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Culturally relevant informal STEM learning for underserved students: effects of repeated exposure to the engineering design process

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Introduction: This study investigates the impact of repeated exposure to the Engineering Design Process (EDP) through culturally responsive STEM lessons, delivered in an informal science learning (ISL) setting to middle school students from underserved communities in California's Central Valley.

Methods: A mixed-methods approach was employed, combining qualitative analysis of student journals and survey responses with quantitative analysis of pre- and post-survey data. The study focused on students' STEM identity, self-efficacy, and perceptions of engineering knowledge.

Results: Qualitative findings highlighted key themes of problem-solving and understanding the EDP, demonstrating that students engaged deeply with the process. Quantitative results indicated significant improvements in students' STEM identity, self-efficacy, and perceptions of engineering knowledge following repeated exposure to the EDP.

Discussion: These findings suggest that embedding the EDP within culturally relevant, hands-on ISL activities can effectively enhance students' engagement with STEM subjects, foster stronger STEM identities, and address educational inequities.

KEYWORDS

embodied learning, engineering design process, informal science, self-efficacy, STEM identity, underserved students

Introduction

STEM (Science, Technology, Engineering, and Math) education is vital for preparing students for the modern workforce, equipping them with skills to succeed in a rapidly changing technological landscape. However, STEM experiences are not widely available in all classrooms. An opportunity gap disproportionately affects students from low-income communities, who are often in schools that offer fewer opportunities to participate in STEM and do not have the resources to access opportunities outside of school (Jordt et al., 2017). To address this gap, educators are exploring new ways to engage students in STEM, as positive learning experiences can increase motivation and reduce resistance to learning (Ballen et al., 2017; Ellis, 2004).

Positive STEM learning experiences are often linked to key constructs like STEM identity—a student's sense of belonging in STEM disciplines. This identity is necessary for students to envision themselves as future engineers or scientists (Singer et al., 2020). Self-efficacy, the belief in one's ability to succeed, also plays a role in fostering this identity (Bandura, 1997; Patrick and Ryan, 2005; Usher and Pajares, 2008). Students with higher self-efficacy are more likely to take on challenges, persist in the face of difficulty, and view themselves as skilled learners in STEM (Usher and Pajares, 2008). Therefore, if STEM learning experiences correlate with increases in measures of self-efficacy and STEM identity, we propose that this observed relationship indicates a positive STEM learning experience.

These impacts raise the question of how such experiences can be structured to support the development of self-efficacy and STEM identity. While practice is fundamental for skill development (Le et al., 2023), it typically benefits students who already have a degree of familiarity and confidence with the material (Dong et al., 2020; Judson, 2012). We argue that simply offering STEM opportunities that lack connection to students' existing knowledge or experiences does not address gaps in students' prior exposure or comfort with the content. Instead, focusing on introducing STEM concepts in ways that are relatable and relevant to the students' lives will be more impactful (Johnson and Elliott, 2020). Culturally responsive teaching offers a means to achieve this connection (Marosi et al., 2021). We posit that this encompasses more than just their ethnic background but their local contexts and lived experiences.

As Cheryan et al. (2017) suggested, connecting STEM content with students' lived experiences is important for engagement and meaning-making, particularly for underserved groups. By connecting STEM learning to culturally relevant contexts, educators can make the subject more accessible and meaningful, enhancing students' self-efficacy and reinforcing their developing STEM identity. This culturally tailored approach is effective in both formal classroom settings and informal learning environments, helping to create positive STEM experiences that inspire confidence and a sense of belonging in students.

Another well-supported approach is experiential learning, also known as active or embodied learning (Kaldi et al., 2011; Weisberg and Newcombe, 2017). Through hands-on engagement, students gain mastery over STEM tasks, which is critical for improving self-efficacy (Bandura, 1997). These mastery experiences build students' confidence to tackle increasingly complex STEM challenges (Luzzo et al., 1999; Patrick and Ryan, 2005; Usher and Pajares, 2008). Embodied learning, which involves physical interaction with the environment (Kosmas et al., 2019; Macrine and Fugate, 2021; Skulmowski and Rey, 2018), has been shown to enhance engagement, motivation, and understanding (Goldin-Meadow et al., 2009; Goldin-Meadow and Singer, 2003; Ping et al., 2021), creating positive school experiences and social learning (Reveles et al., 2004).

Providing students with these hands-on experiences facilitates understanding by allowing them to construct meaning through interaction with their environment (Vygotsky and Cole, 1978). These mastery experiences not only boost self-efficacy (Bandura, 1997; Konak, 2018) but also reinforce STEM identity by helping students see themselves as capable contributors to STEM fields, thus influencing their decisions to pursue STEM disciplines (Haak et al., 2011; Luzzo et al., 1999; Patrick and Ryan, 2005; Reveles et al., 2004).

Informal science learning

Formal education occupies only a small portion of a person's life, making out-of-school experiences crucial in shaping scientific understanding over time (Kim and Dopico, 2016). Therefore, improving STEM education requires identifying barriers and developing collaborations across informal, after-school, and formal platforms (Labov and Olson, 2014). These kinds of experiences are often categorized as Informal Science Learning (ISL), experiences that extend educational opportunities beyond the traditional school day (National Research Council, 2009a). A key implication for ISL is learners' prior knowledge and understanding of the world are just as important as the new knowledge conveyed through specific experiences (Schweingruber and Fenichel, 2010). Pairing ISL hands-on activities with prompts that encourage self-reflection can support the learning process and foster deeper understanding (Schweingruber and Fenichel, 2010; Schweingruber et al., 2014).

Targeted interventions through informal science learning play an important role in reinforcing STEM identities during key transitions, like the shift from middle to high school, when important academic decisions are made (Archer et al., 2010). Middle school is a critical period when students start to lose interest in science and mathematics (Christensen and Knezek, 2017; Thomas and Larwin, 2023) and start to solidify their academic interests and career aspirations (Christensen and Knezek, 2017; Wang and Degol, 2013).

Engineering design process

The STEM activities described in this paper were designed to incorporate science, technology, and math, but all were structured around the engineering design process (EDP) framework (Cunningham, 2018), which consists of five steps (Ask, Imagine, Plan, Create, and Improve). Using the EDP has been shown to enrich scientific literacy (Bethke Wendell and Rogers, 2013; Yoon et al., 2014), attitudes (Cunningham and Lachapelle, 2012), and interests (Aguirre-Muñoz et al., 2021; Guzey et al., 2016). Early exposure to the EDP can also influence students' academic (Kelley et al., 2015) and STEM identities (Talafian et al., 2019).

EDP exposure yields positive outcomes, especially when integrated with culturally responsive teaching (Feder et al., 2009; Gay and Howard, 2000; Ladson-Billings, 2022). Bell et al. (2009) emphasized effective learning experiences consider the intersection of individual, social, and historical contexts. Additionally, Krapp and Prenzel (2011) argue that interest-driven interactions with the environment create optimal learning experiences by blending cognitive engagement with positive emotions.

In response, educators from a research university in the Central Valley collaborated with two underserved middle school populations in the region to introduce engineering concepts through embodied learning in ISL settings. These beyond-the-classroom environments offer opportunities for students to explore STEM concepts more freely than formal classrooms, potentially having long-lasting impacts on their STEM engagement (Staus et al., 2021). This research explores whether repeated exposures to hands-on activities using the EDP framework influences STEM identity, self-efficacy, and perceptions of both general and lesson-specific engineering knowledge.

We hypothesize a single exposure will significantly improve students' STEM identity and self-efficacy compared to pre-test levels, with subsequent exposures yielding smaller gains due to a ceiling effect. In this context, a ceiling effect implies that as students' STEM identity and self-efficacy reach higher levels, there is less room for noticeable improvement, even with additional interventions (Judson, 2012; National Research Council, 2009b). This aligns with Bandura's (1997) research indicating initial successes boost confidence, while repeated experiences result in diminishing returns as familiarity grows. Similarly, we expect a single exposure to significantly enhance perceptions of basic engineering knowledge, supported by evidence that structured out-of-school programs foster science interests and achievement (Bell et al., 2009). We also hypothesize prior exposures will not significantly affect perceptions of knowledge related to the specific engineering type taught (e.g., electrical v. environmental); these perceptions are shaped mainly by the current lesson's content.

The following research questions guide this study:

1. How do students communicate their understanding of the engineering concepts from the lessons and the EDP process in informal settings?
2. To what extent does the number of exposures to hands-on activities using the EDP framework in informal science lessons affect students' STEM identity and self-efficacy?
3. To what extent does the number of exposures to the EDP framework in informal science lessons influence students' perceptions of their basic engineering knowledge?
4. To what extent does the number of prior exposures to the EDP framework in informal science lessons affect students' perceptions of their engineering knowledge specific to the lesson?

We conducted two studies: Study 1 was during an immersive Summer STEM Academy, and Study 2 took place over a series of Saturday STEM Academies held throughout the school year. These differing contexts allowed us to explore the effects of both concentrated and repeated experiences on student outcomes.

Methods

This study used a mixed-methods approach to evaluate the impact of ISL STEM outreach activities on underserved students. Engineering lessons led by the authors engaged students in culturally relevant, action-based science activities, helping students create meaning through realistic, relatable scenarios that encouraged practical knowledge application.

The first study offered a two-day STEM lesson during the Summer STEM Academy, with engineering being the focus of the second day. The second study was part of the Saturday STEM Academies, where students received repeated exposure to engineering lessons throughout the school year. Each study's specific participants, materials, procedures, and data analyses are detailed below. Data were collected using structured surveys with Likert scale questions to measure self-efficacy, STEM identity, and perceptions of engineering knowledge [instrument items, please see Appendices, were borrowed from Patrick et al. (2018), Prybutok et al. (2016)]. Open-ended survey responses and collaborative and individual engineering worksheets from students' engineering journals were collected and coded qualitatively.

The Engineering is Elementary (EiE) curriculum was used as a starting point to identify appropriate engineering fields (The EiE Team, n.d.). EiE encourages critical thinking and problem-solving by guiding learners through the EDP so they can begin thinking like engineers. Available EiE resources comprised elementary-level curriculum binders, selected due to budgetary considerations prioritizing accessible and adaptable materials.

Since the study involved middle school students, materials were modified to align with middle school curriculum standards. The National Academy of Engineering notes challenges in connecting interdisciplinary ideas when individual disciplines are not understood (Schweingruber et al., 2014). To address this, we referred to the Next Generation Science Standards (NGSS) for alignment. Additional adjustments were made to the engineering problems to reflect challenges students may observe in their own communities. Furthermore, familiar places and materials, and OpenAI-generated images reflecting the student population were used to enhance representation and foster connection to the concepts.

Study 1: Summer STEM Academy

Participants

This study included approximately 50 middle school students from a large school district in California's Central Valley, selected from a year-long African American Student Leadership Program. Among those who responded to the 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%).

Materials and procedures

Quantitative measures

Self-efficacy, STEM identity, and perceptions of engineering knowledge (Basic P.E.K) were evaluated using pre- and post-tests. These assessments were eight-point Likert scales, ranging from 'strongly disagree' to 'strongly agree,' alongside open-ended and multiple-choice questions. Survey instruments were adapted from Capobianco (2012), Patrick et al. (2018) and Prybutok et al. (2016) which demonstrated strong internal reliability ($\alpha = 0.86$) in those prior studies, suggesting consistency across responses.

The self-efficacy instrument consisted of a five-item scale that assessed students' confidence in their ability to succeed in STEM-related tasks, aimed to gauge the students' perceived competence in STEM subjects, providing insight into their self-efficacy before and after the intervention. A six-item scale was used to measure students' perceptions of their STEM identity and was designed to capture their identification with STEM careers and activities.

Lastly, a seven-item scale evaluated students' understanding of engineering roles. By focusing on the responsibilities and collaborative nature of engineering, the scale aimed to measure how well students understood the real-world applications of engineering concepts introduced in the lessons.

Open-ended questions

The open-ended questions prompted students to develop short answers focused on specific concepts and environmental engineering skills related to the lesson. The surveys were administered via the Qualtrics platform, and students accessed them on iPads or mobile phones. Please refer to Appendix A for Study 1 Survey Items.

Instruction

This intervention was based on "Water, water everywhere: Designing water filters" (The EiE Team, 2020c). The concepts were enhanced with water testing strips and upgraded filter materials (activated charcoal and filter fiber), along with recommended items like sand and screens. The story provided in the EiE was replaced with information about local watersheds and pollutants in the Central Valley of California, highlighting the region's serious water pollution issues caused by agricultural practices. This context was chosen to resonate with students' lived experiences, fostering motivation to design water filter prototypes as solutions to challenges directly affecting their communities. The lesson was designed to actively engage students in the learning process, incorporating both theoretical and practical components to ensure a comprehensive understanding of the subject matter. Please refer to Table 1 for details on the engineering focus and the specific activities related to the engineering field.

The instructional activities spanned approximately five hours, divided across two days. The lesson began with an activity called "Technology in a bag," where students were given a bag with an object inside and determined whether it was technology. This interactive activity allowed students to physically move to a designated area in the room, labeled 'technology' or 'not technology,' to express their answers. This activity facilitated a discussion on common misconceptions about technology, which were addressed, and students collaborated to refine their understanding of technology.

Members of the research team then presented scientific concepts relevant to the upcoming activities, focused on the water cycle, watersheds, and groundwater contaminants, laying the foundation for understanding the environmental context in which the engineering challenge would occur. The EDP was introduced through a brief video presentation, and its importance in engineering was emphasized, establishing it as a critical framework for approaching the hands-on problem-solving tasks with which they would engage.

Students explored the issue of water pollution, with a particular focus on the Central Valley, where fertilizers and industrial waste exacerbate the problem. The lesson concluded with hands-on activities, during which students conducted contaminant tests on water samples from local watersheds and evaluated the effectiveness of various materials in filtering pollutants. Based on the data they collected, students designed and constructed water filter prototypes, which were tested for their contaminant removal efficiency. Throughout the process, students were encouraged to document their findings and use the data to refine their designs.

Data analysis

Qualitative data analysis

The qualitative data were analyzed using thematic analysis (Braun and Clarke, 2006) to explore how students conceptualized the EDP. One of the open-ended survey responses was transcribed into Excel for initial review (prompt: What steps would an engineer use to solve a problem?). Members of the research team carefully read and coded the responses based on recurring concepts and ideas. Codes were then grouped into broader themes that represented the ways in which students understood and engaged with the EDP.

TABLE 1 Environmental engineering lesson details & NGSS standards (6–12) - Summer STEM Academy.

Type	Activity and NGSS code	Activity description
	Lesson: "Water, water everywhere: Designing water filters" (The EiE Team, 2020c).	
Environmental Engineering	Technology in a bag (ETS1.A)	Evaluated everyday items and determined whether they were technology. Each student had an object in their bag and had to decide whether it was technology or not. They expressed their answer by walking to the side of the room labeled 'technology' or 'not technology.' We discussed misconceptions about technology, and then the definition of technology was agreed upon by the group.
	Environmental Science lecture (ESS2.C, ESS3.C)	Focused on science content related to the water cycle, watersheds, and groundwater contaminants. Introduced scientific concepts (e.g., water cycle and water pollution) relevant for the upcoming activities.
	Introduction to EDP (ETS1.B)	Presented the EDP and emphasized it as an important process for engineers. Students viewed a brief video presentation introducing the EDP, followed by a discussion.
	Investigate the problem (ESS3.C, ETS1.A)	Investigated the problem (water pollution) that needed a technological solution (water filter). The lesson addressed water pollution issues in the Central Valley, caused by fertilizers and industrial waste. Students examined a local news article to highlight the related health concerns.
	Hands-on activities (ETS1.C, ESS3.A)	Conducted tests on water samples and materials for the technology they would develop. Students designed and constructed water filter prototypes, which they then tested to assess the quality of their design in filtering out contaminants. Students conducted contaminant tests on various water samples from local watersheds and tested the efficacy of different filtering materials. They recorded data from each test, which they used to inform their water filter designs.

This table outlines the activities and corresponding NGSS codes for the Summer STEM Academy's "Water, Water Everywhere" lesson. The lesson focused on environmental engineering, incorporating hands-on activities, environmental science content, and the EDP to teach students about water pollution and filtration.

TABLE 2 **Summer STEM Academy engineering journal themes.**

Themes	Descriptions	Examples
Prompt: "What steps would an engineer use to solve a problem?"		
Engineers' problem-solve	Students describe the engineer's role as identifying problems and developing solutions to address them.	1. "An engineer would first find the problem, then list how they could fix it, and then fix it." 2. "They would try to find what's the problem, then see what they can build or do to fix it, and then create it." 3. "They would use blueprints and ideas to solve a problem."
Engineers use the EDP	Students describe the specific steps engineers follow to effectively carry out their work.	1. "Ask, Research, Brainstorm, Plan, Make, Reflect" 2. "Identify needs, Research the problem, brainstorm possible solutions, Choose the most promising solution, Carry-out the solution, Evaluate, Reflect and Improve"

The table presents themes and examples from open-ended responses collected during the Summer STEM Academy. Students were asked to describe the steps an engineer would use to solve a problem, with responses reflecting general problem-solving strategies and specific references to the Engineering Design Process (EDP).

TABLE 3 **Summer STEM Academy pre- and post-test comparisons of constructs.**

Construct & Test	Pre-Test		Post-Test		Mean Diff.	*t*/*Z*	*p* (2-sided)	Effect size (*d* / *r*)	Power (1 - β)	Ranks (+/ -, Sum)	95% CI (Bootstrap)
	M	*SD*	*M*	*SD*							
Self-Efficacy (*t*-test)	2.76	0.81	2.82	0.94	−0.07	0.58	0.566	*d* = −0.10	0.09	-	[−1.22, 1.62]
STEM Identity (Wilcoxon)	3.71	0.97	3.51	1.39	−0.21	1.34	0.041*	*r* = 0.22	0.43	11/212, 24/491	[−1.80, 1.38]
Basic P.E.K. (Wilcoxon)	2.45	0.93	2.27	0.95	−0.17	0.67	0.507	*r* = 0.73	0.73	7/307, 20/39	[−2.75, 2.00]

This table presents pre- and post-test comparisons for self-efficacy, STEM identity, and perceived engineering knowledge (P.E.K.) constructs from the Summer STEM Academy. * Indicates significance at alpha level 0.05, **0.01, *** < 0.001. Paired *t*-tests were used for self-efficacy, and Wilcoxon signed-rank tests were applied for STEM identity and P.E.K. Effect sizes are reported as Cohen's d for the *t*-test and rank-biserial correlation (r) for Wilcoxon tests. Bootstrapped 95% confidence intervals (CI) and post-hoc power (1 - β) values are included.

Quantitative data analysis

SPSS (IBM Corp, 2022) was used for multiple imputations for missing data under 5 %. Two participants were excluded for missing pre-test surveys and seven for missing post-test surveys, leaving a sample size of 37 for analysis.

Pre- and post-test data were tested for normality in R (ggplot2, Wickham, 2024). Shapiro–Wilk tests showed normal distribution for self-efficacy but not for STEM identity and engineering perception. Self-efficacy was analyzed using a paired *t*-test (Cohen's d for effect size), while the Wilcoxon Signed Rank Test (rank-biserial correlation) was used for the other constructs. Power tests were conducted using the pwr package (R Core Team, 2024).

Study 1 results

Qualitative results

When asked to describe the steps an engineer would use to solve a problem, thematic analysis of their responses revealed two major themes: 'Problem-solving' and 'Describing steps of the EDP' (please see Table 2). Students emphasized identifying and resolving problems as central to engineering. For example, students mentioned the need to 'find the problem' before devising potential solutions. One student stated, "*They would try to find what's the problem, then see what they can build or do to fix it, and then create it.*" This reflects a basic, yet crucial, understanding of problem-solving as a fundamental part of the engineering process.

Additionally, 58% of students who answered the prompt demonstrated a solid grasp of what is required for effective problem-solving as an engineer. They described EDP steps such as brainstorming, planning, testing, and refining solutions. One noted, "*Identify needs, Research the problem, Brainstorm possible solutions, Choose the most promising solution, Carry out the solution, Evaluate, Reflect and Improve.*" These themes indicate students grasped the EDP's systematic and iterative nature, reflecting the intervention's success in teaching a foundational understanding of engineering problem-solving.

Quantitative results

Self-efficacy

Although the mean increased slightly (from 2.77 to 2.82, respectively, for pre- and post- test), a paired samples *t*-test found no significant difference in pre-test ($M = 2.76$, $SD = 0.81$) and post-test self-efficacy scores ($M = 2.82$, $SD = 0.95$), $t\ (36) = -0.58$, $p = 0.566$, $1\text{-}\beta = 0.09$. The mean difference in self-efficacy scores was −0.07, (95% CI [−1.22, 1.62]) (please refer to Table 3 for details).

STEM identity

A Wilcoxon signed rank sum test with continuity correction for nonparametric data indicated a significant decrease in STEM identity scores from pre-test ($M = 3.71$, $SD = 0.97$) to post-test ($M = 3.51$, $SD = 1.39$), $Z = 1.34$, $p = 0.040$, $1\text{-}\beta = 0.43$, with a small to medium, rank biserial correlation, effect size ($r = 0.22$). The mean difference in STEM Identity scores was −0.21, (95% CI [−1.80, 1.38]) (please see Table 3).

Perceptions of engineering knowledge (basic)

A Wilcoxon signed rank sum test with continuity correction found no significant change in PEK scores from pre-test ($M = 2.45$, $SD = 0.93$) to post-test ($M = 2.27$, $SD = 0.95$), $Z = 0.67$, $p = 0.507$, $1\text{-}\beta = 0.73$. The mean difference in perceptions of engineering knowledge (PEK) scores was −0.17, (95% CI [−2.75, 2.00]). Please see Table 3 for descriptive and inferential results of all constructs.

Study 2: Saturday STEM academies

Participants

Participants were recruited from a high school and middle school in a mid-sized school district in California's Central Valley, where the student population is 90% Hispanic or Latino, and 83% of students are eligible for free lunch (National Center for Education Statistics, 2024). Students were incentivized to attend Saturday academies to clear unexcused absences, and due to the informal science nature, some students left before completing the post-test survey, as noted in each lesson's section. Participants for each lesson consisted of a different population, with possible overlap across lessons, meaning some students may have participated in more than one academy.

As an icebreaker activity, students were asked their reasons for attending the STEM academies. Many shared that they attended because it helped clear their absences or gave them priority for a week-long university Summer STEM camp. Several students expressed excitement about the opportunity to visit the university campus and experience something different, describing it as a chance to step out of their hometown.

A total of 44 students attended the Geotechnical Engineering lesson, with a balanced gender distribution (47.7% male, 52.3% female). The Optical Engineering lesson had 20 middle school students (55% male, 45% female), mostly 8th graders (85%). The Electrical Engineering lesson had 14 students, primarily female (71.4%), with attendees from 7th to 9th grade. Finally, 20 students participated in the Green Engineering lesson, evenly split by gender, with most in 7th and 8th grade.

Materials and procedures

Engineering journals

Students were asked to complete engineering observation journals, which included tasks designed to walk them through the EDP and enhance their understanding of geotechnical, optical, electrical, and green engineering concepts by guiding them through hands-on activities. The journals featured open-ended questions, true/false statements (comprehension checks), and data recording prompts. For example, in the optical engineering lesson, we presented eight statements about light to the students and asked them to determine whether they were true or false (please see Table 4).

Survey instruments

Adjustments were made to surveys adapted from Capobianco, (2012), Patrick et al. (2018), and Prybutok et al. (2016), to streamline the pre-and post-test surveys in response to logistical constraints (please see Appendix B). The survey was reduced to fit a single page, and the open-ended questions were removed. The Likert scales were reduced from eight to five points, ranging from 'strongly disagree' to 'strongly agree,' to simplify the response process while retaining the reliability of construct measurement. The self-efficacy scale continued to consist of five core items, and the STEM identity remained at six items to assess students' sense of belonging and identification with STEM disciplines.

The engineering knowledge section was restructured to separate general engineering perceptions from discipline-specific perceptions, resulting in two distinct subscales. The general engineering perceptions scale consisted of ten items designed to evaluate students understanding of broad engineering concepts, such as problem-solving, teamwork, and the role of engineering in designing technology. The discipline-specific engineering perceptions scales were tailored to each engineering lesson to measure students' perceived knowledge within the specific engineering focus. By modifying items according to the lesson content, the surveys effectively assessed how exposure to the EDP across various disciplines influenced student perceptions. These changes were consistently applied across all lessons, and the surveys were administered in paper format to accommodate classroom time constraints.

Instruction

Instructional materials were adapted from the following sources: 'A Stick in the Mud: Evaluating a Landscape' (The EiE Team, 2020a); 'Lighten Up: Designing Lighting Systems' (The EiE Team, 2020b); 'An Alarming Idea: Designing Alarm Circuits' (The EiE Team, 2005); and 'Now You're Cooking: Designing Solar Ovens' (The EiE Team, 2020d). Each lesson was structured around the EDP framework and tailored to be culturally relevant and age-appropriate for the study population. Four lessons were conducted—two in the fall and two in the spring—each lasting approximately four hours. Every session began with introducing technology and the EDP, ensuring a consistent foundation. An overview of the lessons and deviations in context and materials from the original EiE plans is provided below. For detailed descriptions of specific activities and their corresponding NGSS codes, please refer to Table 4.

Geotechnical engineering

This lesson focused on earth science concepts like soil stratification and erosion as factors of building stability in earthquake-prone and flood zones. The original EiE context was replaced with local newspaper articles discussing Central Valley flooding, a timely and relevant issue for this community, which had recently experienced floods and flood warnings. This connection to their lived experiences aimed to emphasize the importance of earth science concepts when constructing buildings or bridges in flood-prone areas. Students engaged in taking core samples from model sites to assess soil layers and test the stability of model skyscrapers during simulated earthquakes. This was followed by constructing a model Tarpul bridge. To emphasize the role of topography and soil composition in bridge placement, students participated in a role-playing activity that simulated erosion along a riverbed, using a chalk path to illustrate how water flow impacts soil stability.

TABLE 4 Summary of Saturday STEM Academies by engineering lesson & NGSS standards (6–12).

Type	Activity and NGSS code	Activity description
Lesson: "A stick in the mud: Evaluating a landscape" (The EiE Team, 2020a).		
Geotechnical Engineering	Technology? (ETS1.A)	Students evaluated everyday items to determine whether they were technology, followed by a group discussion to develop a technical definition.
	Earth Science (ESS2.A, ESS2.C)	Introduced soil stratification and erosion, focusing on how these factors influence building stability.
	Materials Testing (ETS1.B)	Students took core samples from model sites to assess soil layers and tested how different soil types and depths affect the stability of a skyscraper model during simulated earthquakes.
	Model Building (ETS1.C)	Used models (a skyscraper and a Tarpul bridge) to simulate the stability of structures, applying concepts from the materials testing.
	Role Play (ESS2.C)	Participated in a role-playing activity to understand erosion and river topology, simulating the effects on stability.
Lesson: "Lighten up: Designing lighting systems" (The EiE Team, 2020b).		
Optical Engineering	Technology? (ETS1.A)	Discussed the definition of technology and the role of optical engineers in designing systems that manage light.
	Photometry (PS4.B)	Covered light interaction with materials, including reflection, refraction, transmission, and absorption.
	Materials Testing (ETS1.B)	Tested reflective properties of materials using lux meters, considering environmental factors.
	Model Building (ETS1.C)	Designed passive lighting systems for fictional clients, incorporating testing insights and client-specific needs.
	Interactive Assessment (ETS1.B)	Conducted a true/false assessment as a competition, reinforcing photometry concepts and incentivizing participation.
Lesson: "An alarming idea: Designing alarm circuits" (The EiE Team, 2005).		
Electrical Engineering	Technology? (ETS1.A)	Discussed defining technology and the role of electrical engineers.
	Energy Transform. (PS3.A, PS3.B)	Introduced energy types and the properties of conductors and insulators, laying groundwork for circuit design.
	Materials Testing (ETS1.B)	Conducted tests on various circuit configurations (simple, series, and parallel) using modified materials, exploring the effects of different conductor and insulator materials on circuit performance.
	Model Building (ETS1.C)	Designed and built functional alarm circuits within a mini milk carton model, using insights from materials testing.
	Creative Ext. (ETS1.B)	Constructed small robots using toothbrush heads and vibration motors, applying electrical circuits in a creative context.
Lesson: "Now you are cooking: Designing solar ovens" (The EiE Team, 2020d).		
Green Engineering	Technology? (ETS1.A)	Explored the definition of technology and the role of Green Engineers in designing sustainable solutions.
	Heat Transfer (PS3.B)	Covered principles of heat transfer, with emphasis on how these processes affect material performance as insulators and conductors.
	Materials Testing (ETS1.B)	Tested the insulating effectiveness of materials in solar ovens and measured reflective properties using lux meters.
	Model Building (ETS1.C)	Designed and assembled solar ovens, with the final challenge of baking s'mores to demonstrate design effectiveness.
	Data analysis & reflection (ETS1.B)	Presented and discussed data visuals to inform design decisions, particularly for heating ovens to melt marshmallows.

This table summarizes the engineering activities from the Saturday STEM Academies, EiE lesson citations, and their alignment with NGSS for grades 6–12.

Optical engineering

The lesson context was adapted from designing passive lighting systems for a pyramid to designing systems on a model house for fictional clients with unique requirements, Cindy Luz Who and Mrs. Grinch. Cindy Luz Who was named to reflect the predominantly Latino student population, as "Luz," meaning "light" in Spanish, is both culturally relevant and a recognizable name within Latino communities. This adaption was particularly relevant to the middle school population, as the lesson took place during the holiday season when decorative lighting is a familiar and engaging theme. The use of colorful reflective materials on their model homes and Christmas-themed fictional characters made the activities fun and relatable for students, reinforcing their connection to the content. Students tested the reflective properties of various materials using lux meters and applied these insights to their lighting system design. The hands-on activities helped reinforce their understanding of light interactions with materials and the practical challenges of meeting client specifications.

Electrical engineering

Materials were adapted from the original EiE unit recommendations, utilizing paper circuit diagrams, copper tape, 3-volt coin batteries, buzzer alarm sounders, and LED diodes instead of traditional wires, D batteries, and light bulbs. The lesson context shifted from building a generic alarm prototype to designing functional alarm circuits within mini milk carton models, simulating home security systems. This lesson was chosen for its relevance to students' everyday interactions with technology that relies on electricity, providing them with an opportunity to understand how energy is transferred and transformed. The hands-on exploration of circuits not only engaged students but also offered a practical connection to the technology that surrounds them. The lesson concluded with a creative extension where students built small robots using toothbrush heads and vibration motors, further reinforcing their understanding of electrical circuits and energy transformations.

Green engineering

This lesson was adapted to test insulation directly in solar ovens placed outdoors, with temperature measurements taken every 30 s. They compared the insulating capabilities of Styrofoam to compostable packing peanuts as a more green solution, and assessed the reflective properties of materials such as mylar, tinfoil, and mirrors by taking lux score measurements. The data informed students about material performance under different environmental conditions. Visual representations of this data were discussed and used to guide the design of solar ovens. The lesson leveraged the sunny, warm conditions of early summer, making it an ideal time for hands-on experimentation in Green Engineering. It encouraged students to apply skills learned in previous lessons while introducing the idea of using sustainable technology to solve environmental issues caused by other technologies. The activity also sparked students' interest and motivation through the familiar and enjoyable task of baking s'mores, fostering engagement while emphasizing the practical application of their design. The lesson culminated in students using their customized ovens to bake the s'mores, reflecting on how well their designs met the objective of sufficient heat generation to melt marshmallows.

Data analysis

Qualitative data analysis

Engineering journals with student responses were gathered and prepared for thematic analysis. Two coders independently transcribed the responses into Excel, categorizing the data by the specific engineering lesson. Thematic analysis was used to identify patterns in students' understanding of the engineering concepts presented.

Quantitative data analysis

Multiple imputation was performed in SPSS (IBM Corp, 2022) for missing data under 5 %. Two participants were excluded for missing post-test surveys, leaving a sample size of $n = 20$. Shapiro–Wilk tests indicated self-efficacy pre-test scores were normally distributed, but post-test scores were not. Both pre- and post-test scores for STEM identity were normally distributed, whereas engineering perception scores were not. Therefore, STEM identity and engineering perception scores were analyzed using paired t-tests with (Cohen's d for effect size) and Wilcoxon Signed Rank Test (with rank-biserial correlation (r) for effect size), respectively.

Group differences by grade level, gender, and prior academies were analyzed using the Kruskal-Wallis test, followed by Mann–Whitney U tests, with effect sizes calculated as rank-biserial correlations (r). The power of all tests was assessed using the pwr package in R (R Core Team, 2024).

Study 2 results

Qualitative results

Students demonstrated a good understanding of the content, as evidenced by the high proportion of correct answers for the "True/False Formative Assessment" included in the Optical Engineering lesson (please see Figure 1). Qualitative analysis of engineering journals revealed several key themes in how students communicated their understanding of the specific engineering concepts and the EDP. Students demonstrated a greater understanding of technology compared to their initial ideas of technology; they successfully recalled engineering concepts, utilized discipline-specific terminology, and effectively integrated science with engineering in their reflections.

Additionally, program participants communicated a deeper understanding of the EDP by showing an awareness of how to achieve success through specific aspects of the process. The hands-on activities served to support understanding in meaningful ways, as students often referred to these experiences to articulate their understanding of the engineering concepts. For example, in their geotechnical engineering journal, one group wrote: "*We think the bedrock will keep the skyscraper stable. The skyscraper fell on the first layer. In the second layer the skyscraper started learning instead. On the third layer the skyscraper stayed straight.*" This response was directly informed by their experience with the "Engage with Models" activity. The themes identified from the engineering journals, along with examples, are detailed in Table 5.

The themes reflect how students understand and apply engineering concepts in a structured educational setting across different engineering fields. One of the primary themes is the students' understanding of technology. This theme captures how students define and describe technology as a human-made process or object designed to solve problems. For instance, in discussions related to optical engineering, students explain that turning on a light is considered a technology because it involves processes, parts, and wires designed by humans. Similarly, in green engineering, students perceive technology as "*anything made by a person to solve a problem.*" This reflects a growing awareness among students that technology is not just about gadgets or machines but rather about the underlying processes and problem-solving nature of human inventions.

Another important theme is the successful recall of engineering concepts, which emphasizes the students' ability to remember and apply science and engineering concepts. For example, in geotechnical engineering, students demonstrated their understanding of

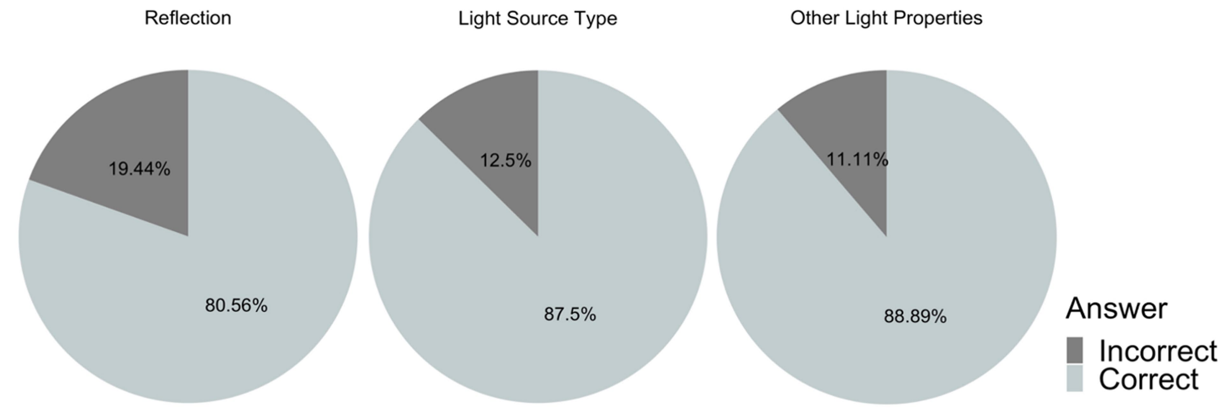

FIGURE 1
Proportions correct and incorrect. Shows the percentage of correct answers for each T/F statement, grouped into three categories: Reflection 80.56% correct, light source type 87.5% correct, and other light properties 88.89% correct. Hands-on activities significantly contributed to their understanding, serving a representational role in their learning.

foundational stability by explaining that a skyscraper should be anchored in the *bedrock layer*, which is the most stable during an earthquake. Similarly, in electrical engineering, students recalled that a *power source*, *wire, light bulb, and battery* are necessary to light up an LED. This ability to recall and apply specific engineering knowledge signifies that students are internalizing core concepts and can actively engage with them.

The theme of discipline-specific terminology illustrates students' use of specialized vocabulary from both science and engineering. This theme captures how students apply the correct terminology when describing scientific phenomena and engineering processes. For instance, in geotechnical engineering, students correctly associate *faster-moving water* with *increased erosion*, showing their understanding of the *relationship between speed and geological changes*. In electrical engineering, they correctly predicted that when one LED in *a series circuit* burns out, it might act as an *open circuit*. This proper use of vocabulary reflects their growing mastery of the language of engineering and science, which is crucial for deeper learning and communication within these fields.

In addition to understanding concepts and terminology, students also demonstrated an integration of science and engineering. This theme is reflected in students' ability to use scientific knowledge to make engineering decisions. For example, in geotechnical engineering, students applied their understanding of erosion to determine the best site for building, considering how water movement affects soil stability. In electrical engineering, students integrated their knowledge of circuits to explain how a series circuit differs from an open circuit in terms of electron flow. This ability to bridge science and engineering shows that students are not only learning isolated facts but are also connecting different domains of knowledge to solve real-world problems.

The theme of gained awareness of how to achieve success captures students' understanding of the steps required to complete a task successfully. Here, students articulated the processes they would follow to achieve success, demonstrating clarity of thought and the ability to envision outcomes. In geotechnical engineering, students mentioned testing and collaboration as part of the design process, expressing confidence that understanding the task would lead to a successful outcome. Similarly, in electrical engineering, students discussed how improving the clarity of a design could lead to better results. This theme highlights students' developing metacognitive skills as they reflect on the actions necessary for problem-solving and success.

Finally, the theme of hands-on activities serving a representational role emphasizes how students used prior practical experiences to inform their responses. For example, in geotechnical engineering, students referred to earlier experiments where they tested the stability of skyscrapers on different layers, using this knowledge to predict the outcome of anchoring a building in bedrock. In electrical engineering, they recalled which materials were strong or weak conductors based on prior activities involving metal, paper clips, and other materials. This theme underscores the importance of experiential learning, where hands-on activities enhance students' understanding and retention of abstract concepts by giving them tangible experiences to draw upon.

This pattern of themes features the multifaceted ways in which students interact with hands-on engineering activities. These insights suggest that students are not only learning the content but also applying critical thinking skills and displaying an appreciation for the problem-solving nature of engineering.

Quantitative results

Optical engineering impacts

A Wilcoxon signed-rank test showed a significant increase in self-efficacy scores from pre-test ($M = 3.29$, $SD = 0.79$) to post-test ($M = 3.72$, $SD = 0.72$), $Z = -2.06$, $p = 0.039$, $1 - \beta = 0.50$, with a medium effect size, $r = -0.46$. Paired t-test indicated significant increases in STEM identity scores from pre-test ($M = 2.66$, $SD = 1.03$) to post-test ($M = 3.30$, $SD = 0.88$), $t\,(19) = -2.42$, $p = 0.026$, $1\text{-}\beta = 0.63$, with a medium effect size, $d = 0.54$; perceptions of engineering knowledge (Basic) scores also indicated a significant increase from pre-test ($M = 2.86$, $SD = 1.11$) to post-test ($M = 3.76$, $SD = 0.91$), $t\,(19) = -4.63$, $p < 0.001$, $1 - \beta = 0.99$, with a large effect size, $d = 1.04$; and significant increase was indicated in perceptions of engineering

TABLE 5 Saturday STEM Academy engineering journal themes and sub-themes with descriptions and examples.

Sub-themes	Descriptions	Prompts	Examples
Theme: Greater understanding of technology			
1. Composite 2. Solves problems 3. Human made	They describe technology as… 1. A process made up of multiple parts. 2. Objects that help solve problems. 3. Created by humans.	*Optical engineering:* It's a rainy day and the sun is covered by clouds, so it is difficult to see details inside the classroom. Why is "turn on the light" technology? *Green engineering:* What is technology?	*Optical engineering:* "it's technology because it uses wires and is made up of parts that were probably thought of by someone that went through a process" *Green engineering:* "a thing made to solve a problem," "anything made by a person"
Theme: Successful recall of engineering concepts			
Knowledge transfer	If they recalled information that was relayed to them by instructors earlier in the lesson.	*Geotechnical engineering*: In which layer would you anchor the skyscraper to keep it stable during an earthquake? Why? *Electrical engineering*: What are the basic components needed to light up an LED?"	*Geotechnical engineering:* "You would want to anchor the skyscraper into the bedrock layer. The bedrock is the most stable layer out of the three" *Electrical engineering:* "The power source, wire, light bulb, battery"
Theme: Discipline specific terminology			
1. Science vocabulary 2. Engineering vocabulary	If they used… 1. Science specific vocabulary. 2. Engineering field specific terminology.	*Geotechnical engineering*: What do you already know about erosion along a riverbank? *Electrical engineering*: Can you predict what might happen if one LED in a series circuit burns out?	*Geotechnical engineering*: "The faster the water moves, the more erosion there will be." *Electrical engineering*: "It might act like an open circuit"
Theme: Integration of science and engineering			
1. Science to inform building site 2. Science to inform efficacy of technology	If they used their science knowledge to… 1. Choose the best site for building. 2. Describe their understanding of how various electrical circuits work.	*Geotechnical engineering:* What do you already know about erosion along a riverbank? *Electrical engineering*: How is this different from what happens in a series circuit?	*Geotechnical engineering*: "The faster the water moves, the more erosion there will be. The water farther from the curve will travel faster" *Electrical engineering*: "It is different by being a open circuit because the electrons do not flow through."
Theme: Gained awareness of how to achieve success			
1. Process 2. Clear understanding 3. Envision expected outcome	If they describe… 1. The processes they need to take to achieve the task. 2. A clear understanding of the task at hand. 3. The expected outcome of the task.	*Geotechnical engineering*: How will you know if your design is successful? *Electrical engineering*: How do you think this design can be improved?	*Geotechnical engineering*: "Model and test," "collaboration," "I know it will be successful because if we understand what we do, we can be successful," "I will know if the design is successful if it does not fall over" *Electrical Engineering*: "I think the design can be improved by making. A more clear design"
Theme: Hands-on activities served a representational role			
Experience and Observation	If they referred to earlier STEM academy activities to inform their response.	*Geotechnical engineering*: In which layer would you anchor the skyscraper to keep it stable during an earthquake? Why? *Electrical engineering*: For conductors, which are strong conductors, and which are weak conductors?	*Geotechnical engineering*: "We think the bedrock will keep the skyscraper stable. The skyscraper fell on the first layer. In the second layer the skyscraper started learning instead. On the third layer the skyscraper stayed straight." *Electrical engineering*: "For conductor strong one are metal, paper clip, tinfoil, and playdough. Weak conductors are felt, plastic paper clips, and clay."

This table summarizes the themes and sub-themes identified in student engineering journals from the Saturday STEM Academies. Each theme reflects students' understanding and application of engineering concepts, as captured through journal prompts and examples from the lessons in geotechnical, optical, electrical, and green engineering. The table provides descriptions and examples of student responses categorized under each theme, showcasing their recall of concepts, use of discipline-specific terminology, and integration of science and engineering knowledge.

TABLE 6 **Saturday STEM Academy pre- and post-test comparisons of optical engineering lesson constructs.**

Construct and test	Pre-Test		Post-Test		Mean Diff.	t/Z	*p* (2-sided)	Effect size (*d* / *r*)	Power (1 - β)	Ranks (+/ -, Sum)	95% CI (Bootstrap)
	M	*SD*	*M*	*SD*							
Self-Efficacy (Wilcoxon)	3.29	0.79	3.72	0.72	-	−2.06	0.039*	$r = -0.46$	0.50	12/5, 120/33	[0.035, 0.042]
STEM Identity (*t*-test)	2.66	1.03	3.30	0.88	−0.65	−2.42	0.026*	$d = -0.54$	0.63	-	[−1.01, −0.06]
Basic P.E.K. (*t*-test)	2.86	1.11	3.76	0.91	−0.9	−4.63	< 0.001***	$d = -1.04$	0.99	-	[−1.57, −0.48]
Optical P.E.K. (*t*-test)	1.99	1.11	3.52	1.12	−1.53	−5.61	< 0.001***	$d = -1.14$	1.00	-	[−1.70, −0.56]

$n = 20$, P.E.K. stands for Perceptions of Engineering Knowledge. * Indicates significance at alpha level 0.05, **0.01, *** < 0.001 and the effect size is reported with the rank-biserial correlation or Cohen's d as appropriate. t/Z reports the *t* statistic for the *t*-tests and the Z statistic for the Wilcoxon Signed-Rank Test. The Ranks column displays the number of positive ranks / the number of negative ranks, the sum of positive ranks / the sum of negative ranks.

TABLE 7 **Saturday STEM Academy pre- and post-test comparisons of electrical engineering lesson constructs.**

Construct and test	Pre-Test		Post-Test		Z	*p* (2-sided)	Effect size (*r*)	Power (1 - β)	Ranks (±, Sum)	95% CI (Monte Carlo)
	M	*SD*	*M*	*SD*						
Self-Efficacy (Wilcoxon)	3.47	0.77	3.61	0.94	−1.05	0.292	−0.28	0.53	5/3, 25.50/10.50	[0.33, 0.35]
STEM Identity (Wilcoxon)	2.57	0.76	2.56	0.86	−0.21	0.834	−0.06	0.07	5/8, 42.50/48.50	[0.85, 0.86]
Basic P.E.K. (Wilcoxon)	3.51	1.02	3.75	0.93	−0.91	0.363	−0.24	0.41	7/7, 67/38	[0.38, 0.40]
Electrical P.E.K. (Wilcoxon)	3.11	1.64	3.46	1.44	−1.10	0.272	−0.29	0.57	8/4, 53/25	[0.29, 0.30]

$n = 14$, * Indicates significance at alpha level 0.05, **0.01, *** < 0.001. P.E.K. stands for Perceptions of Engineering Knowledge. * Indicates significance at alpha 0.05 and the effect size is reported with the rank-biserial correlation. Z: the statistic for the Wilcoxon Signed-Rank Test. The Ranks column displays the number of positive ranks / the number of negative ranks, the sum of positive ranks / the sum of negative ranks.

knowledge (Optical) scores from pre-test ($M = 1.99$, SD = 1.11) to post-test ($M = 3.52$, $SD = 1.12$), $t\ (19) = -5.61$, $p < 0.001$, $1 - \beta = 1.00$, with a large effect size, $d = 1.14$. Detailed statistics, confidence intervals, and rank information are provided in Table 6.

Electrical engineering lesson

Wilcoxon signed-rank tests revealed no significant differences between pre-test and post-test scores across the four constructs (Table 7). A Mann–Whitney U test indicated significant differences in post-test STEM identity scores between students attending one or two lessons (*Mdn.* = 1.84) vs. three or four lessons (*Mdn.* = 3.13), $U = 41.50$, $p = 0.020$, $r = 0.61$, $1 - \beta = 0.62$ (please refer to Figure 2; Table 8).

Green engineering lesson

Paired *t*-tests showed significant increases in self-efficacy scores from pre-test ($M = 3.28$, $SD = 0.85$) to post-test ($M = 3.75$, $SD = 0.73$), $t\ (19) = -2.39$, $p = 0.027$, $1-\beta = 0.62$, with a medium effect size, $d = -0.53$; perceptions of engineering knowledge (Basic) scores showed a significant increase from pre-test ($M = 3.53$, $SD = 0.89$) to post-test ($M = 3.80$, $SD = 0.73$), $t\ (19) = -2.52$, $p = 0.021$, $1-\beta = 0.67$, with a medium effect size, $d = -0.56$. Additionally, a significant increase was observed in perceptions of engineering knowledge (Green) scores from pre-test ($M = 3.12$, $SD = 1.30$) to post-test ($M = 3.63$, $SD = 0.99$), $t\ (19) = -3.12$, $p = 0.006$, $1-\beta = 0.84$, with a large effect size, $d = -0.70$. There were increases in STEM identity scores from pre-test ($M = 2.80$, $SD = 0.94$) to post-test ($M = 3.19$, $SD = 0.85$), though this difference was not statistically significant, $t\ (19) = -1.85$, $p = 0.079$, $1-\beta = 0.42$, with a small effect size, $d = -0.41$. Detailed statistics, confidence intervals, and effect sizes are provided in Table 9.

Impact of prior exposure

Students who attended three or four lessons had significantly higher self-efficacy post-test scores (*Mdn.* = 4.20, $IQR = 0.95$) compared to those who attended one or two lessons (*Mdn.* = 3.40, $IQR = 1.00$), $U = 87.50$, $Z = 2.847$, $p = 0.003$, $r = 0.64$, $1 - \beta = 0.81$. For perceptions of basic engineering knowledge, students who attended three or four lessons also showed significantly higher post-test scores (*Mdn.* = 4.31, $IQR = 1.21$) compared to those who attended one or two lessons (*Mdn.* = 3.38, $IQR = 0.50$), $U = 87.50$, $Z = 2.841$, $p = 0.003$, $r = 0.64$, $1 - \beta = 0.81$. For perceptions of green engineering knowledge, students who attended three or four lessons had higher post-test scores (*Mdn.* = 4.42, IQR = 1.19) compared to those who attended one or two lessons (*Mdn.* = 3.00, IQR = 0.63), $U = 94.00$, $Z = 3.335$, $p < 0.001$, $r = 0.75$, $1 - \beta = 0.92$. No significant differences were found for the STEM Identity construct. Please refer to Figure 3 for graphs of significant grouped results. Please see Table 10 for statistical results.

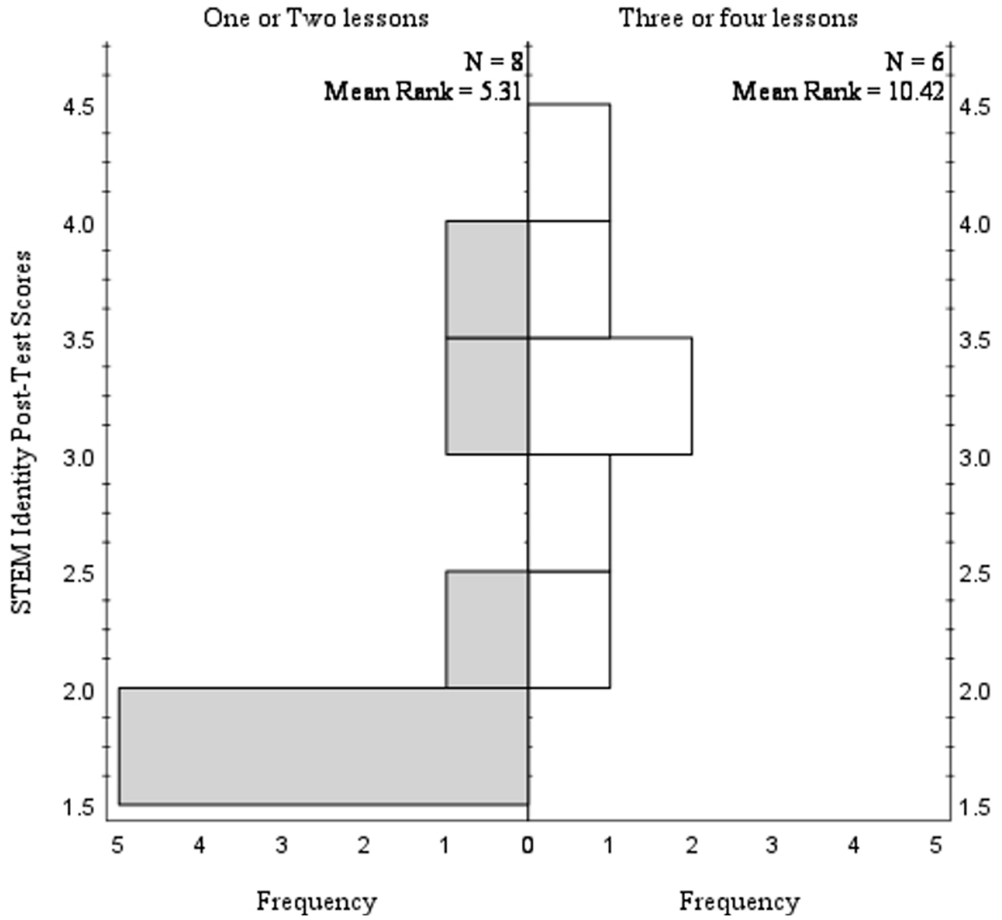

FIGURE 2
STEM identity perceptions by lesson attendance: distribution after electrical engineering lesson. This graph shows the distribution of STEM Identity scores by lesson attendance for the Electrical Engineering lesson. The results are based on the Independent-Samples Mann–Whitney U Tests, which identified a significant difference in STEM Identity perceptions. The X-axis represents the frequency of participants within each group, while the Y-axis indicates the average STEM Identity scores calculated across items within the construct. The graph highlights differences in participants' STEM Identity perceptions based on their attendance.

TABLE 8 Saturday STEM Academy electrical engineering lesson post-test attendance group comparisons.

Construct and time point	Group	*n*	*Mdn.*	*IQR*	*U*	*z*	*p* (exact)	Effect size (*r*)	Power (1 - β)
Self-Efficacy Post-Test	1–2 Lessons	8	3.57	2.50	25.50	0.19	0.852	0.05	0.05
	3–4 Lessons	6	3.80	2.70					
STEM Identity Post-Test	1–2 Lessons	8	1.84	1.19	41.50	2.27	0.020*	0.61	0.62
	3–4 Lessons	6	3.13	1.22					
Basic P.E.K. Post-Test	1–2 Lessons	8	3.46	1.70	36.00	1.56	0.142	0.42	0.34
	3–4 Lessons	6	4.38	1.47					
Electrical P.E.K. Post-Test	1–2 Lessons	8	3.75	2.35	29.50	0.71	0.49	0.19	0.11
	3–4 Lessons	6	4.08	2.13					

*Indicates significance at alpha level 0.05, **0.01, *** < 0.001. P.E.K. Stands for Perceptions of Engineering Knowledge. Mdn., median score of each group; IQR, interquartile range. U is the Mann–Whitney U test statistic and z is the Standardized test statistic. The effect size r stands for the rank biserial correlation, and the power is estimated using the binomial distribution arcsine transformation.

Discussion

Both studies explore whether exposure to the EDP affects middle school students' STEM identity, self-efficacy, and perceptions of engineering knowledge in ISL environments. Findings from the Summer and Saturday STEM Academies highlight the differential impacts of short-term vs. repeated interventions on learner outcomes.

TABLE 9 **Saturday STEM Academy pre- and post-test comparisons of green engineering lesson constructs.**

Construct and test	Pre-test		Post-test		Mean Diff.	*t*	*p* (2-sided)	Effect size (*d*)	Power (1 - β)	95% CI (Bootstrap)
	M	*SD*	*M*	*SD*						
Self-Efficacy (*t*-test)	3.28	0.85	3.72	0.73	−0.47	−2.39	0.027*	−0.53	0.62	[−0.88, −0.06]
STEM Identity (*t*-test)	2.80	0.94	3.19	0.85	−0.39	−1.85	0.079	−0.41	0.42	[−0.83, 0.05]
Basic P.E.K. (*t*-test)	3.35	0.89	3.80	0.73	−0.27	−2.52	0.021*	−0.0.56	0.67	[−0.50, −0.05]
Optical P.E.K. (*t*-test)	3.12	1.30	3.63	0.99	−0.52	−3.12	0.006**	−0.70	0.84	[−0.86, −0.17]

n = 14, * Indicates significance at alpha level 0.05, **0.01, *** < 0.001. P.E.K. stands for Perceptions of Engineering Knowledge.

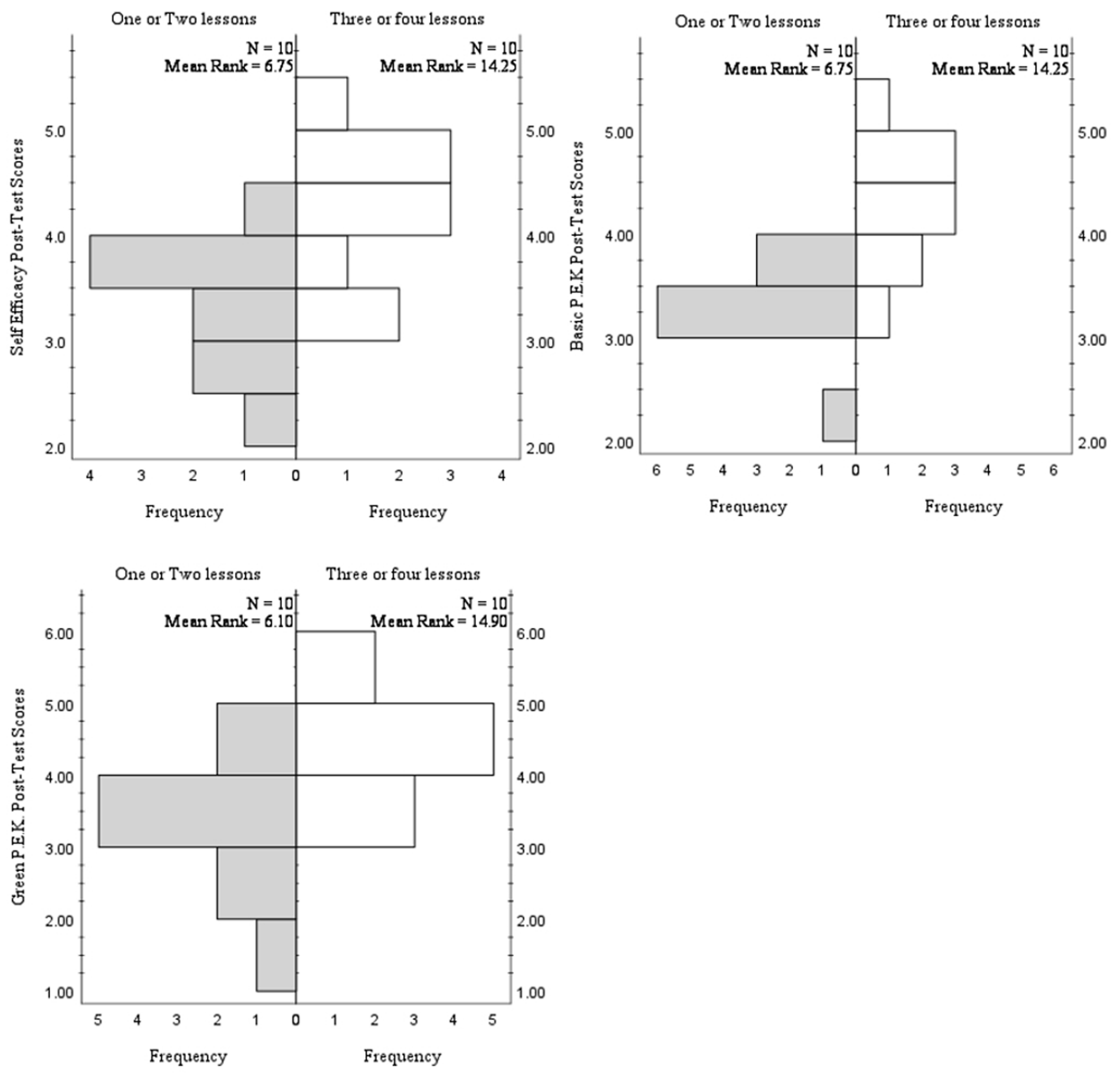

FIGURE 3
Perception scores by lesson attendance: distributions across constructs after green engineering lesson. This figure displays the distributions of perception scores across constructs (Self-efficacy top left, Basic Perceptions of Engineering Knowledge top right, Perceptions of Green Engineering Knowledge bottom left) that showed significant differences between groups, as determined by the Independent-Samples Mann–Whitney U Tests, for the Green Engineering lesson. The X-axis represents the frequency of participants in each group, while the Y-axis indicates the average scores calculated across items within each construct. Only constructs with statistically significant results are included in this figure to highlight key differences in participants' perceptions after attending the lesson.

TABLE 10 Saturday STEM Academy Green Engineering lesson post-test attendance group comparison.

Construct and time point	Group	*n*	*Mdn.*	*IQR*	*U*	*z*	*p* (exact)	Effect size (*r*)	Power (1 - *β*)
Self-Efficacy Post-Test	1–2 Lessons	10	3.40	1.00	87.50	2.85	0.003**	0.64	0.81
	3–4 Lessons	10	4.20	0.95					
STEM Identity Post-Test	1–2 Lessons	10	2.92	1.28	61.50	0.87	0.393	0.19	0.14
	3–4 Lessons	10	3.67	1.85					
Basic P.E.K. Post-Test	1–2 Lessons	10	3.38	0.50	87.50	2.84	0.003**	0.64	0.81
	3–4 Lessons	10	4.31	1.21					
Green P.E.K. Post-Test	1–2 Lessons	10	3.00	0.63	94.00	3.34	< 0.001***	0.75	0.92
	3–4 Lessons	10	4.42	1.19					

*Indicates significance at alpha level 0.05, **0.01, *** < 0.001. P.E.K. Stands for Perceptions of Engineering Knowledge. Mdn.: median score of each group. IQR: interquartile range. U is the Mann–Whitney U test statistic and z is the Standardized test statistic. The effect size r stands for the rank biserial correlation, and the power is estimated using the binomial distribution arcsine transformation.

Qualitative results

The findings from both studies provide valuable insights into how students communicated their understanding of engineering concepts and the EDP, addressing our first research question: *How do students communicate their understanding of the engineering concepts from the lessons and the EDP process?*

Qualitative analysis revealed students engaged with the EDP both conceptually and practically. The lessons fostered a foundational understanding of engineering, enabling students to approach challenges systematically. Embedding the EDP in culturally relevant, hands-on activities reinforced students' learning, aligning with prior research highlighting the benefits of experiential, culturally responsive STEM education (Feder et al., 2009; Gay and Howard, 2000; Kaldi et al., 2011; Ladson-Billings, 2022; Weisberg and Newcombe, 2017).

Students also showcased their growing mastery of discipline-specific terminology, a critical indicator of deeper learning and communication within STEM fields. Their ability to articulate concepts like erosion, circuit design, and structural stability reflects the effectiveness of integrating scientific vocabulary into engineering tasks. This mastery highlights the importance of teaching students not just the "how" of engineering but also the language necessary to communicate their understanding effectively.

Moreover, the theme of integrating science and engineering emerged prominently in student responses. Their reflections revealed a capacity to use scientific knowledge to make informed engineering decisions, bridging disciplinary divides. For example, students applied their understanding of erosion to geotechnical engineering tasks and used their knowledge of electrical conductivity to design functional circuits. This integration reflects the intervention's success in fostering interdisciplinary thinking, a key skill for real-world problem-solving.

An additional insight was students gained awareness of the steps required to achieve success, including collaboration, testing, and iterative improvement. These metacognitive skills, articulated through their reflections, illustrate their ability to plan and execute tasks methodically, reinforcing their understanding of the EDP as a systematic framework.

Finally, students' expanded understanding of technology, moving beyond gadgets to viewing it as a problem-solving process, signifies a critical shift in their conceptualization of engineering. This broadened perspective aligns with the intervention's goals of fostering a comprehensive understanding of engineering's problem-solving nature.

Together, these themes highlight the multifaceted ways students interacted with the EDP, demonstrating that the intervention enhanced their conceptual knowledge and critical thinking and problem-solving skills. These insights further support the efficacy of embedding culturally relevant, hands-on learning into STEM education, particularly in fostering transferable skills and deeper engagement with engineering concepts.

Quantitative results

The quantitative analysis explored how repeated exposure to the EDP within these lessons impacted students' STEM identity, self-efficacy, and perceptions of engineering knowledge. While the singular concentrated exposure in the Summer STEM Academy reflects a statistically significant decrease in STEM identity, the effect size ($r = 0.22$) indicates the practical importance may not be substantial, and the 95% confidence interval [−1.80, 1.38] includes 0 suggesting some uncertainty about the precision of the observed difference.

In contrast, students who attended Saturday STEM Academies to clear absences exhibited slower but measurable increases in STEM identity, suggesting repeated exposure to the EDP gradually enhanced their identification with STEM over time, supporting the role of consistent engagement in building long-term interest (Bell et al., 2009). However, STEM identity plateaued after multiple exposures. This plateau aligns with Staus et al. (2021) who observed rapid engagement with STEM subjects slowed as students become more familiar with the concepts. Without new and progressively challenging content, repeated exposure may not further strengthen STEM identity (Bethke Wendell and Rogers, 2013).

Unlike STEM identity, self-efficacy gains were slower and required multiple exposures to produce significant improvements. This finding aligns with Bandura's (1997) theory of self-efficacy, which emphasizes mastery experiences—repeated, successful engagements with tasks—are essential for building confidence. In the Summer STEM Academy, students did not have significant self-efficacy growth, while students in the Saturday STEM Academies exhibited gradual improvements. This difference may suggest students in the Summer STEM Academy who voluntarily participated had insufficient time to build their self-efficacy or may have already entered with higher levels of self-efficacy. For the Saturday Academy students, continuous engagement was crucial for building confidence, supporting the idea that sustained exposure is particularly beneficial for reluctant learners (Schweingruber and Fenichel, 2010). This suggests the need for providing students with repeated, hands-on experiences that allow them to internalize and apply engineering principles over time (Kosmas et al., 2019).

For Study 2, basic and specific engineering knowledge showed significant gains after repeated lessons, even in topics unrelated to students' previous exposures, suggesting students developed a generalized understanding of engineering principles. The cumulative learning effect supports the idea that repeated engagement with core concepts allows students to transfer knowledge across domains (Bell et al., 2009). Contrary to our hypothesis, prior exposure to the EDP framework did influence students' perceptions of their knowledge of specific engineering types. Students with more prior exposure reported higher knowledge even when the lesson content was new. This result suggests cumulative engagement with the EDP helped students develop a transferable understanding of engineering concepts, emphasizing the importance of repeated exposure in ISL settings.

The contrasting results between the Summer and Saturday STEM Academies offer insight into how different learner profiles respond to ISL interventions. Summer STEM Academy students, part of an African American leadership program, did not show significant gains after a single exposure to culturally relevant, immersive lessons. However, the Saturday STEM Academy students who had to be encouraged to attend exhibited slower but positive growth across all constructs measured. These findings emphasize the need to adapt ISL programs so that they address individual student motivation levels and are available to them more than one time (Schweingruber and Fenichel, 2010). However, caution is necessary in attributing long-term changes to these interventions alone, as noted by Staus et al. (2021). Future research is needed to assess the persistence of these impacts.

Implications for practice

Reinforcing STEM identity is crucial to strengthening students' academic trajectories, especially during transitions like middle to high school, particularly for underrepresented groups (Archer et al., 2010; Wang and Degol, 2013). Several implications for practice emerge to enhance future STEM lessons. Embedding the EDP in culturally relevant, hands-on activities suggests incorporating real-world problems that engage students and help them understand and apply engineering concepts. Additionally, directly involving students in identifying topics they find relatable and relevant at the end of their study period could help guide the development of future lessons. This approach would ensure that topics resonate with students' interests and experiences, fostering greater engagement. Programs targeting students with varying motivation levels should adapt their approaches to provide learners with consistent, long-term STEM exposure to foster gains in STEM identity and self-efficacy.

While short-term experiences may spark initial interest, sustained engagement with progressively challenging content is essential for continued growth in STEM identity and self-efficacy. Programs should focus on scaffolding lessons to build on prior knowledge and integrate various topics over time, promoting cumulative learning. This allows students to deepen their understanding and transfer engineering principles across different fields. Sustained, hands-on experiences are especially beneficial for reluctant learners, enabling them to internalize and apply concepts effectively over time (Kosmas et al., 2019).

Balancing experiential learning with reflective practices is necessary. While hands-on activities engage students, dedicating time for structured reflection deepens understanding (Cheryan et al., 2017; Schweingruber et al., 2014). STEM lessons could benefit from guided journaling or group discussions to encourage students to articulate their learning in more detail.

Ultimately, incorporating culturally relevant, hands-on experiences, sustained engagement, and reflection in STEM education equips students with both the skills and confidence to pursue engineering and related fields. Such practices ensure students—especially those with varied motivations—develop a robust STEM identity and are prepared for future academic and professional challenges.

Limitations

Several limitations must be acknowledged. First, the outdoor data collection during the Optical Engineering lessons may have limited students' written reflections, as they focused more on gathering temperature data than on deeper conceptual reflection. Similarly, the informal STEM Academy settings, while beneficial for engagement and participation, may have led to concise journal responses, suggesting a need for more structured reflection time in future interventions.

Additionally, there was an uneven emphasis on different engineering disciplines, particularly geotechnical engineering, which received more attention in the qualitative analysis due to the lack of quantitative data. This imbalance may have affected the depth of insights across Saturday STEM Academies.

The voluntary nature of student participation also contributed to the small sample size and inconsistent data collection, limiting our ability to generalize the results for larger groups and conduct a true longitudinal analysis. However, this variability in attendance provided an opportunity to assess whether different levels of exposure to the EDP had varying effects on students' STEM identity, self-efficacy, and perceptions of engineering knowledge. Future studies could address these limitations by incorporating a more varied and larger sample size, as well as measuring student attitudes 6 months after exposure to the EDP to assess whether their attitudes toward STEM and Engineering are retained long-term. These adaptations would enhance the generalizability of the results and offer a more comprehensive understanding of the impact of the EDP across different contexts.

Further, differences in student engagement between the two cohorts likely influenced the magnitude of construct gains. Students in the Summer STEM Academy (who voluntarily participated) may have had higher initial motivation levels compared to those in the Saturday STEM Academy (who were incentivized to attend to clear absences). This variation in engagement could have also contributed to differences in the results. Additionally, the reliance on self-reported measures may introduce bias, as students' perceptions may not fully reflect their actual abilities or knowledge.

Finally, while we observed short-term gains in STEM identity, self-efficacy, and perceptions of engineering knowledge, this study does not include long-term data to assess whether these gains are sustained over time. As Staus et al. (2021) argued, understanding the long-term effects of informal science education requires longitudinal approaches. Without follow-up data, we cannot determine whether the improvements in identity, self-efficacy, and knowledge persist after the program ends.

Conclusion

This study demonstrates the nuanced impact of ISL experiences in enhancing STEM identity, self-efficacy, and engineering knowledge through the EDP framework. Repeated exposures in the Saturday STEM Academies led to steady growth in self-efficacy and STEM identity, particularly among less motivated learners. These findings highlight the importance of providing ongoing opportunities for students to engage with engineering concepts and build confidence over time. By focusing on iterative learning experiences, ISL programs can play a crucial role in supporting diverse learners and cultivating a deeper interest in STEM fields.

Repeated exposure to the EDP broadened students' understanding of engineering principles, enabling knowledge transfer across engineering fields. Qualitative analysis demonstrated how students effectively communicated engineering concepts through problem-solving, applying structured steps of the EDP, and integrating science and engineering knowledge. Students also showed an expanded understanding of technology as a process for solving problems, alongside discipline-specific terminology and metacognitive awareness of the steps needed for success. These findings highlight the intervention's role in fostering critical thinking, interdisciplinary connections, and practical application of engineering concepts.

While the short-term gains are promising, future research should assess the long-term effects of repeated STEM exposures to determine if gains in STEM identity, self-efficacy, and engineering knowledge persist over time. Longitudinal studies are essential to evaluate the lasting impact of ISL interventions as students transition through critical educational stages and into STEM careers.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the International Review Board at the University of California, Merced. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

BB-S: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. MA: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. ZA-M: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing. MV: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2025.1534452/full#supplementary-material

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