courses as being an opportunity to demonstrate their capacity to deliver the expected, known answer, rather than participating in a discovery process [3, 4].

There are four domains in which students can make *consequential* choices in laboratory courses: (1) experimental design before doing the laboratory experiment; (2) variables, data collection frequency, and documentation during their experiments; (3) data analysis and interpretation; and (4) communication of their purpose, methods, and conclusions. By considering these domains, we can characterize the opportunities each laboratory experiment offers students to use their agency; we define this as *opportunity structure*, a construct we adapt [5, 6], defining it as a perceived decision space shaped by past experiences, curricular designs, and norms.

To better understand the ways that students perceive the opportunity structure across a wide range of laboratory experiments, we surveyed chemical engineering students in laboratory courses across all four upper-division laboratory courses of the program. We extend the notion of framing agency—the capacity to make decisions consequential to the framing of *design* problems [7-9]—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 into comparatively simple changes that encourage students to take more agentive roles. We sought to answer three research questions:

1. To what extent do students report consequential agency in their laboratory experiments?
2. To what extent do students' perceptions of their agency differ across the two domains of (a) experimental design and (b) communication of results?
3. To what extent do students' perceptions of the authenticity of the experiments differ?
4. To what extent does the opportunity structure vary across multiple courses at two institutions?

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" [10].

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 [11]. Designers direct the process of framing and reframing problems [12]. This ability is consequential as the framing determines the ultimate choices and outcomes a designer can make. This empowerment to make such decisions is a specialized form of agency, termed framing agency [7-9].

The bounds on agency can be thought of as set by the opportunity structure [13], 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; 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 [14].

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 [15]. As students advance in their programs of study, labs become more complex, meaning the number of variables and the relationships between variables increases [11]. 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 [16]. Such problems may even be part of the authentic research process, such as when faculty bring their research into the classroom through course-based undergraduate research experiences [17]. In this way, more authentic problems should support greater agency. However, the preponderance of experience with well-structured problems could sabotage the sense of authenticity for students.

How does framing agency relate to communication?

Writing tasks 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 [18]. These reports can reinforce the idea that work is judged for accuracy, rather than authentically communicating new knowledge to an audience [19]. Yet, authentic technical communication, even when fit into genre and journal expectations, can be an ill-structured, iterative process much like design [20], in that authors define stakeholders (audience), purpose, and make decisions to reach those goals [21]. 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 the agency in a sequence of chemical engineering laboratory courses. We then explored the opportunity structure across a broader range of courses and settings to understand the transferability of our results.

Setting and participants

To answer the first three research questions, we conducted a survey in a chemical engineering department at the University of New Mexico (UNM), which is a Hispanic-serving, research university. Following IRB approval, we collected data in one 3-credit and four 1-credit semester-long laboratory courses (Table 1). The department had between 30 and 75 students in each graduating class. To answer research question 4, we asked instructors from UNM and Montana State University (MSU) to rate the students' agency across specific experiments (Table 1). We provided a scale of 1 (low agency) to 3 (high agency) across four domains (experimental design, experiment, and data collection, data analysis and interpretation, and communication, Table 2).

Table 1. Overview of surveyed laboratory experiments, sample sizes, and course credits

Course sequence	*Description of experiments and sample size*
UNM 1	Bomb calorimetry of sucrose with a benzoic acid standard then analyzed the accuracy of results and the error of the experiment. Students determine the thesis of their communication based on their results and decide what is most compelling. (n = 63)
UNM 2	Calculation of the friction and corresponding pressure drop of water flowing through pipes with different fittings and bends during turbulent flow. They created a 20-minute

	presentation based on their findings from an outline of expectations but presented their own context for how the findings might be relevant. (n = 31)
UNM 3	Batch distillation of ethanol and water mixture with prescribed operating conditions. Students then presented a short talk detailing their findings and the efficiency of the column based on explicit instructions about the content and the order it should be presented. (n = 72)
UNM 4	Optimization of catalytic selective hydrogenization of acetylene into ethylene while minimizing the conversion of ethylene into ethane. The catalysts used by each group were 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 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 (n = 31)
MSU 1	In the heat exchanger optimization laboratory, students develop a model to predict performance of one or more of three miniature shell-and-tube or double pipe heat exchangers (Exergy LLC). They have the ability to control fluid flowrates and measure temperature and pressures (n = 28)
MSU 2	In the friction and fluid flow laboratory, the objective was for students to determine friction factors from pressure drop data for straight copper pipe as well as equivalent lengths for several types of fittings including elbows and a globe valve. Students statistically compare values to those from the literature. The experimental set up was built in-house. (n = 31)
MSU 3	In the continuous stirred tank reactor (CSTR) experiment, students obtain the reaction rate constant for the saponification of ethyl acetate by sodium hydroxide in a CSTR (Armfield Limited, CEM-MKII Reactor). (n = 28)
MSU 4	In the reaction kinetics experiment, students approximate the Michaelis Menten parameters for a reaction of p-nitrophenyl phosphate (PNPP) as catalyzed by the enzyme alkaline phosphatase using a spectrophotometer (Thermo Electron Corp., GENESYSTM 10 Series), statistically compare the results to values in the literature and use the parameters to develop a model that predicts enzyme kinetics as a function of substrate concentration. The model was also compared to theoretical values (n = 33)

Table 2. Tasks with potential opportunity structure across four domains

Domain	*Tasks*
1: Experimental design	Set lab objectives; Select variables; Choose apparatus
2: Experimental oversight	Collect Data; Document in-lab events; Correct for in-lab issues
3: Data analysis & interpretation	Analyze data; Interpret results
4: Communication	Choose type; Format writing; Identify content; Choose audience; Set purpose

Data collection and analysis

We adapted the 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 [22]. Specifically, we adapted questions to the context of experimental design and laboratory decision-making within the original factors (Table 3). In addition, we added two questions about authenticity.

Students completed the survey after completing their laboratory experiment. We used descriptive statistics for all laboratory experiments. We used repeated-measures two-way ANOVA to evaluate differences between the characterization of student agency across sub constructs of agency for all the UNM laboratory courses as well as domains of the laboratory (experimental design versus communication). We used one-way ANOVA to characterize the differences between courses of student conceptions of the authenticity of their experiment.

Table 3. Consequential agency survey, using construct-specific 7-point Likert scales

Questions by construct
Opportunity: Considering the experiment, have you had many or few: • opportunities to make decisions as a team related to your experimental design and interpretation of results? • opportunities to make decisions personally related to your experimental design and interpretation of results?
Constrainedness: Considering these constraints, how free or restricted: • have you felt when making decisions yourself? • have your teammates seemed when making decisions? How free or limiting does the experiment seem to be?
Responsibility: How responsible or not responsible have you felt: • for making decisions personally? • for coming up with your own ways to make progress on the experimental design and interpretation of results? • for the outcomes of the experiment? • for communicating your experimental plan and results? • for making decisions as a team?
Tentativeness: How certain or uncertain do you feel that: *(*Reverse coded)* • you have to carry out the experiment as given to you? * • you have to just collect data as you were asked to? * • there is a single right way to conduct the experimental design and interpretation of results?*
[***Individual / Team***] [Experimental Design / Communication] Agency: Considering the [***individual, team***] decision made in the course of this [experimental / the communication process you described] you described, how important or unimportant was: • the decision? • the impact of that decision on [your experimental design and interpretation of results / on the final communication]?
Learning Agency: How much or little have you learned as a result of: • decisions about the experimental design and interpretation of results [***I:*** you personally made?; ***T:*** a teammate made?] • decisions about the preparation of the communication of your experimental plan and results [***I:*** you personally made?; ***T:*** a teammate made?]
Authenticity How likely or unlikely is it that your results • will be used to inform future research? • will be shared with others outside the course, in a research lab, a publication, or similar?

Results

We organize the results by research question.

Students' perceptions of their agency in laboratory experiments

The first question compared students' general perceptions of their agency across four semesters of upper-division laboratory experiments. Overall, we found that students reported differences in their perceptions of their agency between courses (Figure 1, refer to Appendix 1 for complete descriptive statistics).

To determine the significance of these differences, we conducted a mixed model ANOVA, with a between-subject factor of course and a within-subject factor of agency subconstruct. Due to a significant Mauchly's test of sphericity, $W(6) = 0.69$, $p < .001$, we report results of ANOVA using the Huynh–Feldt correction to correct for degrees of freedom ($\varepsilon = 0.83$) for both the repeated factor and the interaction effect. The assumption of homogeneity of variance has been violated $F(7) = 556.15$, $p < .001$, however, ANOVA is robust to violations of the homogeneity of variance. Normality has likewise been violated ($p < .001$), as expected for Likert-scaled items.

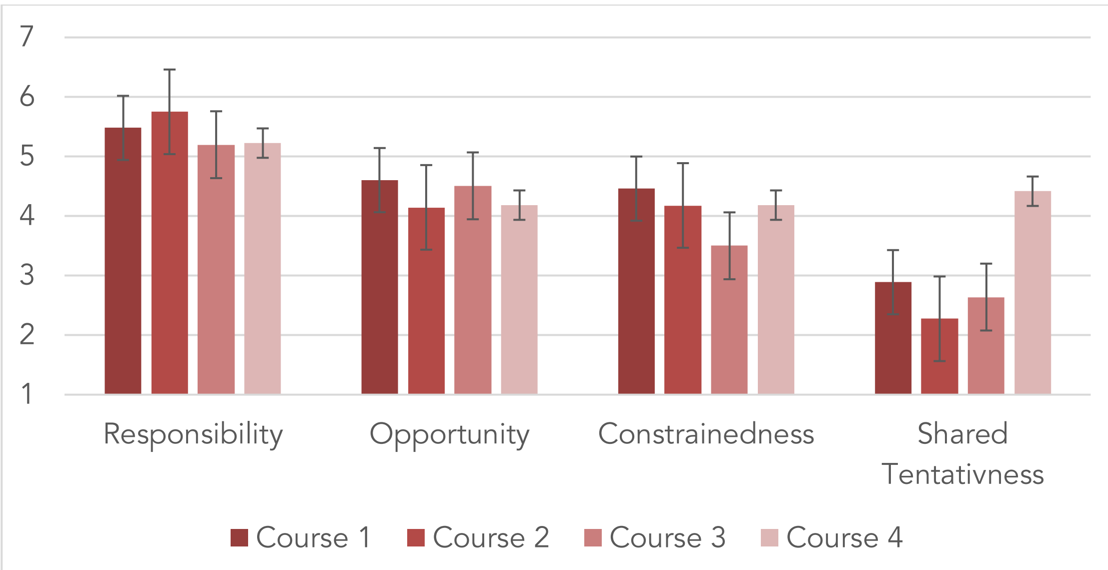

Figure 1. Average scores by course on each subconstruct

We found a significant interaction effect (Table 4) and thus conducted post hoc one-way ANOVAs for each factor (Table 5).

Table 4. Results of two-way repeated measure ANOVA

Effect	*DFn*	*DFd*	*SSn*	*SSd*	*F*	*p*	η^2
(Intercept)	1	192	11992.26	439.53	5238.64	< .001	.91
Course	3	192	35.24	439.53	5.13	< .001	.03
Subconstruct	2.49	477.51	473.31	786.17	115.59	< .001	.28
Course*Subconstruct	7.46	477.51	98.49	786.17	8.02	< .001	.07

There were significant differences between courses related to reported constrainedness, $F(3,192) = 4.6$, $p = .004$, $\eta^2 = .07$, a medium effect. Post hoc Tukey testing showed students in course 1 reported significantly lower constrainedness than students in course 3, $p = .002$. This suggests that the experiments in course 3 may have offered students a more restricted opportunity structure.

There were significant differences between courses related to reported shared tentativeness, $F(3,192) = 17.76$, $p < .001$, $\eta^2 = .13$, a large effect. Tukey testing showed students in course 4 reported significantly higher tentativeness compared to course 1, $p = .001$, course 2, $p < .001$, and course 3, $p < .001$. Overall, this suggests course 4 offered an opportunity structure more aligned with the idea of framing agency, in that the students were likelier to recognize their role in making consequential decisions.

Table 5. Post-hoc one-way ANOVA by subconstruct

	Df	*SS*	*MS*	*F*	*p*
Constrainedness					
Course	3	33.30	11.08	4.60	.004
Residuals	192	462.70	2.41		
Responsibility					
Course	3	7.98	2.66	2.593	.05
Residuals	192	197.07	1.03		
Opportunity					
Course	3	6.66	2.22	1.66	.18
Residuals	192	256.66	1.34		
Shared Tentativeness					
Course	3	85.84	28.61	17.76	< .001
Residuals	192	309.29	1.61		

Students' perceptions of their agency related to experimental design and communication

In research question two, we contrasted students' perceptions of their individual and shared agency related to experimental design versus communication between the four courses. Students varied in their reports of agency across courses and domain (Figure 2, refer to Appendix 2 for complete descriptive statistics).

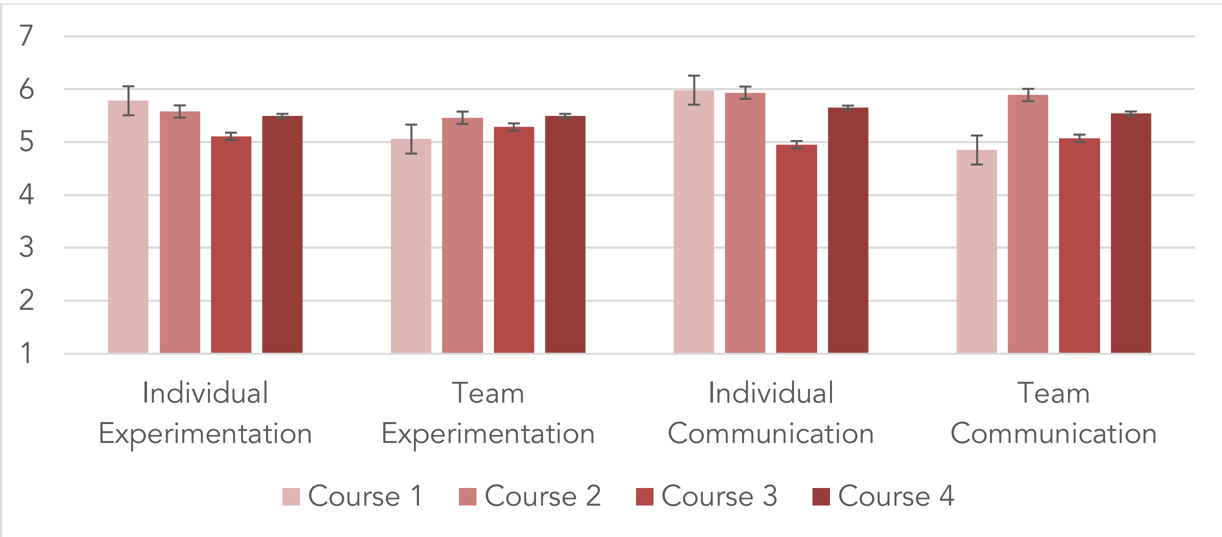

Figure 2. Average scores by course for each domain

We conducted a two-way mixed-design ANOVA to determine the extent of the significance of the variance (Table 6). Due to a significant Mauchly's test of sphericity, $W(6) = 0.74$, $p < .001$, we report results of ANOVA using the Huynh–Feldt correction to correct for degrees of freedom (ε=0.85) for both the repeated factor and the interaction effect.

Table 6. Repeated measures ANOVA of agency in two domains (experimental design and communication) between junior and senior courses

Effect	*DFn*	*DFd*	*SSn*	*SSd*	*F*	*p*	η^2
(Intercept)	1	192	19924.10	663.25	5767.70	< .001	.95
Course	3	192	39.49	663.25	3.81	< .001	.04
Domain	3	487.50	10.44	328.90	6.09	< .001	.01
Course* Domain	9	487.50	51.54	328.90	10.03	< .001	.05

As a posthoc test, we conducted one-way ANOVAs for each domain, with a between-subject factor of course (Table 7). While there were no significant differences across courses in reported team experimental design agency, $F(3,192) = 1.10$, $p = .35$, the results indicate a significant effect of individual experimental design agency between courses, $F(3,192) = 4.29$, $p = 0.006$, $\eta^2 = .06$, a medium effect. Post hoc Tukey testing indicates that students in course 1 reported significantly greater individual agency related to designing their experiments, compared to students in course 3, $p = .003$.

Table 7. Results of one-way ANOVA of individual and team experimental design and communication agency

	Df	*SS*	*MS*	*F*	*p*
Individual Experimental Design Agency					
Course	3	15.84	5.28	4.29	< .001
Residuals	192	236.19	1.23		
Team Experimental Design Agency					
Course	3	5.60	1.86	1.10	0.352
Residuals	192	325.80	1.70		
Individual Communication Agency					
Course	3	42.41	14.14	15.12	< .001
Residuals	192	179.47	0.94		
Team Communication Agency					
Course	3	27.20	9.07	6.95	< .001
Residuals	192	250.60	1.31		

In terms of communication, we found a significant difference in reported individual communication agency between courses, $F(3,192) = 15.12$, $p < .001$, $\eta^2 = .19$, a large effect. Post hoc Tukey testing indicates that students in course 3 reported significantly lower individual communication agency compared to those in course 1, $p < .001$, course 2, $p < .001$, and course 4, $p < .001$. Likewise, we found significant differences related to team communication agency, $F(3,192) = 6.95$, $p < .001$, $\eta^2 = .10$, a large effect. Post hoc

Tukey testing indicates that students in course 2 reported significantly higher team communication agency than those in course 1, $p < .001$, and course 4, $p = < .001$; students in course 4 reported significantly higher team communication agency than those in course 1, $p = .03$.

Students' perceptions of the authenticity of laboratory experiments

For research question three we compared the three inauthentic experiments to the second-semester senior experiment, which was part of faculty research. Students varied somewhat in their reports of authenticity across courses (Figure 3, refer to Appendix 3 for complete descriptive statistics).

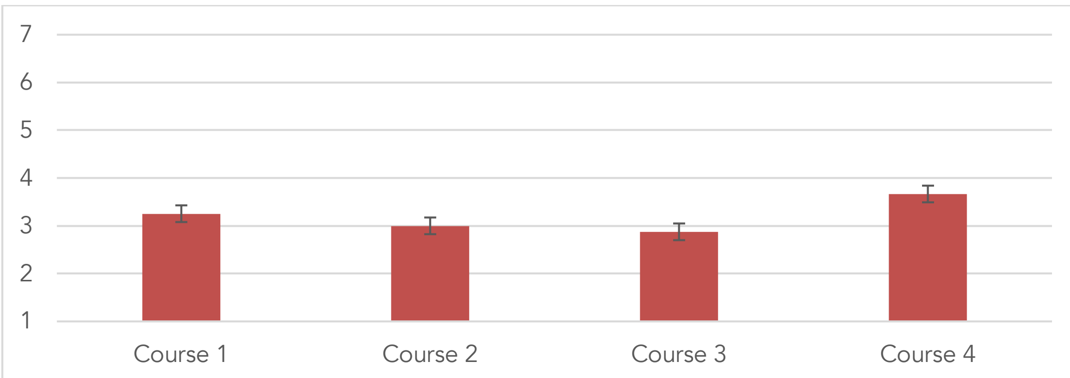

Figure 3. Average scores of authenticity by course

Students reported no significant difference in their perceptions of the authenticity between any of the courses, $F(3, 195) = 1.97$, $p = .12$, $\eta^2 = .03$, a small to medium effect. This indicates that even experiments designed to be authentic do not necessarily translate to perceived authenticity.

Opportunity structure in laboratory experiments

To answer the fourth research question, we consider the variation of opportunity structure across four domains and across two chemical engineering departments (Figure 4, Appendix 4). We found variability in the opportunity structure between chemical engineering programs, as well as between domains within each program. In general, however, instructors reported that their laboratory experiments did not offer an opportunity structure that allowed students to make consequential decisions related to experimental design or reporting of results.

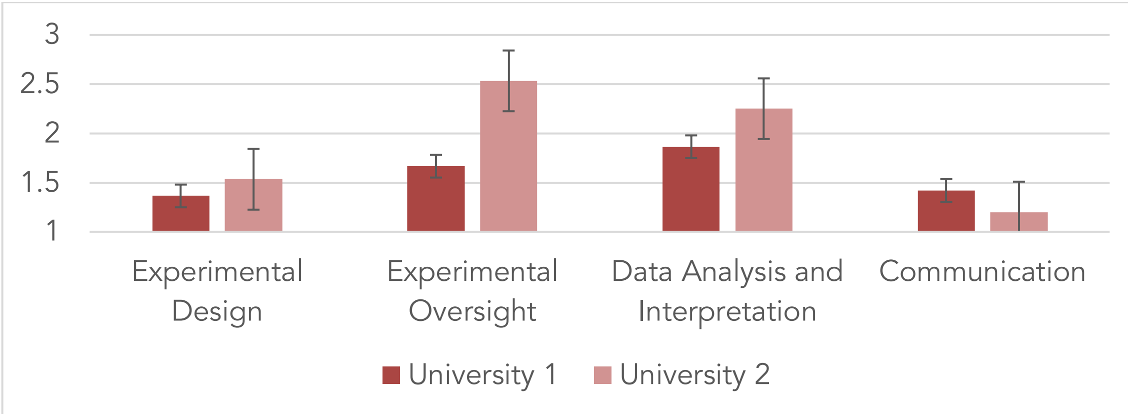

Figure 4. Instructor reported opportunity structure across four domains and two universities on a scale of 1 (low student agency) to 3 (high student agency)

Conclusions and discussion

We sought to characterize chemical engineering students' perceptions of their agency and opportunities for them to make consequential decisions in laboratory courses. We found that students reported a sense of responsibility, a key subconstruct for agency. Yet they also reported ambivalence related to their opportunities to make decisions and their ability to navigate constraints, reflecting their general sense of needing to just carry our experiments designed by others. The fact that students feel as though they are responsible for the outcomes of the experiment, but report they should do what is being asked of them suggests students may be drawing upon their experiences in these experiments with the introductory experiments done in chemistry and physics in which students act much more as executors of the protocol rather than as agents of the scientific process.

In more closely examining agency in two domains, experimental design and communication of results, we found that students expressed some sense of agency. Some courses offered more individual or more shared agency in these domains. We argue that varied assignments across experiments can contribute to the development of both shared and individual agency in these domains. For instance, in some courses, student complete individual reports, in others, team reports. In some, they develop individual plans prior to bringing their plans together as a team. Such activities offer opportunities for students to develop their own reasoning about experiments, while also providing feedback within the team. While this can function well for a planning exercise, we caution against having students create drafts in the same format as the submission. Specifically, we advocate for individual prework that prepares students from bringing ideas together sensibly, rather than pasting chunks together to forms a pastiche. As an example, students could develop handwritten figures depicting the sequence of steps they think should be taken, prior to agreeing on an experimental plan.

In general, students reported low authenticity in their experiments, an accurate assessment given that many of the experiments have remained unchanged for decades. It is noteworthy that students completing the experiment in course 4, designed to be more authentic, reported significantly higher shared tentativeness compared to the less authentic labs. This course also reportedly offered an opportunity structure more aligned with consequential agency than other courses. Yet, students did not identify this course as being more authentic. This contrasts with research suggesting course-based research experiences seem more valuable to students [23]. We interpret this finding as revealing the challenge of overcoming students' expectations about such experiences. This may reflect the impact of a preponderance of experiences with low agency and low authenticity laboratory experiments by this point in their educations. Students have a wealth of experiences that indicate that laboratory experiments are fake, performed merely for practice, and this experience may prevent them from recognizing an authentic experiment as such. In the future, we plan to investigate ways to make the authenticity more apparent to students.

The variation in opportunity structure across chemical engineering programs demonstrates firstly that we should support students to have consequential agency as they move through the laboratory sequence. However, we recognize the challenges that creating opportunity structure that offers this agency presents, especially in larger courses. Limited research has hinted at feasible ways to enhance agency. Studies on undergraduates suggest students may struggle with open-ended experiments, but ultimately appreciate their salience for professional practice [24]. In other settings, such as in physics [25, 26] and environmental engineering [16] higher-agency laboratory experiments were appreciated by students. While this suggests students may be open to changes, these studies shed little light on the relationships between agency, learning, and identity. Recent research on an undergraduate course sequence suggests students can benefit from scaffolded instruction followed by more self-directed laboratory experiments [1]. However, this approach shares challenges with fully authentic research experiences in that it can be challenging to support students, even in teams, who propose varied experimental designs. This limits both scalability and adoption, despite its value. One approach to counter this is providing constraints that limit the ill-structuredness of the problem [4], but this approach can over-constrain opportunities. Our ongoing research furthers this agenda of investigating ways to enhance agency across the domains, especially related to planning and communicating, while retaining attention to feasibility.

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 are from laboratory courses at a single institution. Our ongoing research addresses some of these issues by expanding data collection to additional sites, and conducting design-based research studies [27, 28] that provide a more comprehensive understanding of how students develop agency in response to specific instructional approaches.

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References

[1] E. Burkholder, L. Hwang, E. Sattely, and N. Holmes, "Supporting decision-making in upper-level chemical engineering laboratories," *Education for Chemical Engineers,* vol. 35, pp. 69-80, 2021, doi: 10.1016/j.ece.2021.01.002.

[2] M. R. Hauwiller, J. C. Ondry, J. J. Calvin, A. M. Baranger, and A. P. Alivisatos, "Translatable research group-based undergraduate research program for lower-division Ssudents," *Journal of Chemical Education,* vol. 96, no. 9, pp. 1881-1890, 2019, doi: 10.1021/acs.jchemed.9b00159.

[3] S. E. Brownell *et al.*, "A high-enrollment course-based undergraduate research experience improves student conceptions of scientific thinking and ability to interpret data," *CBE—Life Sciences Education,* vol. 14, no. 2, pp. 1-14, 2015, doi: 10.1187/cbe.14-05-0092.

[4] W. Chen, U. Shah, and C. Brechtelsbauer, "The discovery laboratory–A student-centred experiential learning practical: Part I–Overview," *Education for Chemical Engineers,* vol. 17, pp. 44-53, 2016, doi: 10.1016/j.ece.2016.07.005.

[5] R. A. Cloward and L. E. Ohlin, *Delinquency and opportunity: A theory of delinquent gangs*. New York, NY: The Free Press, 1960.

[6] E. B. Moje, ""To be part of the story": The literacy practices of gangsta adolescents," *Teachers college record,* vol. 102, no. 3, pp. 651-690, 2000, doi: https://www.tcrecord.org/books/PrintContent.asp?ContentID=10517.

[7] V. Svihla, J. R. Gomez, M. A. Watkins, and T. B. Peele-Eady, "Characterizing framing agency in design team discourse," *Proceedings of the American Society for Engineering Education Annual Conference & Exposition,* pp. 1-19, 2019, doi: 10.18260/1-2--32505.

[8] V. Svihla and T. B. Peele-Eady, "Framing agency as a lens into constructionist learning," *Proceedings of Constructionism,* pp. 313-324, 2020. [Online]. Available: http://www.constructionismconf.org/wp-content/uploads/2020/05/C2020-Proceedings.pdf.

[9] V. Svihla, T. B. Peele-Eady, and A. Gallup, "Exploring agency in capstone design problem framing," *Studies in Engineering Education,* vol. 2, no. 2, pp. 96–119, 2021, doi: 10.21061/see.69.

[10] J. Strobel, J. Wang, N. R. Weber, and M. Dyehouse, "The role of authenticity in design-based learning environments: The case of engineering education," *Computers & Education,* vol. 64, pp. 143-152, 2013, doi: 10.1016/j.compedu.2012.11.026.

[11] D. H. Jonassen, "Toward a design theory of problem solving," *Educational Technology Research and Development,* vol. 48, no. 4, pp. 63-85, 2000, doi: 10.1007/BF02300500.

[12] M. A. Runco and I. Chand, "Problem finding, problem solving, and creativity," in *Problem finding, problem solving, and creativity*, M. Runco Ed. Norwood, NJ: Ablex Publishing, 1994.

[13] D. Narayan and P. Petesch, "Agency, opportunity structure, and poverty escapes," in *Moving out of poverty: Cross-disciplinary perspectives on mobility*, D. Narayan and P. Petesch Eds. Washington, DC: The World Bank, 2007, pp. 1-44.

[14] M. Basadur, G. B. Graen, and S. G. Green, "Training in creative problem solving: Effects on ideation and problem finding and solving in an industrial research

organization," *Organizational Behavior and Human Performance,* vol. 30, no. 1, pp. 41-70, 1982, doi: 10.1016/0030-5073(82)90233-1.

[15] J. R. Mohrig, "The problem with organic chemistry labs," *Journal of Chemical Education,* vol. 81, no. 8, p. 1083, 2004, doi: 10.1021/ed081p1083.

[16] J. R. Flora and A. T. Cooper, "Incorporating inquiry-based laboratory experiment in undergraduate environmental engineering laboratory," *Journal of Professional Issues in Engineering Education and Practice,* vol. 131, no. 1, pp. 19-25, 2005, doi: 10.1061/(ASCE)1052-3928(2005)131:1(19).

[17] A. M. Chase, H. A. Clancy, R. P. Lachance, B. Mathison, M. M. Chiu, and G. C. Weaver, "Improving critical thinking via authenticity: the CASPiE research experience in a military academy chemistry course " *Chemistry Education Research and Practice,* vol. 18, no. 1, pp. 55-63, 2017, doi: 10.1039/C6RP00171H.

[18] R. W. Hicks and H. M. Bevsek, "Utilizing problem-based learning in qualitative analysis lab experiments," *Journal of Chemical Education,* vol. 89, no. 2, pp. 254-257, 2012, doi: 10.1021/ed1001202.

[19] I. I. Z. Abidin, S. F. H. S. Zain, F. E. M. Rasidi, and S. Kamarzaman, "Chemistry lab reports at university: To write or not to write," *Journal of College Teaching & Learning,* vol. 10, no. 3, pp. 203-212, 2013, doi: 10.19030/tlc.v10i3.7937

[20] E. Howell, D. Reinking, and R. Kaminski, "Writing as creative design: Constructing multimodal arguments in a multiliteracies framework," *Journal of Literacy and Technology,* vol. 16, no. 1, pp. 2-36, 2015. [Online]. Available: http://www.literacyandtechnology.org/uploads/1/3/6/8/136889/jlt_v16_1.pdf.

[21] M. Sharples, *How we write: Writing as creative design*. Routledge, 2002.

[22] V. Svihla, A. Gallup, and S. P. Kang, "Development and insights from the measure of framing agency," *Proceedings of the American Society for Engineering Education Annual Conference & Exposition,* pp. 1-17, 2020, doi: 10.18260/1-2--34442.

[23] L. C. Auchincloss *et al.*, "Assessment of course-based undergraduate research experiences: A meeting report," *CBE Life Sciences Education,* vol. 13, no. 1, pp. 29-40, 2014, doi: 10.1187/cbe.14-01-0004.

[24] B. Young, H. Yarranton, C. Bellehumeur, and W. Svrcek, "An experimental design approach to chemical engineering unit operations laboratories," *Education for Chemical Engineers,* vol. 1, no. 1, pp. 16-22, 2006, doi: 10.1205/ece.05005.

[25] Z. Y. Kalender, M. Stein, and N. Holmes, "Sense of agency, gender, and students' perception in open-ended physics labs," *arXiv preprint arXiv:2007.07427,* 2020.

[26] Z. Y. Kalender, E. Stump, K. Hubenig, and N. Holmes, "Restructuring physics labs to cultivate sense of student agency," *Physical Review Physics Education Research,* vol. 17, no. 2, p. 020128, 2021, doi: 10.1103/PhysRevPhysEducRes.17.020128.

[27] V. Svihla, "Advances in design-based research in the learning sciences," *Front Learn Res,* vol. 2, no. 4, pp. 35-45, 2014, doi: 10.14786/flr.v2i4.114.

[28] The Design-Based Research Collective, "Design-based research: An emerging paradigm for educational inquiry," *Educ Res,* vol. 32, no. 1, pp. 5–8, 2003, doi: 10.3102/0013189X032001005.

Appendix 1. Descriptive statistics by sub construct

Course	*Subconstruct*	*n*	*Mean*	*SD*
1	Responsibility	63	5.48	1.08
	Opportunity		4.60	1.06
	Constrainedness		4.46	1.20
	Shared Tentativeness		2.89	1.61
2	Responsibility	31	5.75	0.96
	Opportunity		4.15	1.47
	Constrainedness		4.18	1.76
	Shared Tentativeness		2.27	0.89
3	Responsibility	72	5.19	1.02
	Opportunity		4.51	1.14
	Constrainedness		3.50	1.82
	Shared Tentativeness		2.64	0.98
4	Responsibility	30	5.23	0.91
	Opportunity		4.18	1.02
	Constrainedness		4.18	1.26
	Shared Tentativeness		4.42	1.40

Appendix 2. Descriptive statistics by domain for each course.

Course	*Domain*	*n*	*Mean*	*SD*
1	Individual Experimental Design Agency	63	5.78	0.95
	Team Experimental Design Agency		5.06	1.48
	Individual Communication Agency		5.98	0.83
	Team Communication Agency		4.85	1.34
2	Individual Experimental Design Agency	31	5.58	1.24
	Team Experimental Design Agency		5.46	1.49
	Individual Communication Agency		5.94	1.04
	Team Communication Agency		5.89	0.94
3	Individual Experimental Design Agency	72	5.11	1.27
	Team Experimental Design Agency		5.29	1.20
	Individual Communication Agency		4.95	1.12
	Team Communication Agency		5.07	1.15
4	Individual Experimental Design Agency	30	5.50	0.84
	Team Experimental Design Agency		5.50	0.84
	Individual Communication Agency		5.66	0.73
	Team Communication Agency		5.54	0.81

Appendix 3. Descriptive statistics for authenticity for each course.

Course	*n*	*Mean*	*SD*
1	63	3.25	1.39
2	31	3.00	1.87
3	72	2.88	1.58
4	31	3.67	1.65

Appendix 4. Descriptive statistics for opportunity structure (1= low, 3 = high) for laboratory courses at two universities (P = primary university from which other data were collected, T= additional university to support transferability)

Course	*1: Set Objectives*	*1: Select variables*	*1: Choose Apparatus*	*2: Collect data*	*2: Document*	*2: Correct*	*3: Analyze data*	*3: Interpret results*	*4: Choose type*	*4: Format writing*	*4: Identify content*	*4: Choose audience*	*4: Set purpose*
P1	1	1	1	1	1.5	1	3	2.5	1	1.5	2	1	2.5
P2	1	1	1	1	1	1	1	1	1	1	1	1	1
P3	1	2.5	1	2	2.5	2	2	2	1	2	2	1.5	1.5
P4	1.75	2.5	1	2	2.25	2.25	1.75	2.25	1.25	1.75	1.75	1.75	1.25
T1	1	2	2	2	2	3	2	3	1	1	2	1	1
T2	1	2	1.25	2.5	3	3	2.25	1.5	1	1	2	1	1
M	**1.14**	**1.90**	**1.29**	**1.86**	**2.10**	**2.29**	**1.95**	**2.14**	**1.05**	**1.29**	**1.81**	**1.19**	**1.24**
Domain M	**1.44**			**2.08**			**2.05**		**1.31**				