Sparking Engineering Passion: Hands-on Science and Engineering Adventures for Diverse Future Innovators

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Melissa Almeida, a Ph.D. student in Cognitive and Information Sciences at the University of California, Merced, is deeply engaged in the intersection of learning, cognitive science, and STEM education. Her research evaluates the impact of classroom interventions, focusing on embodied cognition and the educational use of augmented and virtual reality technologies. Moving beyond initial feasibility, her work aims to evaluate the educational outcomes and psychosocial benefits of embodied learning pedagogies in general, as well as those afforded via these technologies. Her solid academic foundation includes a Master's degree from the University of California, Merced, and a Bachelor's degree in Psychology from California State University, Stanislaus. Her approach to innovating STEM education is informed by a seasoned background in business information technology and management. This unique blend of skills and experiences drives her research and dedication to developing inclusive educational environments and advancing the integration of empirically beneficial technological pedagogies in the classroom. Through her work, Melissa aims to contribute meaningful insights into the effective integration of technology in education, aspiring to shape the future of STEM learning environments to be more engaging and accessible for all students.

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Sparking Engineering Passion: Hands-on Science and Engineering Experiences for Diverse Future Innovators

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Abstract

This inquiry explores the role of discipline-specific engineering interventions in enhancing engineering exposure among middle and high school students from two rural districts in the southwest. Adopting a mixed-methods research design, this paper examines the influence of educational activities related to environmental, geotechnical, and optical engineering within STEM curricula. The interventions, tailored to each engineering field, aimed to enhance students' self-efficacy, identity, and knowledge in engineering through active participation in the Engineering Design Process. Findings indicate significant gains in students' engineering knowledge post-intervention, with qualitative assessments of worksheets validating their engagement, alongside their content and conceptual understanding. These results suggest that targeted, field-specific engineering experiences may help to cultivate an engineering mindset, particularly within underserved populations. This paper emphasizes the potential of such focused interventions to bridge the educational gap and inspire future innovation in engineering among diverse youth groups.

Keywords

Underserved Students, Self-Efficacy, STEM identity, Engineering Design Process, informal education

Introduction

STEM (Science, Technology, Engineering and Math) education is a critical component of modern education and workforce, as it provides students with the skills and knowledge necessary to succeed in today's rapidly changing technological landscape, but it is not always accessible to everyone. The equity gap in STEM education is a significant issue, and individuals from low-income communities often lack the STEM experiences that their more affluent peers receive [1]. To address this gap, educators are exploring new ways to engage students in STEM experiences that promote positive associations. A positive class experience can impact students in profound ways, for example, they are less likely to feel resistance towards learning and begin to develop an increased motivation and positive attitude [2], [3].

How can educators engage students with STEM experiences that are positive, especially when teaching concepts that students have little exposure to? According to Aristotle, "For the things we have to learn before we can do them, we learn by doing them, e.g. men become builders by building and lyre players by playing the lyre; so too we become just by doing just acts, temperate by doing temperate acts, brave by doing brave acts." While there is certainly truth to this sentiment; the experiences referenced would have been those that were both familiar and accessible to the individuals who pursued them. Therefore, the first hurdle is introducing concepts in ways that are approachable and relevant to learners. Research indicates that one way to do so is through experiential learning, also known as active or embodied learning. These hands-on approaches can improve students' retention and transfer of knowledge [4]. Embodied learning involves pedagogical practices that engage the body and the environment in the learning process [5]. It has positive effects on engagement, motivation, and content understanding [6], [7], [8], and creates positive school experiences where students can engage in social interactions that impact their learning [9]. Creating these opportunities for students facilitates their understanding as knowledge can be constructed through interactions with the environment [10]. Through these interactions, students develop their STEM identity and passion, which influences their decisions to pursue STEM disciplines [11], [9]. Educators from the University of California, Merced (UCM) collaborated with two middle schools in the Central Valley of California to introduce students to engineering concepts, provide exposure to engineering through embodied learning, and have students demonstrate that they can carry out the tasks in the activities.

The design of these activities were informed by the Engineering Design Process (EDP) framework which has shown to positively influence scientific literacy [12], [13], attitudes [14], and interest [15], [16]. Early exposure to the EDP has the potential to influence students' academic identity [17] and utilizing it in an active setting can impact STEM identity. The UC Merced educators led engineering lessons that aimed to engage students in action-based activities that integrated science and engineering. The activities were customized for the student population from this community to help them create meaning of the content. Realistic situations were presented to prompt them to develop an understanding of how to apply the information they were learning. We investigated whether these experiences influenced students' attitudes about STEM and whether it improved their content knowledge and self-efficacy.

Methods

This study employed a mixed-methods approach to assess the efficacy of an informal, out of school, STEM educational intervention among middle school students. Data were collected using structured surveys, which included a series of Likert scale questions designed to measure constructs related to self-efficacy, STEM identity, and engineering knowledge. Additionally, collaborative and individual worksheets were collected and qualitatively coded.

Summer 2023 Environmental Engineering Academy

Participants

This academy, comprised of approximately 50 middle school students from one of the larger school districts in the area (to retain their anonymity, we do not name thme here)., These students were selected from a year-long African American Student Leadership Program. Of the participants who responded to our pre & post-surveys, 32 identified as female (68.1%), 12 as male (25.5%), and 3 as other or preferred not to disclose their gender (6.4%).

Instruction

The engineering lesson was one day of a 5-day summer leadership camp at the University of California, Merced. Our instruction activities were broken up into two 2-hour blocks. Initially, students were acquainted with the fundamental role of engineers, followed by activities designed to simulate an environmental engineer's responsibilities.

The lesson focused on environmental engineering and introduced them to science content related to watersheds, the water cycle, and contaminants—specifically nitrates in groundwater. Water pollution in the Central Valley is largely attributed to fertilizers and industrial waste, which we illustrated as a relevant problem by engaging them with local news articles to highlight related health concerns.

Students first engaged with activities utilizing common objects and identifying what problems they solved. This exercise aimed to broaden their understanding of the concept of technology as more than electronics. Next, a brief video presentation introduced the EDP and emphasized how engineers utilize technology to solve problems. Next, students conducted contaminant tests on various water samples from watersheds in the Merced area. Collaborative brainstorming sessions led students to propose potential interventions for the water contamination crisis, with several volunteers suggesting the construction of a water filter.

In alignment with the EDP, educators guided the students through a series of steps: testing different filter materials, observing their effectiveness for filtering contaminants out based on water clarity and odor, and noting particulate reduction. The teams then transitioned to the planning stage, where they designed a water filter prototype, selected filter materials based on their earlier findings, and crafted a detailed diagram of their intended construction.

Following the design phase, each team completed their prototype and conducted an evaluation using a 16-parameter water quality testing strip to determine the prototype's effectiveness. Groups that completed these steps quickly were encouraged to refine their designs in iterative cycles to enhance the water quality outcomes. This process enabled several groups to test and improve upon multiple iterations of their water filter designs.

October 2023 Geotechnical Engineering Academy

Participants

Middle and high school students from a mid-sized school district (n = 44) signed up to participate in the Saturday STEM Academy. Students who attended received credit for past school absences. That is, when they attend they can erase prior school absences. The gender distribution within this cohort was well-balanced, with 21 male students (47.7%) and 23 female students (52.3%). These students were organized into three distinct classrooms, each accommodating roughly 14 students.

Instruction

During the academy, an interactive activity titled "*Technology in a Bag*" introduced students to the concept of technology. By evaluating various items, they engaged in a group discussion to determine whether or not each item represented technology, leading to the development of a technical definition of the term.

Subsequently, the role of Geotechnical Engineers was explored. Students were introduced to the types of knowledge a Geotechnical Engineer needs to possess to perform their job well. Students were asked to assess their pre-existing knowledge about technology and earth sciences, including soil stratification within the earth's crust. Soil layer characteristics were covered, and we emphasized the EDP and its importance in the field of engineering.

Embodying the role of Geotechnical Engineers, students undertook a simulation to select a construction site capable of withstanding seismic activity. This involved a hands-on experience with core sample analysis using a provided model, allowing them to hypothesize and test which soil layers would offer stability to a high-rise structure.

The practical aspect continued as students evaluated optimal sites for constructing a Tarpul wire bridge, considering factors such as soil type and river topology. Through experimentation with organic and rocky soil samples and their compaction levels, students determined the most stable soil foundation for the bridge. The activity engaged students in conducting stability testing with weights and applying the EDP to analyze their data and refine their engineering solutions.

December 2023 Optical Engineering Academy

Participants

For this Academy, 22 middle school students participated in the lesson. While around 8 high school students functioned as mentors and helpers. The participant demographics for the middle school students were composed of 12 males (54.5%) and 10 females (45.5%). A substantial majority of the students were in the 8th grade, making up 86.4% (n = 19) of the cohort, while the 7th graders represented 13.6% (n = 3). Attendance records indicated that 9 students (40.9%) had previously attended the academy in October, while 13 students (59.1%) were engaging with the academy for the first time.

Instruction

As with previous lessons we started by addressing the students’ understanding of technology and its practical applications. This session utilized a technology scavenger hunt, to foster a broader conceptualization of technology via a collaborative effort to imagine technological solutions for hypothetical classroom issues, promoting teamwork and innovation. This activity set the stage for an in-depth exploration of Optical Engineering, as lighting was one of the issues students identified as a potential issue in classrooms.

Next, an introduction to Optical Engineering, where students were acquainted with the field and its applications. Through a scenario featuring two fictional clients requiring specialized natural lighting systems, the significance of Optical Engineers' work was highlighted. This scenario served not only to demonstrate the real-world relevance of Optical Engineering but also to cultivate students' critical thinking and problem-solving skills.

In project-based activities, participants experimented with materials to examine their light-reflective properties. This material testing informed the design of daylighting systems for model houses, allowing students to directly apply the EDP. Through this hands-on approach, students synthesized their theoretical learning with tangible engineering tasks, and embodied the role of engineers in solving contemporary challenges.

Tools and Instruments

Quantitative Instruments

For the quantitative analysis, we administered structured pre- and post-intervention surveys to evaluate changes in students' self-efficacy, STEM identity, and engineering knowledge. These surveys, which featured a series of items on a 5-point Likert scale, were deployed immediately before and after the STEM academy sessions. The surveys aimed to capture students' beliefs in their academic abilities, their identification with STEM fields, and their comprehension of engineering design processes. Additionally, we monitored prior attendance academy sessions to explore the effects of sustained engagement in STEM education.

Qualitative Instruments

The qualitative data were collected from the worksheet packets provided to students during the academy. These packets included various tasks designed to enhance their understanding of environmental, geotechnical, and optical engineering concepts through active engagement. The worksheets featured both open-ended questions and true/false statements, which prompted students to synthesize and apply the concepts learned during the hands-on activities.

Data Analysis

Statistical Analysis

Data were analyzed using SPSS software, Version 29 [18]. The analysis included independent samples t-tests to compare the pre-test scores of participants based on their prior attendance at a Saturday STEM Academy. Paired samples t-tests were then conducted to evaluate the impact of the intervention on the students' self-efficacy, STEM identity, and engineering knowledge. The assumptions for each test were verified prior to analysis. Hedges' g was calculated to estimate the effect sizes, providing a measure of the magnitude of the intervention's impact while accounting for the small sample size.

Qualitative Analysis

Following the academy, worksheets with student input were gathered and prepared for thematic analysis. This process entailed discarding empty pages and extracting pages with written responses for further examination. Two coders independently transcribed these responses into Excel, where the data was categorized by the specific engineering lesson. Through thematic analysis, we sought to identify patterns within students' engagement and their understanding of the engineering concepts presented. The analysis included worksheets across the three engineering disciplines, assessing content comprehension and the effectiveness of the instructional interventions.

Results

Summer 2023 Environmental Engineering Academy

To assess student's content knowledge gains for the Environmental Engineering lesson, we used student worksheets. The worksheets were used to measure the students' understanding of the lesson using codes such as "Health effects," "Pollutant causes disability," "Pollution exposure," and "Pollution source." You can refer to Table 2 for an example of student responses (raw data) categorized according to these codes. During this intervention, two instructors and a few helpers directed the activities for over 40 students. While students seemed to be engaged by the activities, some may have felt lost or uninterested. After reviewing the "Research the Problem" worksheet, we determined that the students had a good grasp of the issue at hand: the San Joaquin Valley is notorious for having high water contamination that affects numerous communities and poses a threat to public health. To construct their responses, the students referred to a news article from The Humanitarian titled "Living in California's San Joaquin Valley May Harm Your Health." The instructors also provided information on the types of pollutants present in the region's water and their effects on public health. Based on the students' responses, it was evident that they comprehended the impact of water pollution on health, particularly with respect to disabilities. Additionally, they recognized that the number of people exposed to water pollution in the area was concerning.

Table I
Research the Problem Themes and Responses

Worksheet	Question	Raw Data	Code
Research the problem	How is this article relevant to you?	"This article is relevant to us because we drink tap water and it could effect over health."	Health effect
		"One of the most harmful is arsenic, which can cause blindness and partial paralysis, also, is linked to cancer."	Pollutant causes disabilities
		"More than 1 million people in the region have been exposed to unsafe drinking water."	Pollution Exposure

Table I. Highlights the worksheet type, the question students developed responses for, the student's response and the code assigned to it.

October 2023 Geotechnical Engineering Academy

In the Geotechnical Engineering intervention, we evaluated two worksheets: "Core Sample" and "Evaluating a Landscape." The latter was divided into four separate worksheets. For the "Core Sample" worksheet, we found three codes: "Information transfer," "Experience and observation," and "No elaboration." Our objective was to assess how students developed predictions for this worksheet. While a few worksheet responses did not address the "why?" aspect of the question, the responses from those that did elaborate demonstrated that the students had successfully recalled the information presented in the lesson. Additionally, students referred to their experiences interacting with their models to develop a prediction.

"Evaluating a Landscape" worksheet contained four codes for the first question: "Location," "Stability," "Transportation," and "Quality." The students had valid ideas about the problem at hand. Some students identified that getting from one side to the other was a challenge, and therefore, the Tarpul bridge would aid in transportation. Other responses focused on the stability of the bridge and ensuring its quality by considering the soil. The second question on the worksheet, “Point location,” “Change in river,” and “Water speed” were the codes used. The students linked erosion with changes to the river and identified factors that could influence erosion, such as the curves of the river or the speed of the water. Their responses indicated that they had learned about erosion and recognized that it was a factor that engineers needed to consider when selecting a location to build the Tarpul bridge. The third question on the worksheet contained four codes: “Stability,” “Compaction and soil type stability,” “Compaction stability,” and “Soil type stability.” The students’ responses indicated that they recognized the impact of soil types and compaction levels on the stability of the Tarpul bridge. The final question on the worksheet was a metacognitive one: “How will you know if your design is successful?” This question allowed us to examine how students would evaluate the success of their work. Four codes were identified: “Task understanding,” “Location selection,” “Expected outcome,” and “Method,” with two subcodes, “Method: Collaboration” and “Method: Model testing.” The groups of students varied in their responses, but the ones that stood out were those that described methods that would help them carry out the task successfully, such as collaborating or testing their models. Additionally, some of the student responses showed that they considered what the outcome would be if they were successful.

Table II
Evaluating a Landscape Worksheets, Responses and Themes

Worksheet	Question	Raw Data	Code
Core Sample	In which layer would you anchor the skyscraper to keep it stable during an earthquake? Why?	"You would want to anchor the skyscraper into the bedrock layer. the Bedrock is the most stable layer out of the three"	Information transfer
		"We think the bedrock will keep the skyscraper stable. The skyscraper fell on the first layer. In the second layer the skyscraper started leaning instead. On the third layer the skyscraper stayed straight."	Experience and Observations
		"We would tell them to anchor it to the bedrock at the bottom." "We think bedrock is gonna be the strongest"	No elaboration
Evaluating a Landscape: Ask #1	The problem that we need to solve is:	"Where is the best place to build a tarpul"	Location
		"The problem we need to solve is that stick is weak"	Stability
		"To get to the other side"	Transportation
		"How to make good bridges and soil + landscapes"	Quality
Evaluating a Landscape: Ask #2	What do you already know about erosion along a riverbank?	"More likely to happen at curves outside"	Point location
		"Changes the shape of the river"	Change in river

		"The faster the water moves, the more erosion there will be. The water farther from the curve will travel faster."	Water speed
Evaluating a Landscape: Ask #3	What do you already know about how soil type and compaction affect the TarPul?	"It can hold more stable"	Stability
		"The more rockier and compact the soil is, the sturdier the structure will be"	Compact and soil type stability
		"More compact more stable"	Compact type stability
		"With rocky soil will help a lot"	Soil type stability
Evaluating a Landscape: Ask #4	How will you know if your design is successful?	"I know it will be successful because if we understand what we do, we can be successful"	Task understanding
		"With a nice location"	Location selection
		"Collaborating"	Method (subcode: Collaboration)
		"Model and Test"	Method (subcode: Model testing)
		"If it can hold more weight without falling or sinking"	Expected outcome

Table II. Displays the worksheets and corresponding questions that students responded to. The raw data column contains their responses, while the code column lists the codes identified from them.

December 2023 Optical Engineering Academy

Quantitative Assessment

An independent samples t-test revealed no significant differences in Pre-Test total scores between participants who did and did not attend the October 2023 STEM Academy. For Pre-Test Self Efficacy, participants who did not attend the October Academy session had a mean score of 19.62 (SD = 4.74), compared to a mean score of 20.33 (SD = 5.68) for those who attended, p = .750. For Pre-Test STEM Identity, non-attendees had a mean score of 29.77 (SD = 11.92), versus attendees who had a mean of 33.89 (SD = 4.76), p = .339. For Pre-Test Engineering Knowledge, mean scores were 24.31 (SD = 17.34) for non-attendees and 34.67 (SD = 13.62) for attendees, p = .150. The effect sizes were small with Hedges' g values of -0.135, -0.408, and -0.625 respectively.

Paired samples t-tests were conducted to assess changes in self-efficacy, STEM identity, and engineering knowledge following the intervention. Results indicated significant increases in self-efficacy scores from pre-intervention (M = 19.91, SD = 5.023) to post-intervention (M = 22.97, SD = 4.396), t (21) = -2.686, p = .014, with a moderate effect size (Hedges' g = -.552, 95% CI [-.982, -.111]). STEM identity scores also significantly increased from pre-intervention (M = 31.45, SD = 9.699) to post-intervention (M = 37.56, SD = 6.118), t (21) = -2.484, p = .022, with a moderate effect size (Hedges' g = -.510, 95% CI [-.936, -.074]). Engineering knowledge showed the greatest increase with scores rising significantly from pre-intervention (M = 28.55, SD = 16.419) to post-intervention (*M* = 48.08, SD = 17.166), t (21) = -5.234, $p < .001$, and a large effect size (Hedges' g = -1.075, 95% CI [-1.584, -.551]).

Qualitative Assessment

We analyzed two worksheets, “Technology in the Classroom” and “True/False Formative Assessment,” for the Optical Engineering lesson. For the former, we identified five codes: “Helpful,” “Composed of multiple parts,” “Human made to resolve problem,” “Human made,” and “Resolves problem.” The students understood that technology is an object composed of multiple parts that creates a system made by humans to solve a problem. For the “True/False Formative Assessment,” we presented eight statements about light to the students and asked them to determine whether they were true or false (see Table 3). The themes of the True/False statements are “Reflection,” “Light source type,” and “Other light properties.” Statements 1, 2, and 5 fall under the “Reflection” theme, 4 and 8 are under “Light source type,” and the rest fall under “Other light properties.” The students demonstrated a good understanding of the content on the formative assessment, as evidenced by the high proportion of correct answers to the True/False statements (see Fig. 1).

Table III
True or False Statements

	T/F Statement:
1	We see black when an object reflects all visible wavelengths of light
2	When light falls on a mirror, the light is reflected
3	Photons are electromagnetic radiation
4	Fire is an example of an artificial source of light
5	A mirror cannot change the direction of light that falls on it
6	Some mediums can bend the path of light
7	As light travels from its source the intensity increases.
8	Stars are examples of naturally luminous objects

Table III. List of the true/false statements presented to the students.

Figure I

Proportions Correct & Incorrect

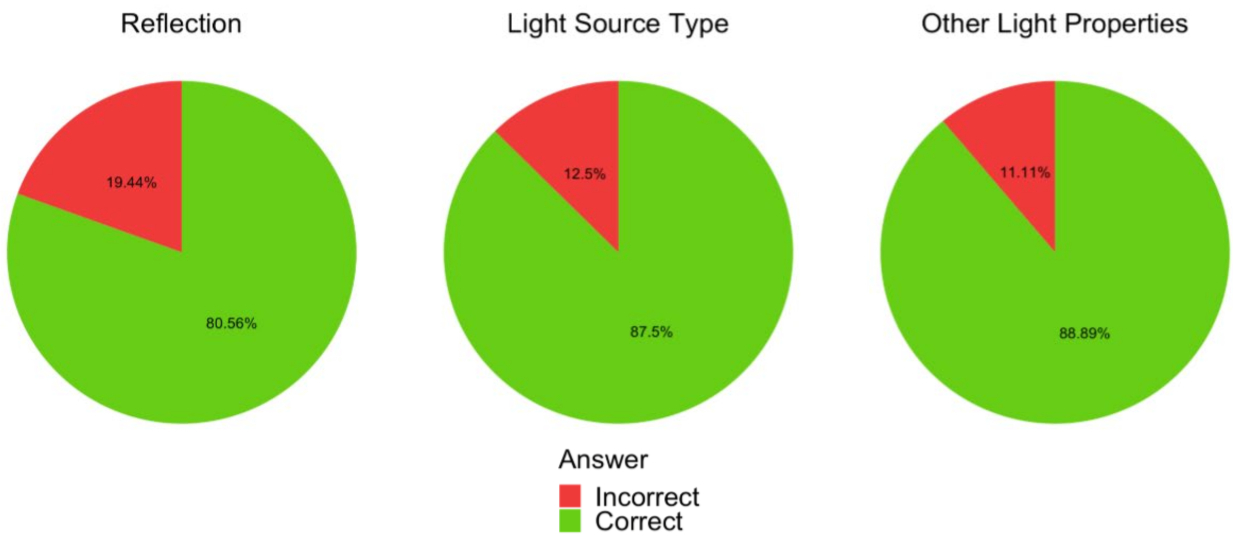

Figure I. Shows the percentage of correct answers for each T/F statement, grouped into three categories: Reflection 80.56% correct (statements 1, 2, and 5), Light Source Type 87.5% correct (statements 4 and 8), and Other Light Properties 88.89% correct (Statements 3, 6 and 7).

Discussion

In our study, we aimed to assess the impact of integrated science and engineering activities on middle school students from two school districs in California's central valley. Utilizing the Engineering Design Process (EDP) as a framework, we structured the activities to teach students about environmental engineering, geotechnical engineering, and optical engineering. Our findings indicate that hands-on experiences play a vital role in deepening students' understanding of engineering concepts and their real-world applications.

For instance, during the environmental engineering academy, students explored topics such as water quality and the effects of nitrates in groundwater. Engaging in brainstorming sessions, they proposed solutions to address water contamination issues and constructed water filters to test their hypotheses. Similarly, in the geotechnical engineering academy, students assumed the role of geotechnical engineers, identifying stable building sites capable of withstanding earthquakes. They conducted experiments with model skyscrapers, analyzing data to determine the most stable soil and compaction types. In the optical engineering academy, students designed lighting systems for fictional clients, experimenting with various materials to assess light reflection. They then applied their designs to model houses, evaluating their effectiveness.

Quantitative improvements in self-efficacy, STEM identity, and engineering knowledge post-intervention, despite small effect sizes, suggest that even brief, focused interventions can positively impact students' perceptions and understanding of engineering fields, at least in the short-term. Although the effect sizes were not large, it's noteworthy that these interventions were relatively brief, occurring over single-day academies or weekend sessions

However, our study had limitations, such as allowing some students to take home their packets, potentially biasing our data. Future research should ensure that worksheets are completed during activities, accompanied by explicit field notes to provide deeper insights into student responses and engagement.

Overall, our study highlights the importance of hands-on experiences in STEM education. By fostering social interactions and providing opportunities for embodied learning, we can empower students to develop a profound understanding of engineering concepts and their practical implications. Further research could look into the long-term effects of embodied learning experiences on students' sustained engagement with STEM subjects.

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