2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering
Education for 130 Years
ASEE
Paper ID #39184

Exploring the Role of Mentorship in Enhancing Engineering Students' Innovation Self-Efficacy

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Abstract

This paper explores a learning environment that may foster innovation in the engineering curriculum. In this study, the innovation self-efficacy of undergraduate environmental engineering students is explored in a target course before and after a curricular intervention which has been shown to have the potential to enhance innovation self-efficacy. A design mentor and an education mentor outside of the course supported the students through their engineering design process. During the start and end of this curricular intervention, a survey consisting of the Very Brief Innovation Self-Efficacy scale (ISE.5), the Innovation Interests scale (INI), and the Career Goals: Innovative Work scale (CGIW) was administered to measure students' shift in: 1) Innovation Self-Efficacy, 2) Innovation Interests, and 3) Innovative Work. Formal feedback from the mentors was utilized in interpreting the survey outcomes. Results generated from this survey show a modest increase in innovation self-efficacy. Nevertheless, less impact was found compared to the previous year when innovation attitudes were weaker in the pre-survey.

Introduction

Education for innovation is of critical importance in our era (Xiao, 2022; Anderson et al, 2014; Law and Geng, 2019; Barack and Usher, 2019). Innovation will be necessary to meet the Grand Challenges for environmental engineering in the 21st Century identified by the National Academies (NASEM, 2019). There are a variety of definitions for innovation, but at its most basic "innovation simply involves the introduction of a new (or significantly improved) product or service in the marketplace or the implementation of a new (or significantly improved) process" (Medina et al., 2005). Sometimes the concept of innovation in engineering seems to be used almost interchangeably with creativity and/or entrepreneurship. Knowledge about innovation in industry has been embedded in higher education programs with the understanding that engineering students need to be prepared to become the next generation of innovation leaders (Cropley, 2015; Law and Geng, 2019). Previous research found students' self-rated skills and abilities related to innovation were strongly correlated to creativity (0.816), moderately correlated with product development (0.614), start-up processes (0.619), leadership (0.545), and financial value (0.517), and weakly correlated with risk (0.354) and teamwork (0.269); the students encompassed majors in engineering, social sciences (including economics and business), math and natural sciences, engineering, and others. (Barakat et al., 2014).

It would not be unexpected if some of the characteristics of innovation vary from one industry, job type, or discipline to another. Dyer et al. (2008) characterized four innovative behaviors: questioning, observing, networking, and experimenting. One might imagine a researcher might be strong in questioning, experimenting, and observing, and weaker in networking; alternatively, an entrepreneur bringing a new product to market might excel in networking, questioning, and observing. Balau et al. (2012) distinguished between different types of innovation, such as technological innovation, product innovation, and process innovation. Environmental and chemical engineers are more often designing processes, in comparison to product design by mechanical engineers. More specific examples could contrast innovation for profit through new luxury products versus innovation for meeting basic human needs for water and sanitation in pursuit of sustainable development. In addition, innovation to bring a new product to market is likely a different skill set than innovation in basic research.

Previous research has found other differences among students in different engineering disciplines in relation to their social responsibility attitudes (Canney and Bielefeldt, 2015) and motivations toward engineering majors (Meyers and Mertz, 2011). The U.S. Bureau of Labor Statistics data shows that among all engineers, 43.5% are employed in industry and 15.3% in federal, state or local government; this is significantly different in environmental engineering where these sectors employ 7% and 28%, respectively. Studies have explored innovation in the public sector, noting this setting is distinct from private settings (Arundel et al., 2019; Damanpour and Schneider 2008). In addition, some of the definitions of innovation seem directly incompatible with these public sector jobs; Medina et al. (2005) in discussing other literature state "the criteria for success in innovation are commercial, while for invention they are technical." Thus, the disciplinary setting of this work in environmental engineering is significant.

In a previous study, the innovation self-efficacy of undergraduate students enrolled in two junior and senior level environmental engineering courses was found to increase after students completed an activity on designing K-12 STEM projects related to the course outcomes (See full instrument in Bolhari and Tillema, 2022). In a follow-on study, it was of interest to evaluate the impacts of the addition of mentors into the curriculum design activity. Previous research found that various forms of mentoring might increase innovation self-efficacy. In co-curricular activities with communities via the group Design for America (DFA), student teams received brief weekly coaching sessions with professional designers, and interviews identified these as helping students build their innovation skills and confidence (Gerber et al., 2012). In a study with working adults, mentoring had a weak but statistically significant impact on creative self-efficacy (Bang and Reio, 2017).

Research Questions:

This research aims to answer the following two research questions:

1. How did the innovative attitudes of students enrolled in an environmental engineering course change after completing an open-ended team project to design a lesson to teach a water chemistry concept to K-12 students?
2. Did changing the team project to include meetings with two mentors (one for design and the other for a K-12 STEM teacher) change the impacts on students' innovation attitudes?

Methods

Adopting Validated Instruments and IRB Protocol

The pre- and post-survey is a critical component to answering the research questions posed in the study. The pilot survey implementation took place in the primary author's engineering Water Chemistry course of Fall 2022 under University of Colorado Boulder's Institutional Review

Board (IRB) protocol number 21-0473. The assessment tool was implemented before the curricular intervention (week 5 of the course in September 2022) and was implemented again immediately after the intervention ended (week 13 of the course in November 2022). This survey is a combination of the Innovative Behavior Scale (Dyer et al., 2011), Very Brief Innovative Self-Efficacy Scale, Innovation Interests Scale, and Career Goals Innovative Work Scale (Schar et al., 2017). IRB procedures and properties were followed throughout the work associated with this research.

Curricular Intervention

Data were collected from engineering Water Chemistry, an upper-level undergraduate environmental engineering course at the University of Colorado Boulder in Fall 2022. The timetable for the curricular intervention is depicted in Figure 1. The heart of curricular intervention was a 10-week class project where students were grouped up into thirteen teams (eleven teams of 5 students and two teams of 4 students).

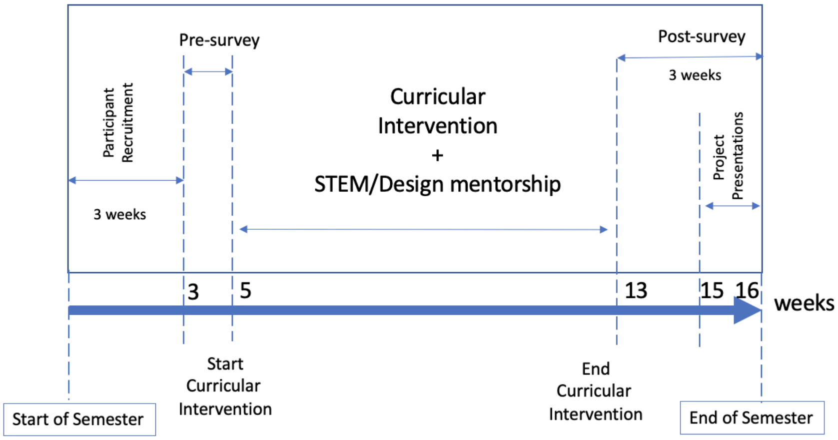

Figure 1- Timeline of the curricular intervention design and mentorship.

The start of the intervention posed an open-ended, hands-on, team-based design project where students were asked to:

1. Design a K-12 STEM activity of their choosing using Water Chemistry principles, for a target grade or a range of grades. Students were offered extra credit for creating video demonstrations of their lessons and experiments for STEM teachers' classroom use.
2. Seek written input from their Design Mentor by week 8. Two Design Mentors were project consultants from the University of Colorado Boulder and were introduced to the class in week 5. Students were encouraged to utilize Idea Forge's makerspace and the water chemistry lab for setting up their projects.
3. Seek written input from their STEM Education Mentor by week 8. The STEM Mentor was a K-12 STEM teacher, recruited from our local public school district, and was introduced to students in week 5. The STEM Mentor assisted students in design of developmentally appropriate content for the target grade or the range of grades.

4. Align their activity with either of these K-12 educational STEM standards: Common Core State Standard, Next Generation Science Standards (NGSS), or International Technology and Engineering Educators Association (ITEEA) Standards for Technological Literacy (STL).
5. Map out their activity to be hosted on the '*TeachEngineering'* digital library to reach a global audience. *TeachEngineering* is a standards-aligned, free-access curricular resource aimed at engaging students in exploring real-world engineering and engineering design principles focused on K-12 engineering education and offers more than 1,800 lessons and hands-on activities contributed by 57 contributors (including 40 National Science Foundation (NSF) funded GK-12 and Research Experience for Teachers (RET) engineering education grants) and with over 3.5 million users annually (TeachEngineering, 2023). The students had the opportunity to pursue classroom testing of their designed activities and lesson-plan publication with *TeachEngineering* after the intervention (after the post-survey) unless they notified the course instructor to object to this pursuit.
6. Presenting their design to the class by utilizing PowerPoint slides with or without a physical model and voting for the top three designs at the end of the semester.

A similar study was conducted in 2021 with the difference that steps 2 and 3 of the abovementioned intervention were missing. As a result, this 2022 study seeks to understand the impact of adding mentorship in enhancing the innovation self-efficacy of participants. The 2022 course consisted of 63 students, 59 environmental engineering students, 2 civil engineering majors, and 2 integrated design majors. One student (1.5%) was in their sophomore or second year of their undergraduate education, 34 students (54%) were in their junior or third year, 23 students (36.6%) were in their senior or fourth year, and 5 students (or 7.9%) were fifth-year seniors.

The 2021 course included similar student majors and ranks; specifically, a total of 62 students, 59 environmental engineering students, 1 civil engineering major, and 2 integrated design majors. Two students (3.2%) were in their sophomore or second year of their undergraduate education, 33 students (53.2%) were in their junior or third year, 22 students (35.5%) were in their senior or fourth year, and 5 students (or 8.1%) were fifth-year seniors.

Assessment Instrument

The assessment instrument used in the study was based on Schar et al. 2017. The survey included three aspects: Innovation Self-Efficacy (ISE) 5 items, Innovation Interests (INI) 4 items, and Career Goals: Innovative Work (CGIW) 6 items. The survey was previously evaluated for validity and reliability, using a dataset of ~5800 junior, senior, and 5th-year engineering students from 27 schools in 2016. The majors of these students were not reported, but if they mirror the engineering undergraduate degree recipients reported by the ASEE the dataset would be largely comprised of mechanical (24%), computing (12%), and electrical (10%); environmental only made up 1% of the graduates in 2016-2017 and civil/environmental an additional 0.8%. Schar et al. quote Bandura in that "scales of perceived efficacy must be tailored to the particular domain of functioning that is the object of interest" and "tailored to activity domains."

The key difference between the survey used in the current study (both 2021 and 2022) and the items in previously published studies was the response scale. Dyer et al. (2008) used a 7-point scale from strongly disagree to strongly agree. In the Schar et al. (2017) study a 5-point scale was used from not confident to extremely confident and a separate 'prefer not to answer' option. In the current study, the response options were one to six and the Google form limited the response scale to a lower and upper anchor; the lower anchor word used was "prefer not to answer" (PNA) and at the high-end terms were "extremely confident." (See full instrument in Bolhari and Tillema, 2022.)

Given the change in the response scale and the environmental engineering student context in this study, which might differ from other engineering disciplines, basic statistics were conducted to evaluate the internal consistency and reliability of the items (results in Table 1). Note that item responses corresponding to PNA were deleted (leaving a blank) prior to the reliability and validity calculations. The test was conducted on all of the combined pre and post-survey data from three environmental engineering courses in 2021 and 2022, giving a total of 153 responses (after responses more than 30% were incomplete, and answers of PNA were removed from the dataset). For the innovation self-efficacy (ISI) scale, the five items had good reliability. Neither Cronbach's alpha (based on the covariances among the items) nor the alpha based on standardized items (based on the correlations among items) could be improved by removing any of the 5 items. For the innovation interests scale (INI), the reliability was weak. The weaker alpha with only 4 items is not unexpected. The innovation interest scale had improved reliability when the 4th item was removed (Cronbach's alpha increased to 0.6189 and standardized alpha to 0.6145). This was not unexpected to the second author, who perceived the face validity of this item to be weak from an environmental engineering perspective. The career goals innovative work scale (CGIW) had good reliability; the reliability metrics were not improved by removing any 1 of the 6 individual items.

Table 1 - Internal consistency reliability.

Scale	# items	Cronbach's alpha	Standardized alpha	3 factor model loadings avg (range)
Innovation Self-efficacy (ISI)	5	0.7398	0.7507	0.52 (0.32 - 0.74^)
Innovation Interests (INI)	4	0.543	0.5649	0.40 (2 factors 0.75-0.80 #;)
Career Goals: Innovative Work (CGIW)	6	0.7685	0.7731	0.56 (0.26 - 0.76+)

^ 3 items more strongly loaded to another factor; + 2 factors loaded more strongly to another factor; # two factors did not significantly load to this factor (2 factors -0.11 to 0.15); instead loaded at 0.61 and 0.53 on the Career goals innovative work factor;)

The validity information on the structure of the survey instrument was weaker. An attempt to verify the structure with three factors using factor analysis found that the items did not cleanly load onto three separate factors as intended. For example, a number of the items loaded strongly onto two factors including three of the 5 Innovation Self-efficacy items, 2 of the 4 Innovation Interests items, and 2 of the Innovative Work Goals items. When the second author examined the items from the perspective of face validity, she believes that some items are not strongly aligned with typical environmental engineering work environments, particular items that specifically refer to products, business ideas, and marketplace.

Survey administration

The pre and post were administered on weeks 8 and 13 accordingly and they did not require students to answer all items. The only required question to answer was the consent to participate in the study. Since the primary author was the instructor of record for this course, an independent third party with no power or authority over the students was recruited to administer the pre/post surveys. This third party recruited the participants via email.

Respondents

Characteristics of the research participants are listed in Table 2. A limitation of the 2021 study was that the demographics of the participants were not requested and as a result are unknown.

Table 2 - Characteristics of the research participants in the 2021 and 2022 study.

Characteristic	2022 pre	2022 post	2021 pre	2021 post
Course enrollment	63	63	62	62
N survey respondents	47	40	25	21
Response rate, %	75%	63%	40	33
Gender: % male % female % non-binary % transgender	 47 47 4 2	 35 50 10 5	N/A	N/A
Race/Ethnicity % White/C % Hisp/Latinx % Multi/Biracial % not listed	 70 15 11 4	 73 8 13 8	N/A	N/A

^ Asian or Pacific Islander, Native American or Alaskan Native, Black or African American were listed as options, but no students selected these

Data Analysis

On the 2022 post-survey data two responses had 6 or more Prefer Not to Answer (PNA) ratings among the 15 innovation items; these responses were removed in their entirety from the dataset; a similar data cleaning removed one post survey response from 2021 (5 PNA responses). For the remaining responses, PNA responses were deleted on a per-item basis. Comparison among groups used t-tests on the average response for each innovation sub-scale. Although non-parametric statistics are generally best for Likert-type response data, t-tests have also been found to be robust for these analyses (Norman 2010; Sarle 1995).

Formal feedback collected from the mentors

The mentors were provided with a Google document that included some basic instructions about meeting with their teams and encouraged them to document their notes from meeting with the teams. While they were instructed to focus on answering technical questions (design mentors) and alignment of their projects with the K-12 STEM curriculum (teacher mentor), they were asked to note if they observed any among five innovative behavioral components: questioning, observing, experimenting, idea networking, and associational thinking. The team numbers and student names were pre-filled into the table, with space to record both the first and design review meeting and fill in the mentor's name, meeting date, individuals attended, and meeting length.

Results

A summary of the survey results is provided in Table 3, where the multiple items that comprise the scale have been averaged together. In 2021 there were significantly higher post scores in innovation self-efficacy, interest, and career goals. In 2022 there was a more modest increase in innovation self-efficacy among the students on the post-survey; there were no significant changes in innovation interest or career goals. In 2022, the innovation attitudes on the pre-survey were more positive. The end-of-semester innovation scores were similar in 2021 and 2022.

Table 3 - Student Innovation Attitudes: Average and standard deviation

	2021 pre (n=25)	2021 post (n=20)	2022 pre (n=47)	2022 post (n=38)
Innov Self Efficacy	3.9 ± 1.2	4.7 ± 1.0 **	4.4 ± 1.2 P	4.7 ± 1.1 *
Innov Interest	4.0 ± 1.2	4.7 ± 1.0 **	4.4 ± 1.1 p	4.6 ± 1.2
Innov Career Goals	4.2 ± 1.1	4.6 ± 1.3 *	4.5 ± 1.2 P	4.6 ± 1.1

T-test, 2-tailed, post compared to pre in the same year: * $p<.05$, ** $p < .01$

T-test, 2-tailed, pre 2022 compared to pre 2021; p = $p<.05$; P = $p<.01$

Looking at specific items within the survey, those with the greatest difference between the averages on the post-survey in 2022 versus 2021, and the largest differences between post and pre are shown in Table 4. Implications of data depicted in Table 4 can be to ask questions on the pre-survey about previous and current activities likely to build innovation interest or self-efficacy (such as participating in the Engineering Entrepreneurship minor; etc.).

Table 4 - Largest differences between post and pre-innovation items.

Item	Post 2022 - Post 2021	Post 2022 - Pre 2021	Post 2021 - pre 2021
Giving an "elevator pitch" or presentation to a panel of judges about a new product or business idea Finding resources to bring new ideas to life. [interest]	-0.8	0.2	1.3
Build a large network of contacts with whom you can interact to get ideas for new products or services. [self-efficacy]	-0.7	0.0	0.9
Connect concepts and ideas that appear, at first glance, to be unconnected. [self-efficacy]	0.5	0.3	0.6
Ask a lot of questions [self-efficacy]	0.1	0.5	0.5
Selling a product or service in the marketplace. [career goals]	0.0	0.5	0.6
Experiment as a way to understand how things work [interest]	0.0	0.2	1.0

Course Evaluation

On end-of-the-semester Faculty Course Questionnaire (FCQ) students in this class had a 63% response rate. In the ABET Student Outcomes section, 53% of the respondents rated this class as 5 (1: lowest and 5: highest) on ABET Student Outcome 5 (SO5: teamwork) and 55% of the respondents rated this class as 5 (1: lowest and 5: highest) on ABET Student Outcome 6 (SO6: experimentation). Selected student comments with regard to the course intervention are listed below which were recorded in the write-in comments on FCQ:

"The group project for the TeachEngineering website was a fun and interesting assignment. I feel like we all learned a lot in the process, and it can potentially benefit K-12 students as well."

"I enjoyed the TeachEngineering aspect of this course and its timeline."

"The projects were creative and initiated originality while still learning the concepts."

"The benefit I saw to the project is that it encouraged me to create social connections with other people in the class. I felt like I knew people in my group by the end of class, something other classes don't accomplish."

Mentors' Feedback

There were 13 teams in the course in fall 2022. Both technical mentors and the K-12 STEM mentor recorded notes from meetings with teams. Design mentors recorded notes for meetings with 11 design teams; 2 teams met with their design mentor twice and 9 teams only once. For the majority of the meetings, the design mentor noted "...the team did not go into great enough depth to exhibit the five innovative behavioral components." The meetings were typically 30-min and the mentor noted, "It is honestly hard to gather much information on the innovative behavior components in the context of short meetings like this. I think some training in how to ask probing questions might help future design reviewers in gathering useful information on this." For one team in the initial meeting, the mentor noted, "This team exhibited basic questioning and experimentation planning." For one particular team, the mentor noted "I have a hunch that [student name] was already modeling the innovative behaviors listed above before enrolling in this class. It would be interesting to learn if this influenced her peers toward developing some of these traits." This comment points to the important role that peer mentoring might play in fostering innovative attitudes among other students, similar to other literature (Elliott et al., 2020). The K-12 teacher mentor recorded notes for meeting with 6 teams (1 meeting each); these were limited to simple observations about their meeting content and the teacher's recommendations to the teams; no notes were made on the innovation aspects.

Instructor's Observations

Level of innovation and innovativeness: Innovativeness is defined as "the degree to which an individual or other unit of adoption is relatively earlier in adopting new ideas than other members of a social system" (Rogers, 1995). In the literature, innovation has been divided into three categories of product, process, and business systems (Johne, 1999; North & Smallbone, 2000; Boer & During, 2001; Hovgaard & Hansen, 2004). Although innovativeness was not directly measured through this research, the primary author who was also the instructor of record of the course noted the following observations in the areas of innovative products and processes:

- <u>Product innovation</u>: In 2022, two teams out of thirteen incorporated artificial intelligence into their design by utilizing Augmented Reality (AR) goggles and a Merge cube. One team demonstrated the impact of ocean acidification on coral reefs while the other demonstrated the carbonate system in nature. Although the instructor had prepared a module on AR in water chemistry which was made available to everyone in class no teams in 2021 tried it. In 2022, 12 out of 13 teams designed novel activities that did not exist in the *TeachEngineering* database before compared to only 6 out of 17 teams that had novel designs in 2021. Some examples of novel design in 2022 include: inspecting the effect of ocean acidification on aquatic plant growth, oil spill cleanup using physical and chemical methods, acid-mine drainage cause and impacts on the environment, source of metal complexes and environmental issues related to it, eutrophication, the impact of pollution on Arctic ice melt, adhesive and cohesive properties of water, and impact of ocean acidification on coral reefs' change of color using dyed eggshells. These observations point to the literature which shows that product innovation is a successful change in an entity and can occur in the form of either goods or services (Kubeczko and Rametsteiner, 2002).

- Process innovation: Process innovation is the introduction of new elements in the production process (Damanpour et al. 1989). In 2022, all 13 teams designed processes to motivate K-12 students' participation in class which manifested itself in their activity design and classroom presentations. Some examples include a team that utilized Kahoot quizzes, three teams that included a type of prize (i.e., objects, candy, and gift cards); five teams that created a video, one team wore themed shirts of their activity, and all 13 teams brought a physical model to class to communicate their design (e.g., Pyrite for acid-mine drainage, AR goggles and Merge cubes, sand dollars, ice melt with chemicals, candy mix and fruits for acidity, aquatic plants, dyed eggs). In 2021, only 7 out of 12 teams were involved in an innovative process during their design or presentations.

Another observation made by the instructor was the variety of projects in 2022 compared to 2021. In 2021 the majority of projects were on acid/base chemistry and derivative activities such as the impact of acid on seashells. In the 2022 pilot, the instructor conducted a class reflection where a representative from each team shared their design ideas. Students quickly realized that the majority of them are thinking about similar acid/base chemistry designs and brainstorming ways to differentiate them from other teams or to choose other topics (e.g., metal complexes). This reflection session occurred a week after the project introduction and one week before teams met with their design mentors. This idea sharing early in the design process tremendously assisted teams in diversifying their designs to avoid redundancy to product and process innovation.

Study Limitations

There are a variety of limitations in this exploratory research. A key limitation is the inability to pair the data from the pre- and post- surveys per student. This limits the ability to conclude that changes occurred in the innovation attitudes of individuals. A second limitation is that meeting with the mentors was optional in 2022. It is unclear whether or not the students who completed the post-survey met with the design mentors and/or K-12 mentor. When comparing the 2021 and 2022 classes, the effects of the COVID pandemic and remote instruction likely differed (based on key courses related to innovation self-efficacy that may have been remote, hybrid, or in-person). Another limitation is that activities beyond the K-12 lesson design activity may have impacted students' innovation attitudes between the pre- and post- surveys; for example, some students might have been enrolled in courses in pursuit of a minor in Engineering Entrepreneurship that includes innovation. In addition, there may have been a team/peer effect on these innovation attitudes; team-level dynamics were not controlled. More broadly, there is the difficulty that the survey scale "lower end" anchors were 'prefer not to answer'; this prevents comparing the data from this study to other research that has used the same survey items (but it is consistent with the 2021 data). Sample size has clearly limited our ability to discern differences in innovation dimensions (Innovation Self-efficacy, Innovation Interests, Career Goals

Innovative Work) in smaller demographic groups. Another limitation of this study was that the demographics of the respondents were not recorded in 2021 and therefore they are unknown.

Summary and Conclusions

Our pilot study sought to measure those skills and knowledge in engineering students through the lens of Innovation Self-Efficacy (ISE). We deployed a 15-item survey (Innovation Self-Efficacy 5 items, Innovation Interests 4 items, and Career Goals: Innovative Work 6 items) and distributed it to engineering students at a senior-level environmental engineering course at the University of Colorado Boulder. The survey sought to explore engineering students' innovation self-efficacy before and after a course intervention which had previously been shown to have the potential to increase students' innovation self-efficacy. Student teams were assigned two mentors throughout the intervention to assist them with designing and mapping their design to the target audience. Results generated from this survey show a modest increase in innovation self-efficacy. Nevertheless, less impact was found compared to the previous year when innovation attitudes were weaker in the pre-survey. We found that there was no evidence that enhanced mentoring associated with the activity resulted in better gains in students' innovation self-efficacy. However, the qualitative observations indicate that enhanced mentoring resulted in developing product and process innovation which can be referred to as innovativeness. Innovativeness is the cultural aspect of an entity exhibited by the tendency to create or adopt new products, processes, or business systems. Literature supports that having a formalized or structured process of new product development enhances innovativeness (Crespell et al., 2006). Comparison of 2021 and 2022 data depicts that the presence of mentorship may not have highly impacted ISE but has demonstrated elevated levels of product and process innovation. Future studies can include direct measurement of the innovativeness of designed products and investigate its relationship to innovation self-efficacy.

Acknowledgment

National Science Foundation (NSF) for funding this research with award number 2205067. Funding was also received from the University of Colorado Boulder's Engineering Education and AI-Augmented Learning Interdisciplinary Research Theme (EE-AI IRT) program. PhD student Ayush Shahi assisted us in the administration of the pre/post surveys and Dr. David Delaine for his insight on intervention design.

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