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Engaging High School Students in Robotics and Artificial Intelligence Through Engineering Design Robotics Education

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Abstract

Engineering design education is an effective instructional approach for enhancing students' motivation, interest, and creativity while introducing them to the engineering design process (EDP). However, there is limited knowledge on how to integrate the EDP into robotics education, particularly AI-robotics, and how students experience AI-enabled robotics project-based learning grounded in an EDP. This pre-/posttest embedded mixed-methods study adds to the scarce body of literature on interdisciplinary education in engineering design, robotics, and AI. This project developed, implemented, and evaluated a project-based engineering design AI-robotics curriculum that introduced novice Computer Science (CS) high school students to robotics, machine learning, and AI. Students' collaborative robotics projects were grounded in an EDP to introduce the students to engineering practices and promote engagement and interest through design-based, hands-on learning. An analysis of quantitative and qualitative data revealed an improvement in students' CS attitudes, collaboration, and social interactions after participating in the curriculum. Recommendations for designing AI-robotics projects grounded in an EDP are discussed.

Keywords: educational robotics; artificial intelligence; engineering design process; project-based learning; K–12 computer science education

1. Introduction

Engineering design education is one of the core parts of the Next Generation Science Standards (NGSS) framework. NGSS integrates engineering design into K–12 science education and elevates its importance to be on par with scientific inquiry (National Research Council, 2013). Engineering design education promotes engineering "habits of mind" such as creativity, system thinking, collaboration, ethics, communication, and optimism (Katehi et al., 2009). Engineering also offers an effective framework for project-based learning (Resnick et al., 2000) and has been successfully used for enhancing student motivation, interest, and creativity (T.-S. Chang et al., 2022).

Robotics is a popular educational tool for introducing programming to Computer Science (CS) novices because of its ability to visualize algorithms and programs using robots (Anwar et al., 2019). Educational robotics is beneficial for improving problem-solving, creativity, motivation, communication, and collaboration (Anwar et al., 2019; Esteve-Mon et al., 2019; Stork, 2020; Tengler et al., 2020). It is also recognized as an effective approach for introducing students to engineering (Kaloti-Hallak et al., 2019). However,

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there is limited research on interdisciplinary robotics and engineering education, and little is known about how to integrate the engineering design process (EDP) into robotics curricula. Nonetheless, preliminary findings indicate the benefits of this approach for facilitating meaningful learning, creativity, collaboration, and interest in STEM. For instance, Ziaeefard et al. (2017) developed an educational program with educational co-robots as a platform for utilizing the EDP as a means of enhancing middle and high school students' interest in science and promoting hands-on learning. Their co-robotics pedagogy followed the eight NGSS practices of science and engineering: (1) asking questions and defining problems, (2) developing and using models, (3) planning and carrying out investigations, (4) analyzing and interpreting data, (5) using mathematics and computational thinking, (6) constructing explanations and designing solutions, (7) engaging in argument from evidence, and (8) obtaining, evaluating, and communicating information (NGSS Lead States, 2013). Kaya et al. (2017) used LEGO robotics in an elementary science teaching methods course to introduce the EDP to preservice elementary teachers. Sen et al. (2021) integrated the EDP into robotics hands-on STEM activity for gifted middle school students. Students were introduced to the EDP through hands-on 3D modeling and 3D printing STEM activities, after which they built a robot using the LEGO Mindstorms set and created a 3D design prototype of their robots using the EDP.

While conventional robots such as LEGO robots are used for assembling and programming the robots, robots that include AI capabilities provide a more diversified learning experience allowing students to interact with the robot using natural language or voice and image recognition (Chu et al., 2022). However, communicating AI concepts to students remains difficult even for domain experts (Long & Magerko, 2020), largely because AI has developed over an extended period and encompasses a broad and complex set of ideas. This complexity poses particular challenges for learners without technical backgrounds. Educational robotics offers a promising entry point for introducing such learners to foundational AI and machine learning (ML) concepts, including sensing, action, and perception (Chu et al., 2022). By allowing students to explore how AI systems perceive their environment, gather data, and respond to real-world conditions, robotics can make AI processes more visible and accessible (Olari et al., 2021). Moreover, because AI is a complex and broad domain that has not been extensively taught within K–12 robotics contexts, little is known about which AI/ML knowledge and skills can be effectively taught in high school CS classrooms (Karalekas et al., 2023).

Moreover, teaching AI and ML through educational robotics supports a coherent learning progression, beginning with programming and core CS concepts before advancing to more sophisticated AI/ML ideas—an approach shown to be critical for effective AI learning (Vrieler et al., 2021). Despite this potential, limited research has examined instructional strategies that meaningfully integrate AI/ML within robotics-based learning environments (Long & Magerko, 2020; Rizvi et al., 2023) and how AI-powered robotics impacts student learning experiences and attitudes toward CS. For example, a recent systematic review of AI in K–12 education identified very few studies focused on AI program implementation, with only a single study explicitly incorporating robotics (Lee & Kwon, 2024).

This study addressed the gap in the literature on the integration of EDP and AI/ML into K–12 robotics education. This project integrated engineering design and AI/ML into a high school robotics classroom to provide students with interdisciplinary project-based learning (PBL). The study developed, implemented, and evaluated an interdisciplinary project-based Engineering Design + Robotics + AI curriculum with novice CS high school students. Students' collaborative robotics PBL was grounded in an EDP (TeachEngineering.org) to introduce students to engineering practices and promote engagement and interest through design-based, hands-on learning (T.-S. Chang et al., 2022).

2. Theoretical Framework

2.1. Project-Based Learning

PBL is a learner-centered instructional approach that engages students in active learning around projects. Thomas (2000) conducted a comprehensive literature review to identify defining characteristics of PBL, revealing a considerable diversity of PBL definitions and a lack of a universally accepted theoretical framework or model of PBL. Thus, PBL definitions often state that "projects are complex tasks, based on challenging questions or problems, that involve students in design, problem-solving, decision making, or investigative activities; give students the opportunity to work relatively autonomously over extended periods of time; and culminate in realistic products or presentations" (Thomas, 2000, p. 1). Other definitions of PBL highlight the importance of authentic contexts and assessment practices, and the shift in teachers' roles from direct instruction to facilitation (Moursund, 1999), student collaboration and reflection (Diehl et al., 1999), the development of a community of inquiry, and the use of driving questions alongside cognitive (technology-based) tools (Marx et al., 1994).

In STEM education, PBL engages students in integrative STEM practices that connect concepts from multiple STEM subject areas often emphasizing the use of technology (Johnson et al., 2015). STEM PBL begins with a clearly defined end product that communicates explicit expectations and constraints, emphasizing students' construction of tangible artifacts to demonstrate their understanding. Projects are typically open-ended and conducted in small groups, requiring students to organize their work, manage resources and time, and collaborate effectively (Sahin, 2013). While this flexibility can sometimes make classrooms appear disorganized, it supports student ownership of learning and the development of collaboration skills. The interdisciplinary nature of STEM PBL is central to its effectiveness and has increasingly influenced instruction in STEAM and educational robotics. Moreover, there is growing recognition of the need for research to develop robust theoretical frameworks for STEM project design (Slough & Milam, 2013) and integrated STEM approaches, as well as to better understand how engineering-based initiatives can strengthen communication and collaboration (Burrows et al., 2018).

2.2. Engineering Design Robotics Education

Educational robotics promotes maker-centered learning that engages learners in making with learning technologies (Stahl & Hakkarainen, 2021). Making with robots is inspired by Papert's (1980) constructionism ideas about knowledge creation through invention, design, and making of embodied objects with digital tools.

Integrating the EDP into robotics education helps students connect CS concepts with real-world engineering practices using robotics. The EDP is an iterative process of design and reflection that involves the definition of a problem, synthesis of relevant information and resources for the solution, and evaluation of developed solutions (Cross, 2021). The EDP engages students in design-based learning where students use creative problem-solving to generate "uniquely satisfying solutions" to these problems (Koberg & Bagnall, 1981). Not only does the EDP introduce students to engineering practices, but it also motivates them to learn about STEM, even those who are less interested in STEM (Bers & Urrea, 2000).

Drawing on Sen et al.'s (2021) definition of EDP-STEM as "a pedagogical approach including engineering practices applied through various technological materials with the integration of theoretical knowledge of science and mathematics" (p. 3), we define *engineering design robotics education* as project-based robotics education that is based on engineering design (EDP; Figure 1). The literature offers various EDP models, including Think–Make–Improve (Martinez & Stager, 2013), Engineering is Elementary (Moffett et al.,

2011), Engineer Your World (Berland et al., 2014), and Picture STEM (Moore & Tank, 2014). Each EDP model presents unique design practices, yet they all share common processes and themes (Hynes, 2012). In the present study, we used the TeachEngineering.org EDP—a flexible and well-recognized tool for engaging students in hands-on, inquiry- and project-based learning that fosters STEM proficiency (National Research Council, 2013). The choice of the TeachEngineering.org EDP in our robotics curriculum was twofold. First, this EDP is strongly aligned with the NGSS framework by mirroring NGSS expectations of integrating science and engineering practices, emphasizing problem solving rather than following fixed procedures, while supporting learning of disciplinary core ideas, practices, and crosscutting concepts. Second, the TeachEngineering.org EDP is often taught in a K–12 science classroom, and therefore high school students might already have experience with this EDP.

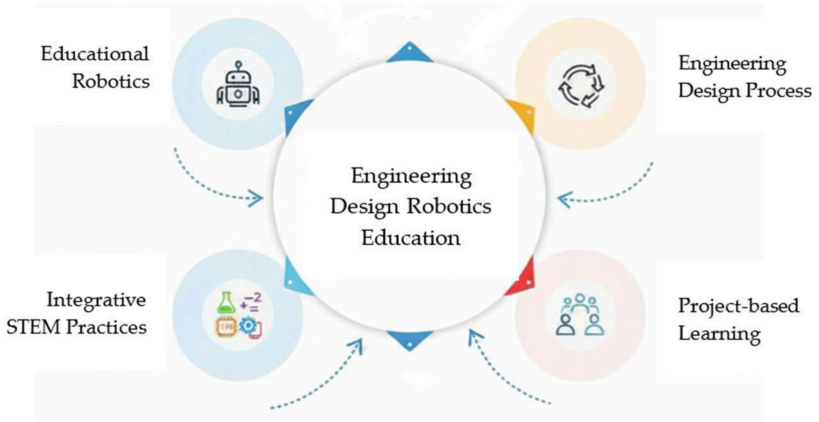


Figure 1. The engineering design robotics education framework.

2.3. CS Attitudes and Perceptions That Impact Participation in CS

Engineering design robotics education provides a powerful PBL context in which students engage with authentic, hands-on design challenges that integrate computational, engineering, and scientific thinking. As a technology-rich learning platform, robotics has strong potential to capture students' interest and motivate them to explore technology- and STEM-related pathways. Decades of learning sciences research demonstrate that students' attitudes and perceptions are critical for broadening participation in STEM. Nevertheless, many U.S. students lack basic interest in STEM—the strongest factor influencing students' intent to pursue a STEM career (Tillinghast & Mansouri, 2022).

The theory of planned behavior explains the relationship between behavioral intent, attitudes and perceptions, positing that behavioral intention is the most direct predictor of human behavior, including intent to participate in STEM. These intentions are influenced by perceived behavioral control, social norms related to the behavior, and individuals' attitudes toward that behavior (Ajzen, 2001; Montaño & Kasprzyk, 2008). Consistent with this theoretical framework, researchers in CS education argue that CS confidence, CS identity, and belongingness in CS are important factors that can explain students' participation and persistence in CS (McChesney et al., 2022).

Confidence or self-efficacy is the belief in one's own coping abilities (Bandura, 1978). CS self-efficacy explains why an individual chooses to participate in CS-related activities, e.g., CS extracurricular activities, CS classes in school, and a CS career. It plays a critical role in K–12 students' CS interest development and future participation in CS (Clarke-Midura et al., 2020).

Identity encompasses individuals' perceptions of who they are and who they might become (Markus & Nurius, 1986) and is deeply connected to learning processes (Wortham,

2005). Within CS education, CS identity plays a pivotal role in shaping students' participation, reflecting the degree to which they view themselves as belonging to the CS community (Shaw & Kafai, 2020). Research shows that CS identity correlates with CS self-efficacy, particularly among females (Aivaloglou & Hermans, 2019), and that females have lower self-identification as computer scientists than their male peers, which discourages them to participate in CS (Vrieler et al., 2021)

Belongingness explains the extent to which students feel that they are accepted and connected to their environment (Baumeister & Leary, 2017). A sense of belongingness in CS is central to self-representation of students who experience negative stereotypes about their social identity in CS (Master & Meltzoff, 2020). A lower sense of belongingness leads to lower academic performance and less interest. Students who feel that they belong tend to ask more questions and show higher engagement and motivation in class.

In robotics PBL contexts, these factors play a prominent role because maintaining and deepening youth interest in STEM depends on ongoing participation, teamwork, and engagement. Prior studies suggest that students' learning goals, confidence in their abilities, and perceptions of the relevance and value of STEM tasks play a substantial role in shaping their engagement in robotics PBL (Jormanainen et al., 2024, 2025). However, these studies do not include AI-powered educational robotics. Advancements in AI have created an additional layer of learning interactions and experiences in AI-robotics educational contexts through sensors and ML that enable robots to collect data about their physical environment, interact with users, recognize voice and images, and respond based on the received input (Olari et al., 2021). These AI-enabled learning experiences may promote engagement but also create confusion and uncertainty because of the probabilistic nature of ML algorithms (Eguchi, 2022). Examining students' AI-powered robotics learning experiences and their influence on CS attitudes is important for developing our understanding about how students learn in AI-enabled learning environments. Yet research in this area remains extremely scarce (McLaughlin et al., in press).

2.4. Research Questions

This pre-/posttest embedded mixed-methods study explored the following research questions:

RQ1. *How did high school students' CS confidence, enjoyment, career aspirations, and belongingness in CS change after participating in engineering design AI-robotics PBL?*

RQ2. *How did engineering design AI-robotics PBL influence high school students' learning experiences?*

CS confidence, enjoyment, career aspirations, and belongingness in CS were assessed using the Attitudes Towards Computing scale (Wanzer et al., 2019). This scale was selected because it includes short sub-scales assessing key CS attitudes, which is appropriate for classroom-based research, and because it was validated with high school students. Qualitative data sources such as interviews with the students and robotics teacher, students' learning artifacts, and classroom observations were used to further explore students' CS attitudes and learning experiences.

3. Method

3.1. Participants and Settings

The research took place in a public high school located in a distant town in the Midwest of the United States. The school serves more than 700 students from families with a below-median state and national household income; 24.4% of families live below the poverty level. The school is classified as "needs support to meet state standards" by the State Department of Education and Workforce.

Ten high school students (age M = 15.8, SD = 0.92; 3 females and 7 males; 1 Hispanic, 1 multiple races, 8 White students) enrolled in an *Introduction to Computer Science* course at the high school participated in the engineering design AI-robotics curriculum. The curriculum was implemented over a three-month period as part of the regular course schedule. Instruction took place during normal school hours in 50 min class periods, five days per week. The sample included one senior (grade 12), two juniors (grade 11), six sophomores (grade 10), and one freshman (grade 9). None of the students had prior experience with robotics or block-based coding. All participant names reported throughout the manuscript are pseudonyms.

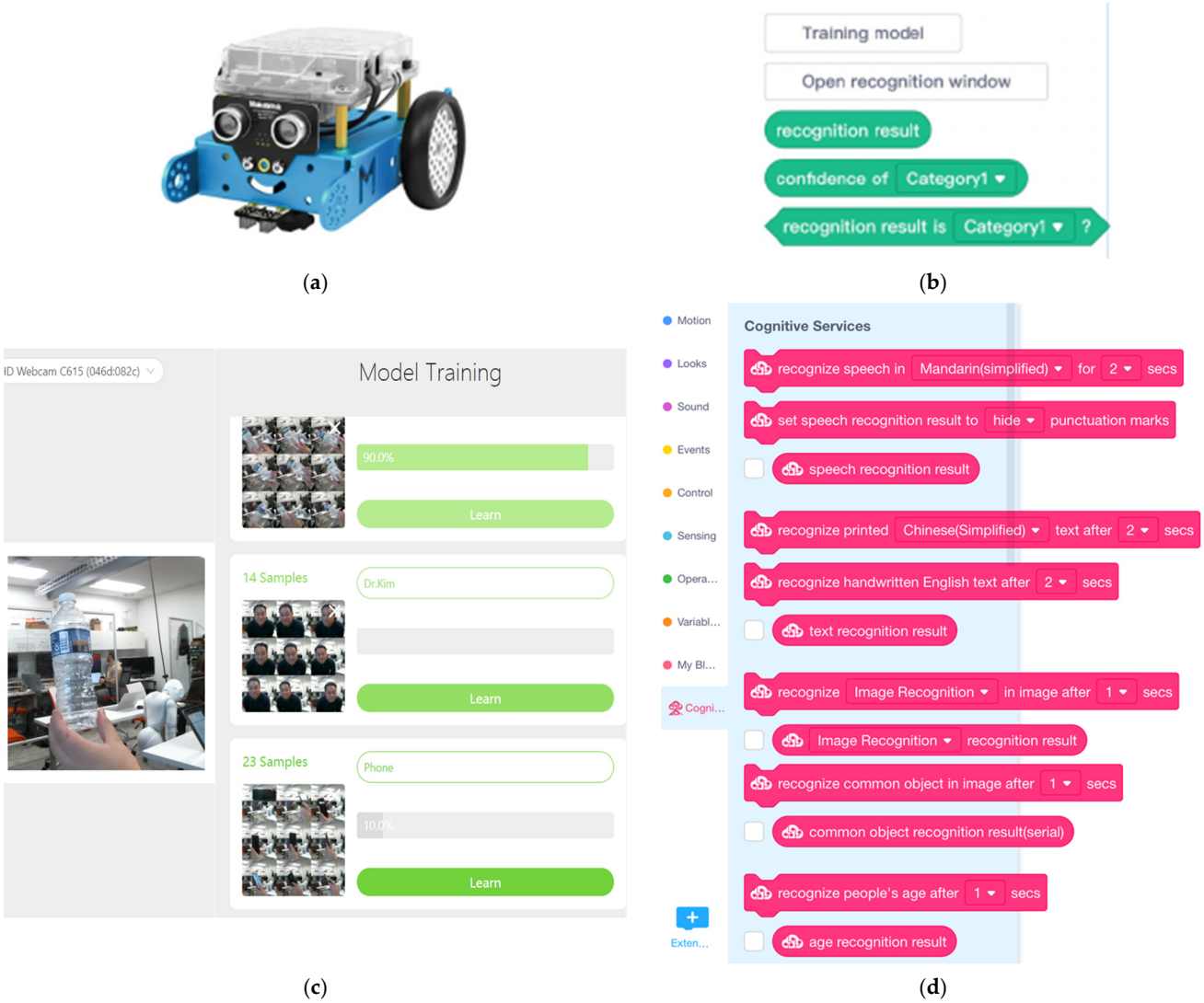
Five college students majoring in Computer Science from a large Midwestern research university mentored the high school students during the curriculum. High school students self-selected into teams of 2–4 members based on their preferences to work on their robotics projects. In total, there were five teams of high school students, each mentored by a dedicated mentor. Hereafter, we use the term *students* to refer to the participating high school students. The third co-author was the high school robotics teacher who collaborated with the research team to develop and implement the curriculum.

3.2. Engineering Design + Robotics + AI Curriculum

We used the mBot robotics kit (mBot, n.d.), a Makeblock entry-level programmable robot, in the curriculum. The mBot (Figure 2a) works with the mBlock block-based programming platform. It includes two non-AI sensors: a Quad RGB sensor for color recognition and an Ultrasonic sensor for the distance detection of an object. Both sensors were integrated into the curriculum. In addition, the curriculum used the Cognitive Services and Teachable Machine extensions available in Makeblock (Makeblock, n.d.). These extensions helped introduce students to advanced AI and ML capabilities for natural language processing, and voice and image recognition (Figure 2; Matar et al., 2024). Students trained various object recognition models using the Teachable Machine extension (Figure 2b,c) to identify recyclable and landfill objects. Additionally, they used the Cognitive Services extension (Figure 2d) for speech recognition. Integrating ML and AI into the mBlock application requires gathering data, processing it, and choosing suitable ML algorithms or pre-trained models.

The major goal of the curriculum was to engage high school students in programming AI/ML concepts in the context of engineering design robotics education, beyond focusing on programming skills. Toward this end, we chose to use a block-based coding environment to avoid the challenges of text-based programming. The curriculum included eight modules that utilized block-based coding using Scratch and mBlock. Scratch was implemented at the beginning of the unit to introduce students to block-based coding, followed by coding robots in mBlock. Table 1 shows an overview of the curriculum unit, including the target concepts and objectives of each module. At the end of each module, students were presented with reflection questions to further promote learning and facilitate classroom discussions. At the end of the curriculum, students worked in teams to complete a *Smart Trashcan* robotics engineering design challenge aligned with the TeachEngineering.org EDP. Although all teams were asked to design a *Smart Trashcan* robot, students were not told how the robot should gather or sort waste, interact with users, or which materials should be used for making the robot. Each team designed and iteratively refined a visually appealing mobile Smart Trashcan robot that gathered trash, incorporated ML/AI techniques (e.g., voice-to-text for user interaction and image recognition for classifying recyclable versus landfill waste), and aimed to promote more responsible waste-disposal behaviors. Students were guided to give their Smart Trashcan robots a creative identity or theme that reflects the mission to promote responsible waste disposal. This robotics engineering design challenge

was designed to demonstrate how robots can help people and the environment, which was found to be effective for promoting a sense of belonging in CS, particularly in girls (Malinverni et al., 2021; Sorenson et al., 2019).



(**a**) (**b**)

(**c**) (**d**)

Figure 2. (**a**) mBot robot. (**b**) Teachable Machine coding blocks. (**c**) Model training in mBlock. (**d**) Cognitive Services coding blocks.

Before the robotics engineering design challenge, students were introduced to the TeachEngineering.org EDP. The TeachEngineering.org EDP guided students to conceptualize the purpose of their robots and the problem that the robots needed to address (Ask), research existing technologies (Research), imagine various possible solutions (Imagine), select the best solution, and create a plan for building their robots (Plan). Then they engaged in the iterative Create -> Test -> Improve cycle, where they built their robot prototypes using various everyday materials, programmed and tested their robots to see if they could complete the challenge, and redesigned their robots to improve their functionality and design. Students used servo motors to create their robots' functionality and design features. This robotics project combined novel design, hardware incorporation, and utilization of AI-powered services to develop a Smart Trashcan robot. Students used robotics design journals to document their EDP and reflect on their robotics projects using guided questions. At the end of the project, students (1) created a 2 min video demonstrating their robot's capabilities and explaining their engineering design process, and (2) wrote an

end-of-project reflection using guided questions. Additionally, students participated in a robotics competition judged by their CS mentors and the research team and publicly presented their robots at a school event to share their projects with the school community.

Table 1. Engineering design + robotics + AI curriculum unit overview.

	Module	Objective
1.	About Me	Explore and experiment with sprites, costumes, backdrops, and sounds to create an interactive collage in Scratch.
2.	Music Video	Create a program in Scratch that blends interactive sprites with sounds; use control blocks to become familiar with computational principles of sequence and loops.
3.	Storytelling	Create a program in Scratch that tells a story by exploring two distinct ways of coordinating sprite interactions (timing and broadcasting) and become familiar with computational concepts of events and parallelism.
4.	Tangible Computing	Introduce tangible computing with mBot by creating the following short programs: Let mBot move; Move in a square; Ambulance; Celebrate Christmas; Solar car; Superpower; Artist.
5.	Sensing	Create the following short programs that utilize mBot's sensors: Detecting obstacles; Obstacle-avoiding car; Follower; Let me down; Cliff detection; Track patrol; Remote control mBot.
6.	Interacting	Create the following short programs that introduce human–robot interaction: Let mBot sprite say "hello"; It's dawn, it's dark; Tell us the distance; Voice-controlled mBot; Trampoline game with mBot; Greeter; Electronic instruments.
7.	AI & Machine Learning	Introduce AI and machine learning through text-to-voice, model training, and object recognition.
8.	Design Challenge	Introduce the EDP and apply it to the Smart Trashcan robot design challenge.

3.3. Procedures

At the beginning of the curriculum, participants completed an informed consent procedure and filled out a background survey (demographics and academic background, technology available at home, etc.). Students completed the Attitudes Towards Computing survey (Wanzer et al., 2019) before and after the curriculum unit. At the end of the curriculum, students participated in focus group interviews (30 min) on Zoom. In addition, we conducted a semi-structured interview with the robotics teacher to learn about the teacher's experiences with the curriculum (30 min).

3.4. Instruments

CS Attitudes and Perceptions were measured using the Attitudes Towards Computing scale (Wanzer et al., 2019; Appendix A). The scale included 11 five-point Likert-type items that were conceptualized as Computing Confidence (four items; *Cronbach* $\alpha = 0.84$), Computing Enjoyment (four items; *Cronbach* $\alpha = 0.74$), Computing Importance and Perceived Usefulness (four items; *Cronbach* $\alpha = 0.81$), and Computing Identity and Belongingness (three items; *Cronbach* $\alpha = 0.76$). Sample items of the Computing Confidence sub-scale included: "I am sure I could do advanced work in computing" and "I think I could handle difficult computing problems." Sample items of the Computing Enjoyment sub-scale included: "I enjoy computing" and "I feel comfortable computing." Sample items of the Computing Importance and Perceived Usefulness sub-scale included: "I will be able to get a good job if I learn computing" and "I will use computing in many ways throughout my life." Sample items of the Computing Identity and Belongingness sub-scale included: "I feel like I "belong" in computer science" and "I take pride in my computing abilities." The scores within each dimension were averaged to calculate each attitude score.

3.5. Qualitative Data Sources

Qualitative data sources included: (1) students' learning artifacts (robotics design journals, threads of code, end-of-project written team reflections, and final robotics presentation videos), (2) two student focus group interviews, (3) an interview with the robotics teacher, and (4) classroom observations.

Sample focus group interview questions with students included: "Can you tell me about your experiences with the robotics curriculum?" "What did you like?" "What could have been better?" and "What was your favorite part/activity in this project and why?" Sample teacher interview questions were: "Can you tell me about your experiences with the robotics curriculum?" and "Did the curriculum offer an inclusive learning experience for all students?"

3.6. Research Design and Data Analysis

The study employed an embedded pre-/posttest mixed-methods research design. Given the small sample size, we used the Wilcoxon signed-rank test to examine the pre-/posttest gains in CS attitudinal and affective variables (RQ1). The qualitative data were used to augment the quantitative data of students' CS attitudes and perceptions and further explore their CS learning experiences. Students' end-of-project reflections and focus group interviews as well as the teacher interview and classroom observations were used to qualitatively analyze students' CS attitudes and perceptions (RQ1). Students' learning artifacts, such as threads of code, design journals, and final robotics presentation videos, as well as student focus group interviews and the teacher interview, were used to examine students' learning experiences (RQ2).

Qualitative data were analyzed using a reflexive thematic analysis (RTA; Braun & Clarke, 2019, 2021) to identify themes across data sources using Nvivo software version 14. We used this method because it is theoretically flexible and appropriate for exploratory qualitative work across heterogeneous data sources.

In the first phase, we listened to all audio-recorded data and re-read all transcripts carefully to "get to know" the data, and documented our initial analytical thoughts for each source. In the coding phase, the second author conducted initial coding across data sources to capture findings relevant to the research questions. Our code segments included line-by-line, short sentences to full speaking turns to capture the main idea expressed by participants. Then, the second author regularly met with the first author to discuss the coding decisions, how data segments were coded, and to revise, name, and define brief descriptions of the codes. In phase 3, we grouped the codes into initial themes for each research question. In Phase 4, we reviewed and checked the themes against the full dataset and against the research questions to refine theme boundaries. In Phase 5, we defined and named the final themes, which the first and second authors discussed to interrogate interpretations and refine theme labels. In the final phase, we selected the representative excerpts and structured findings around the two research questions. Appendix B presents codes, themes, and exemplar data excerpts developed across the six phases of RTA.

We followed several established procedures (Lincoln & Guba, 1985; Nowell et al., 2017) to enhance the trustworthiness of our qualitative analysis, including a triangulation of multiple data sources (students focus groups and teacher interviews, students' learning artifacts and final project presentations), peer debriefing among the research team, and reporting direct quotes from participants. We also documented coding procedures, records of our analysis decisions, and revision logs; iteratively refined the codebooks; and reviewed and revised the theme definitions and interpretations to support the dependability and confirmability of the qualitative analysis.

The quantitative and qualitative findings were then synthesized in Section 5.

4. Results

4.1. Quantitative Findings

RQ1: Students' CS Attitudes and Perceptions

Table 2 presents the means, standard deviations, and Wilcoxon signed-rank test results for all study variables. Students reported above-average pretest scores for all CS attitudes and perceptions. Computing Importance and Perceived Usefulness was scored the highest (M = 4.35, SD = 0.63), while Computing Identity and Belongingness was scored the lowest (M = 3.43, SD = 0.63) on a scale from 1 to 5. Descriptively, all scores increased from pre- to posttest. However, the Wilcoxon signed-rank test yielded non-significant results for all study variables, indicating that the curriculum did not significantly change students' CS attitudes and perceptions.

Table 2. Students' CS attitudes and perceptions: pre-/posttest means and standard deviations, Wilcoxon signed-rank test results, and effect sizes (N = 10).

	Pretest	Posttest	Time Effects		
	M (*SD*)	M (*SD*)	*T*	*ρ*	*r*
Computing Confidence [a]	3.68 (0.76)	3.88 (0.70)	32.00	0.254	0.26
Computing Enjoyment [a]	4.08 (0.54)	4.18 (0.60)	8.50	0.194	0.29
Computing Importance and Perceived Usefulness [a]	4.35 (0.63)	4.44 (0.59)	27.00	0.584	0.12
Computing Identity and Belongingness [a]	3.43 (0.63)	3.47 (0.82)	17.50	0.944	−0.02

Note: [a] All scores range from 1 to 5.

4.2. Qualitative Findings

4.2.1. RQ1: High School Students' CS Attitudes and Perceptions

Our analysis of qualitative data produced three major themes addressing students' CS attitudes and perceptions: (1) CS enjoyment and positive experience, (2) building CS confidence and belongingness through teamwork, and (3) differentiated CS career aspirations.

CS Enjoyment and Positive Experience: Enjoyment was a recurring pattern across different data sources. Students in both focus groups described the project as engaging and expressed satisfaction and happiness with their robotics projects and designs in their end-of-project team reflections. Students highlighted that having different activities such as designing the mBot costume and then coding the robot made their experience particularly enjoyable.

Our analysis suggests two major sources of student CS enjoyment: (a) alternating between coding and designing a physical mBot costume, and (b) seeing how their code translated into the mBot behavior. Several students mentioned that working on the design was a refreshing change from coding, as it allowed them to envision and construct something tangible. For example, Brandon explained that comparing a robot's movement to human walking helped him better understand motion planning for the robot, highlighting the practical, hands-on aspect of educational robotics. He said:

> *"For me, it was helpful because I just imagined a human actually walking, doing these maneuvers. Coding can be physical or imagination, but I just imagined a person walking and doing all of these motions it's doing and how the AI is gonna respond to an item. So I think of that when I'm coding and my partner created the little robot we have. And I think it's really nice to build actually something and see it physically in front of me and not just on the computer screen."*

Brandon connected the robot's movements to his own experience of walking, using that real-world knowledge to reason about how the mBot should move. This highlights his understanding that coding involves more than typing commands, as it requires imagining

motion and translating ideas into physical action. Having a tangible robot in front of him reinforced this thinking by allowing him to immediately observe how code shaped the robot's behavior. This suggests that students valued the activity not simply for coding or building, but because the integration of design and programming made both more meaningful and easier to understand.

Another pattern of enjoyment related to the moments when students finally succeeded after extended periods of failure to make their robot work. Each team described the moment their robot worked as deeply satisfying, even after earlier frustration. For example, the Rosie the Robot team's design journal documents repeated failures throughout the week: Monday, "*Program not responding. Detected over 200 speech instances—overloaded?*"; Tuesday, "*Code all together is still not working*"; and Thursday, "*Not moving in response to voice. Not responding when it sees trash and recyclables*." Yet in their final reflection, when asked, "Are you happy with your robot?" they responded, "*YES! YES! YES!*" and their final project video demonstrated a fully functioning robot. The intensity of this response suggests that their enjoyment was strongly tied to overcoming challenges and achieving a tangible outcome.

Similarly, the Gunter the Penguin team articulated this dynamic explicitly: they were happy with Gunter "*because we put out hard labor into it and seeing it work and the codes moving from computer to an actual robot is pretty cool*." These remarks suggest that students felt happy and satisfied because they had successfully worked through a difficult problem and completed something meaningful. Their enjoyment came not from the project being easy, but from overcoming challenges and seeing a real result from their effort.

Building CS Confidence and Belongingness Through Teamwork: This theme captures how the collaborative aspect of the curriculum supported positive changes in students' CS confidence and belongingness in the classroom. We identified this theme through two connected patterns in the data. First, students took on different roles within their teams, allowing them to contribute in visible and meaningful ways. Second, the teacher noticed changes over time in how students interacted with peers during the project.

Across teams, one or two students typically focused on coding, while another student focused on designing the mBot, and some team members moved between the tasks. This division of labor positioned each student as a recognizable contributor to specific aspects of the project. For example, in the Rosie the Robot team's final presentation, each member explained their role: "*I did the coding for the robot*," "*I helped develop the code and paint Rosie's main structure*," "*I helped compose and produce Rosie's structure using the design process*." They further mentioned that, *"During the project, we worked very well as a team, each of us with specific roles."* Similarly, Carlos from the Gunter the Penguin team explained how responsibilities were shared within his team: "*We both . . . worked on the design part of it and the coding. He [his team partner] worked on the movability. I worked on the [robot] arm and the top part."* We interpreted these examples as evidence that role differentiation helped students clearly articulate their individual contributions, ensuring that each team member could publicly demonstrate what they had accomplished.

The second pattern reflected changes in how students connected with peers that they might not have interacted with otherwise. The teacher noticed that students started working together in new ways that were different from the usual patterns she saw in her CS class:

> *"It was nice to see them, actually collaborating. Because it's hard sometimes in a computer science. . . class I'm thinking of one in particular, that was very quiet, and he just was shining. In this project, he developed confidence, he was talking to everyone in the class, which he hadn't done before. And he was volunteering if he noticed another group having issues he would go over and help them. . . .it was just great."*

This shift mirrors our classroom observations and illustrates how the collaborative, hands-on nature of the project encouraged students to step outside their comfort zones, engage with peers, and take initiative. These behaviors appeared to strengthen both CS confidence and belongingness.

The teacher described a similar change among three girls from the Rosie the Robot team, mentioning that they "*were quiet and... they never voluntarily [worked in groups]*" but became close friends through the project. Our classroom observations supported these changes in student behavior and teamwork, suggesting that the curriculum created conditions in which previously quiet students became more socially visible and recognized as valued collaborators.

Differentiated CS Career Aspirations: An analysis of student and teacher interviews indicated that the curriculum shaped students' CS career aspirations in multiple ways. Some students entered the program with an existing interest in CS and used the project to reinforce that commitment. Others developed new CS aspirations, while a third group enjoyed the experience but ultimately clarified that their future goals lay outside the CS field. Several students explicitly noted that the curriculum influenced their intention to take additional CS courses or consider CS-related careers.

For students with pre-existing CS interest, the project served as confirmation of their plans. Tyler explained, "*I already wanted to go into computer science but this helped strengthen that idea*." Similarly, the teacher described a female student who shifted her plans toward continuing in CS: "*She was thinking about going to a Career Center, but she likes computer science so much now that she's going to stay at the high school and keep taking our classes, and now she's talking about majoring in it*."

Other students framed CS as a tool that could support broader career goals. Brandon, for example, described how the curriculum helped him connect computing to real-world impact through biomedical engineering. Rather than expressing a desire to become a computer scientist, he explained how CS could help him design products for diabetic patients:

> "*I think this strengthened my bond with... computer science because you're building something like out of your imagination from this. And for me and like my future career, I want to build a product for like diabetic patients. And this kind of helped me... understand how to do that and like do like prototypes and demos of it... trying to figure out what is wrong and fixing the bugs with it.*"

Nevertheless, enjoyment of the curriculum did not always translate into clear CS career interest. Some students remained uncertain due to other career plans or limited knowledge of what the field includes. Anna remarked, "*I'm still thinking about it. I really do like computer science. It's fun and everything, but like, I don't know all the fields of it... but like, I would like to get into it whenever I get older*."

Taken together, these varied responses suggest that the curriculum functioned less as a pipeline-recruitment intervention and more as a career-clarification experience, helping students develop a more realistic understanding of what CS entails and how it may or may not align with their future career aspirations.

4.2.2. RQ2. High School Students' Learning Experiences

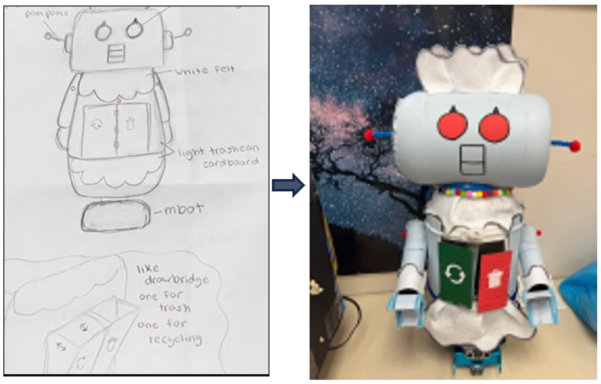
An analysis of students' threads of code, robotics project presentations, design journals, classroom observations, and student focus group interviews produced three key themes: (1) engagement in authentic engineering design practices; (2) personalization as a catalyst for ownership, motivation, and programming growth; and (3) technical/AI-related issues as productive learning opportunities.

Engagement in Authentic Engineering Design Practices: This theme highlights how students used the EDP to develop their robotics projects. Specifically, they collaborated to

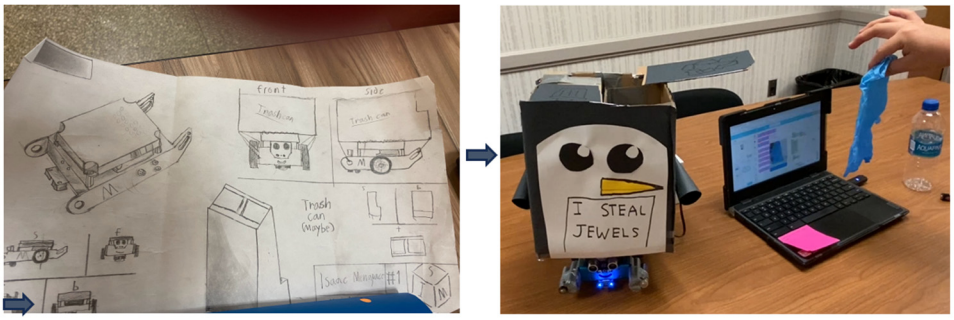
define the problem, brainstorm ideas for their robot's functionality (e.g., collecting and identifying trash, distinguishing between recyclable and non-recyclable items), sketched their initial robot designs with a chosen character theme, designed the robots based on these designs, coded, and troubleshot the project. When something did not work, they went back and changed it.

This back-and-forth was visible in the students' design journals. The Gunter the Penguin team, for example, planned for their robot to move on its own and detect objects, but the two functions interfered with each other. They documented in their journal, "*[the robot] wouldn't stop while detecting/opening the correct door and then it wouldn't stop at all*," and by the next day, they had changed their approach: "*we changed the code from automatic movement to remote control movement so we can maneuver it ourselves since it wouldn't stop moving*." We interpreted this as a practical design choice, not a failure. When the team realized autonomous movement was not working well, they decided to give up that feature and instead focus on a control system that worked more reliably.

Figure 3a–e depict the five teams' robotics sketches from their design journals and final robot designs created as part of the EDP. Figure 3a shows an example of a robot design that has two doors in its front section for recyclable or landfill waste. Figure 3b represents a design that features a robot with two sliding doors on top that open to receive either recyclable or landfill waste. Figure 3e presents an example of a robot design that was not fully functioning. The lid on top of the container was supposed to open to accept recyclable or landfill objects, but the team could not figure out how to create a lid and embed servo motors to support this functionality.

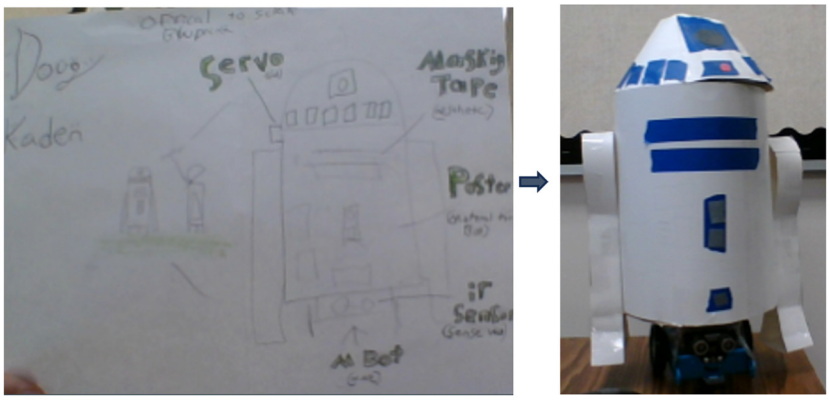


(**a**)



(**b**)

Figure 3. *Cont.*



(**c**)

(**d**)

(**e**)

Figure 3. (**a**) Rosie the Robot: example of a sketch created as part of the engineering design process and the final robot design. (**b**) Gunter the Penguin: example of a sketch created as part of the engineering design process and the final robot design. (**c**) R2-D2: example of a sketch created as part of the engineering design process and the final robot design. (**d**) Pac-Man robot: example of a sketch created as part of the engineering design process and the final robot design. (**e**) Lakers: example of the final robot design.

The teacher described how working on the robotics engineering design challenge contributed to student engagement: "*When they actually had the [robotics engineering design challenge], okay, here's your challenge, and you need to build this and code it, that's when they were completely engaged*."

Students also described the EDP as something they could use in other projects. Kelly highlighted the applicability of the EDP to various projects beyond the classroom: "*I think the design process was pretty fun, because now I can use it on different projects, not just in here. So I know the different steps and how to focus on one step first. And how I collaborated together to come*

up with our final idea in the code." Without being prompted, she identified three different parts of the EDP: how it can be used in different contexts, how to complete tasks step by step, and how people can work together effectively as a team. Emma expanded on this: "*I thought the design process is really cool. And how we like wrote down all the steps and stuff and brainstormed, and I think it worked out really good for the robot in the end*." This comment suggests that documenting the EDP steps and brainstorming the process contributed to their successful project outcome.

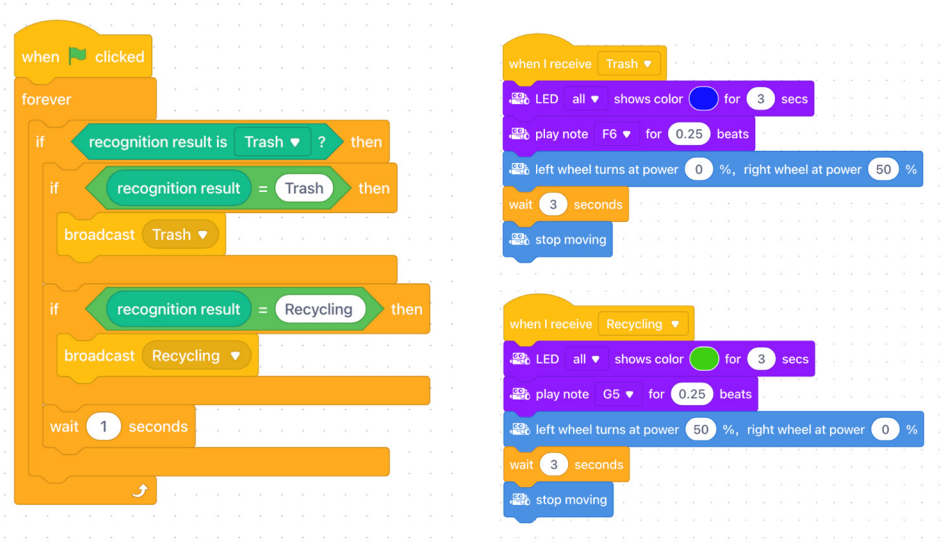
Personalization as a Catalyst for Ownership, Motivation, and Programming Growth. The most important pattern in this theme is that students did not just decorate their robots with a character or a theme. The robot themes they chose shaped the engineering and programming decisions they made. Each team selected a character/theme for their robot, all inspired by popular culture, i.e., Rosie the Robot from the American animated sitcom "The Jetsons" (Hanna-Barbera Productions, 1962–1987; Figure 3a), R2-D2 from "Star Wars" (Lucas, 1977; Figure 3b), Pac-Man from the classic video game (Iwatani, 1980; Figure 3c), Gunter the Penguin from the American animated television series "Adventure Time" (Ward, 2010–2018; Figure 3d), and Lakers for the Los Angeles Lakers basketball team (Figure 3e). In each team, the character/theme concept created design constraints that the team had to solve through engineering and design decisions.

The Rosie the Robot team's design journal presents this clearly. Their initial brainstorm specified four behaviors they wanted Rosie to have: "*Light when trash goes in, different sound when recycled. Comes when you say Rosie. Object recognition. Eyes light up red when trash, green when recycled*." However, their plan for Rosie to "*come when you say Rosie*" created some technical challenges because the mBot did not support voice recognition by default. Therefore, the team integrated a voice extension, added conditional logic, and connected it to motor control and LED behaviors. This example illustrates how the team's design choices, i.e., naming the robot "Rosie" and having it respond to its name, led them to make programming and computational decisions they otherwise would not have made.

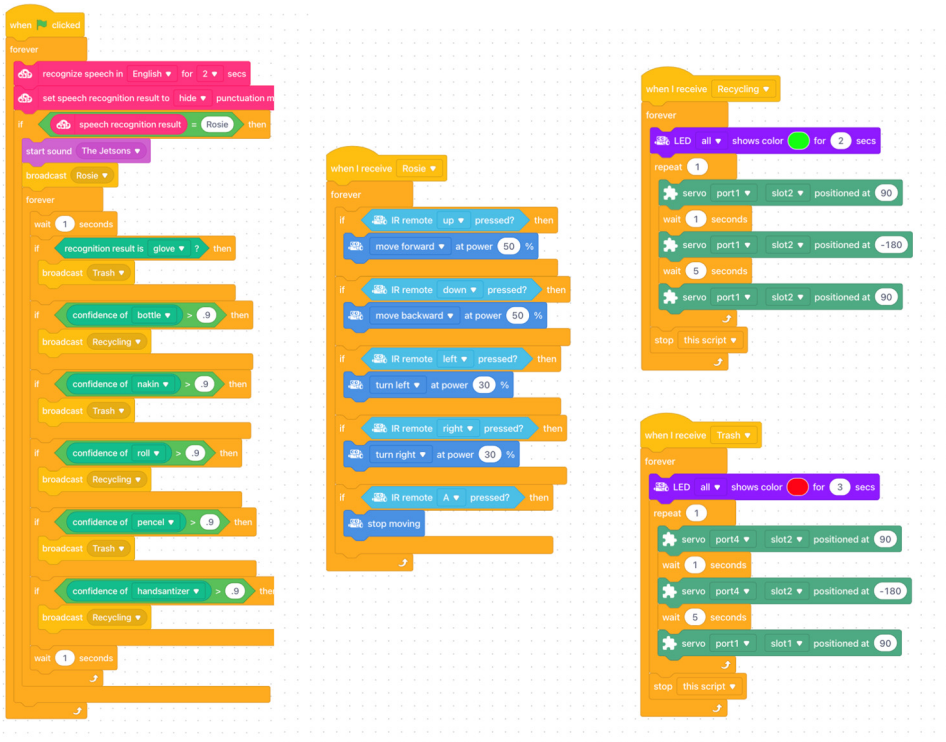
Similarly, the Pac-Man team designed their robot as an arcade cabinet, which impacted the position of the servo motor that opened the trash flap. Their design journal recorded the resulting redesign: "*First we tried to use the rubber band to pull the lid up, but when it wasn't suiting our needs we changed our plan to the second option which was to put the servo motor inside the can and to have it push the lid up from the inside*." These design choices caused a mechanical problem, which pushed the team to change and improve their design.

Alongside these design decisions, we traced the changes in the teams' codes over the course of the project. The team design journals and codes (Figure 4) demonstrate progression from simple, single-function code early on toward programs that combined several functions to run the robot's different behaviors. This hands-on experience deepened their understanding of coding concepts and enabled them to apply their knowledge to a real-world robotics challenge. Moreover, each team personalized the code segments in their program, e.g., object recognition, object avoidance, LED, and mBot sounds. Even variable names were personalized to align with the robots' themes.

Technical/AI-Related Challenges as Productive Learning Opportunities: This theme is about how students faced technical and AI problems and what they did with them. Across the data, students described object recognition errors, problems with ML models, sensor issues, and unpredictable robot behavior.

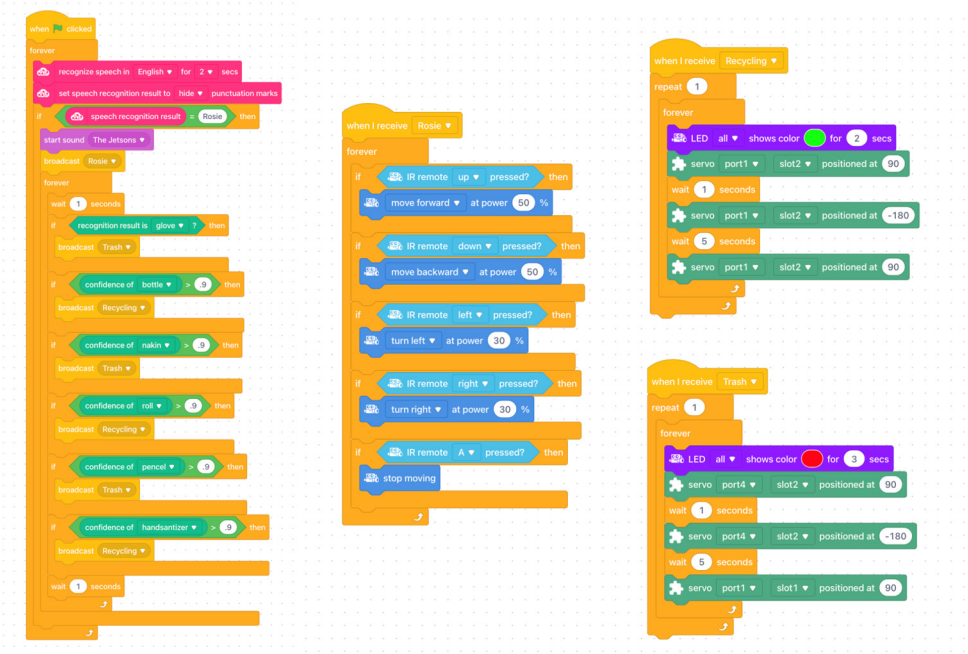


(**a**) First code iteration

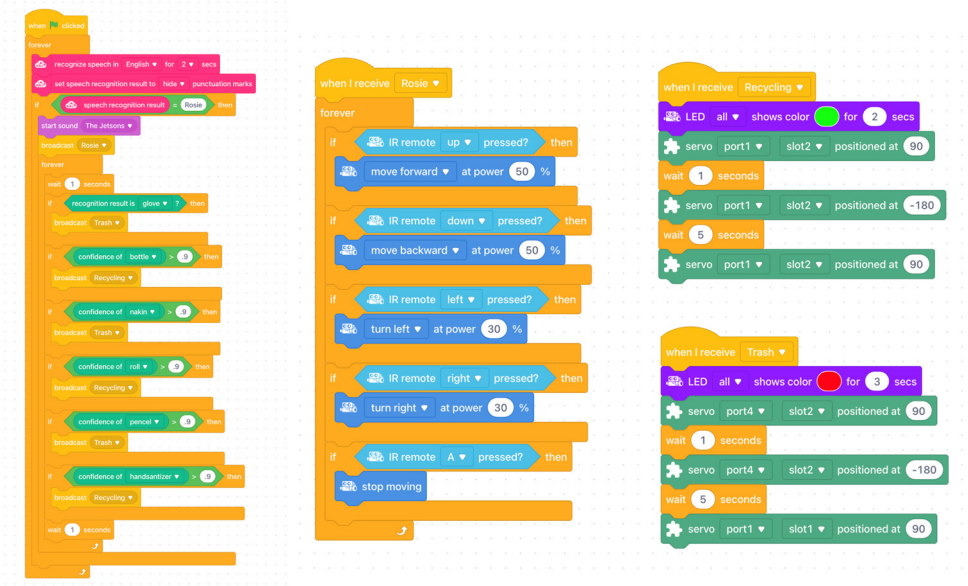


(**b**) Second code iteration

Figure 4. *Cont.*



(**c**) Third code iteration



(**d**) Fourth code iteration

Figure 4. Coding progress of a robotics team.

For instance, one team mentioned that the item sensing did not work well, and their robot's doors became stuck initially. They troubleshot the program by "*looking through the code step by step to see what the issue was. And finding the exact point the door got stuck and giving it support*". The R2D2 team struggled with their ML training model when the detection did not work correctly. In their design journal, they documented two techniques they applied to solve this problem: "*We changed the required confidence for the robot to open, and we changed some of the items it detected*." These two decisions represent a growing understanding of the major ML concepts. Similarly, Kevin mentioned challenges with his team's object

recognition model: "*We were having some issues with the detection. Like it was detecting like the wrong thing. Like if we would put recycle in front of it, it would think it was like trash*".

The teacher also described an instance in which the training model misclassified a student, creating an opportunity to discuss bias and limitations in ML:

"It was kind of nice to see the training model, because in AP Computer Science Principles, they talk about bias and how it can, in an unintended way, enter into the training model and that sort of thing. And the students got to see. . . the kinds of issues that can happen when you're trying to do that, because, you know, it would recognize backgrounds and, like, [Brandon]—it recognized him as a marker, because he was wearing black on top and white on the bottom, it looked like the marker they trained it on". This example illustrates the kinds of authentic experiences students encountered while working with ML models. In this case, the model incorrectly classified a classmate because features of his clothing resembled an object included in the training data.

Nevertheless, working towards a tangible goal (i.e., physical robot design) helped students better grasp the concepts they were learning. Students highlighted the iterative approach of their problem-solving and troubleshooting to successfully complete their projects. For instance, Kelly said, *"I really liked it. I think it was really fun to try and problem solve and figure out what was going wrong. . .we figured it out eventually"*. Overall, such moments facilitated student troubleshooting skills and provided them with a concrete understanding of how unintended bias, feature selection, and training data limitations can influence ML model behavior.

5. Discussion

Despite the growing importance of engineering design education and AI in our society and their educational benefits in supporting authentic PBL, K–12 students are seldom introduced to these ideas. Challenges such as insufficient teacher training, limited resources, and difficulties integrating the EDP and AI into the existing curriculum often hinder its adoption (Besser & Monson, 2014). This mixed-methods study contributes to the limited literature on interdisciplinary PBL in high school settings, connecting engineering design, robotics, and AI/ML. Using the engineering design robotics approach, it developed an innovative curriculum in robotics and AI/ML grounded in the EDP.

5.1. RQ1: How Did High School Students' CS Confidence, Enjoyment, Career Aspirations, and Belongingness in CS Change After Participating in Engineering Design AI-Robotics PBL?

The first research question examined how engineering design AI-robotics PBL influenced high school students' CS confidence, enjoyment, career aspirations, and belongingness using a mixed-methods research approach. Quantitative findings showed that, on average, after participating in the curriculum, students reported increased perceptions of all assessed CS attitudes. But the pre-/posttest gains were non-significant. An analysis of qualitative data produced three major themes: (1) CS enjoyment and positive experience, (2) building CS confidence and belongingness through teamwork, and (3) differentiated CS career aspirations.

CS Enjoyment and Positive Experience. Students reported high CS enjoyment at both pretest and posttest ($M_{pretest}$ = 4.08 and $M_{posttest}$ = 4.18 on a 5-point scale). Although the intervention did not produce measurable gains, the medium effect size (r = 0.29) indicates measurable pre-/posttest gains in students' CS enjoyment after participating in the curriculum. These findings are consistent with prior research that has demonstrated that robotics PBL increases student engagement and satisfaction (T.-S. Chang et al., 2022). Qualitative findings provided deeper insight into how students experienced enjoyment during the project. Students consistently expressed satisfaction, happiness, and pride in their final robotics designs, describing the coding and building process as "fun" and "interesting."

Specifically, students emphasized that alternating between different activities—such as designing physical robot components and coding behaviors—made the experience more engaging. Students described the design work as a refreshing shift from screen-based programming because it allowed them to construct something tangible and immediately observe how their code affected the robot's actions. Similar findings were documented in studies that reported that students in the robotics classroom expressed satisfaction and happiness with their projects, particularly enjoying the variety of tasks, such as designing and coding, which kept the learning process dynamic and engaging (K. Wang et al., 2023). This is consistent with research suggesting that diverse activities within a project help maintain student interest (Mitnik et al., 2009). Papert's (1980) theory of constructionism posits that students learn best when they construct knowledge through creating tangible artifacts, such as robots. The hands-on aspect in robotics education of students enjoying their work being physically manifested is well supported by literature as a means of deepening students' understanding of complex concepts.

Taken together, the findings suggest that the engineering design AI-robotics PBL experience supported students' sustained CS enjoyment by providing a creative, hands-on environment that blended coding with physical design. The lack of significant quantitative change may be explained by a ceiling effect, as students already reported high enjoyment prior to the intervention. However, qualitative evidence indicates that students' enjoyment was reinforced through project ownership, the variety of learning tasks, and the opportunity to see their computational work come to life in a physical artifact. These findings suggest that AI-robotics PBL may be particularly valuable for maintaining students' positive attitudes toward CS while also offering meaningful and motivating learning experiences.

Building CS Confidence and Belongingness Through Teamwork: Developing CS confidence and a sense of belongingness in the CS classroom is critical for supporting student participation in CS (Master & Meltzoff, 2020). In this study, students' CS confidence ($M_{Pretest}$ = 3.68; $M_{Posttest}$ = 3.88, on a 5-point scale) and belongingness ($M_{pretest}$ = 3.43, $M_{posttest}$ = 3.47 on a 5-point scale) increased after participating in the curriculum, but the pre-/posttest changes were non-significant. These moderately high scores are likely because participants did not have prior CS experience. Although the pre-/posttest gain in CS confidence was not statistically significant, the medium effect size (r = 0.26) suggests a meaningful upward trend that may not have reached significance due to sample size or variability in student responses. Qualitative findings offered considerable evidence that students experienced growth in confidence, particularly through collaboration, role-taking, and peer interaction. Regarding belongingness, qualitative findings provided insights into how the curriculum helped students connect with each other and with robotics. Students described working effectively in teams and assuming specific responsibilities (e.g., designing robot parts, coding behaviors, or focusing on robot mobility), which allowed each team member to contribute in a valued way. Such experiences may have strengthened students' sense of competence and belonging—two factors often associated with confidence development in STEM learning environments (Master & Meltzoff, 2020).

Overall, the results suggest that engineering design AI-robotics PBL created an authentic collaborative space where students could take initiative, contribute meaningfully, and experience success through teamwork and problem-solving. Prior research demonstrated that these experiences were conducive to developing student confidence and belongingness (Danielson & Björkman, 2025). While statistical significance was not observed, the combination of positive quantitative trends and qualitative evidence indicates that the intervention may have had a meaningful impact on students' confidence-related experiences.

Differentiated CS Career Aspirations: Students rated their beliefs about computing importance and perceived usefulness high ($M_{pretest}$ = 4.35 and $M_{posttest}$ = 4.44 on a 5-point scale) with no statistically significant change over time and only a small effect size. The high pretest ratings suggest a ceiling effect due to the fact that many students already held positive attitudes toward CS careers prior to the intervention. Nevertheless, qualitative findings revealed meaningful ways the curriculum influenced students' career thinking. Several students described increased interest in pursuing a CS career or taking additional CS courses, with some indicating that the experience strengthened an existing interest, suggesting that the engineering design AI-robotics PBL experience may reinforce students' commitment to CS pathways by making CS learning more engaging, relevant, and personally meaningful.

In addition, students' reflections indicated that the curriculum helped them connect CS with real-world problem solving and societal impact. For example, one student described how designing prototypes and debugging robotics code helped him envision future work developing products to support diabetic patients. This finding highlights how engineering design AI-robotics PBL can support career aspiration development by helping students see CS as a tool for innovation and helping others, rather than as an abstract technical subject (Alshahrani et al., 2018). Research has shown that well-structured and engaging CS curricula can significantly impact students' interest in the field. For instance, Miller et al. (2019) reported that students exposed to rigorous and relevant STEM courses in high school were more likely to pursue STEM-related careers. C. C. Chang and Chen (2020) found that implementing an integrative STEM robotics curriculum significantly improved high school students' interest in considering careers in engineering, programming, robotics, and related fields.

At the same time, qualitative evidence showed that not all students developed stronger CS career aspirations. Some students enjoyed the experience but maintained other career plans, while others expressed uncertainty due to limited awareness of CS fields. These findings echo existing research that high school may be too late to make a significant impact on some students' long-term career aspirations in STEM (littleBits, 2019) and the importance of discussing CS careers to increase student awareness of CS (Goode, 2010).

Overall, the results suggest that engineering design AI-robotics PBL may play an important role in sustaining and strengthening CS career aspirations for some students, particularly by highlighting real-world relevance and societal impact. Although quantitative changes were minimal, qualitative findings indicate that the curriculum influenced how students envisioned themselves in relation to CS, suggesting promising potential for AI-robotics PBL as a pathway-building learning experience.

5.2. RQ2: How Did Engineering Design AI-Robotics PBL Influence High School Students' Learning Experiences?

The second research question explored students' learning experiences using a qualitative research approach. Integrating the EDP into collaborative robotics PBL provided high school students with valuable interdisciplinary learning experiences in engineering design and robotics. The findings suggest that the engineering design AI-robotics PBL environment shaped students' learning experiences through three interconnected mechanisms: (1) engagement in authentic engineering design practices; (2) personalization as a catalyst for ownership, motivation, and programming growth; and (3) technical/AI-related challenges as productive learning opportunities.

Engagement in Authentic Engineering Design Practices as a Foundation for Learning. This theme revealed that students meaningfully engaged in the EDP while developing their robotics projects. Students collaborated to define the problem, brainstorm potential solutions, sketch and design their robot prototypes, develop code, and refine their projects through repeated troubleshooting. This finding suggests that the AI-robotics PBL environ-

ment successfully positioned students not merely as learners of programming concepts, but as designers and engineers working through a structured design process. Importantly, students articulated an understanding of the EDP as a transferable framework, indicating that they viewed engineering design as applicable beyond the immediate classroom context. This aligns with the goals of engineering-focused PBL, which emphasize not only product creation but also development of design thinking, iterative problem-solving, and collaborative engineering practices (Sarty, 2025).

Students' reflections further suggest that documenting design steps and brainstorming activities supported their ability to execute and refine their projects. The engineering design journals and student interviews revealed that the EDP was not simply an instructional structure imposed by the curriculum, but a cognitive scaffold that supported decision-making, planning, and coordination of work. In this way, the AI-robotics PBL environment encouraged students to approach robotics development as an iterative process rather than a linear task. This is especially significant because AI-robotics projects often involve uncertainty, where outcomes cannot always be predicted in advance due to technical limitations, sensor inaccuracies, and model errors (Eguchi, 2022). Therefore, EDP framing may serve as a particularly effective structure for AI-robotics experiences because it normalizes iteration, refinement, and redesign as expected components of learning.

Personalization of Robotics Projects. A second major theme is that students consistently personalized their robotics projects, both in terms of physical design and computational implementation. Teams selected pop-culture-inspired themes, integrating these identities into both the external appearance of their robots and the internal structure of their code. This suggests that personalization functioned as a meaningful design feature of the learning environment rather than a superficial aesthetic choice. Students' thematic decisions shaped how they conceptualized their robot's purpose and functionality, influencing choices related to LED patterns, sounds, movement behaviors, and even variable naming conventions. Moreover, selecting these familiar themes contributed to a sense of enjoyment and ownership in the project, fostering creativity to explore advanced AI and robotics concepts (Schwartz, 2016; Weida & Bradbury, 2024). In this study, personalization appeared to deepen students' commitment to the project and sustain motivation over time.

In addition, student code artifacts demonstrated that students progressed substantially in their programming capabilities. Many students began with simple single-function scripts but gradually expanded their programs into multi-function structures, eventually integrating these functions into coordinated main programs. This progression suggests that the AI-robotics PBL environment supported students' development of computational thinking practices such as decomposition, modular design, and abstraction. Importantly, these practices emerged through the demands of the project rather than through isolated coding drills. As students attempted to implement real robot behaviors—such as object recognition, object avoidance, LED feedback, and motion control—they were required to structure code in ways that supported coordination among multiple robotic operations. This indicates that AI-robotics projects may provide an authentic context for students to develop more advanced programming skills that reflect real computational design practices. These findings echo existing research on how educational robotics contributes to developing students' design-based learning and advanced programming skills (Y. Wang, 2023) but also expand our knowledge about the AI-enabled learning experiences in the robotics classroom (Novak et al., 2026).

Technical and AI-Related Challenges as Productive Learning Opportunities. A third theme revealed that students encountered technical challenges and AI-related issues throughout the project, particularly in areas such as object detection accuracy, sensor reliability, and mechanical functionality. While such challenges could be viewed as barriers to learning,

the findings suggest that these difficulties played an important role in shaping students' learning experiences. Students described troubleshooting as "fun" and emphasized the satisfaction of working through problems step-by-step until a solution was found. This suggests that the PBL environment supported a productive struggle, where technical setbacks became opportunities to engage in deeper reasoning and iterative refinement (van Zyl et al., 2025).

Notably, students' difficulties with object detection highlight an important feature of AI learning: AI systems are imperfect and can behave unpredictably (Eguchi, 2022). For example, students described instances where the robot misclassified objects. Such moments provided students with experiential insight into the limitations of AI, particularly issues related to classification accuracy and model reliability. These findings suggest that AI-robotics PBL can support foundational AI literacy by allowing students to directly observe that AI decisions are probabilistic, error-prone, and dependent on training conditions and sensor input. Rather than learning about AI limitations in abstract terms, students experienced these constraints firsthand while trying to make their robot function successfully (Chu et al., 2022).

6. Lessons Learned and Implications for Designing Engineering Design AI-Powered Robotics PBL

6.1. Lessons Learned

The implementation and evaluation of the engineering design AI-robotics curriculum yielded several important lessons for educators, researchers, and curriculum developers. These lessons highlight both the opportunities and challenges associated with implementing engineering design AI-robotics PBL with novice high school CS learners.

1. High school students are capable of sophisticated robotics and AI work. Despite having limited prior robotics experience and no AI/ML experience, students successfully integrated advanced AI/ML and robotics concepts such as sensor use, and object and speech recognition into their robotics projects. Their final projects demonstrated both technical growth and strong creativity.
2. Effective robotics instruction requires intentionally building technical communication with novice robotics learners. Communicating robotics and AI concepts to students with no prior technical background was initially difficult, as topics such as ML, AI, and sensor integration could easily overwhelm them. We recommend introducing complex ideas gradually using simplified language, relatable examples, and interactive demonstrations to support student comprehension and engagement.
3. Students need structured support and sufficient time to engage in the EDP during robotics engineering design challenges. Teachers should facilitate regular classroom discussions and intentionally build opportunities for students to document and reflect on their design decisions, challenges, and revisions. Embedding engineering design into the robotics challenge helped students better understand engineering practices while producing personally meaningful and engaging robot designs.
4. Engage students in the exploration of different CS and STEM careers as part of the curriculum. Use curriculum activities to connect CS classroom experiences to STEM and CS careers.
5. Successful curriculum implementation depends on building trust and long-term partnerships with schools. Strong collaboration with teachers requires time, particularly when CS teachers have limited experience with robotics or AI/ML. Therefore, substantial instructional support may be needed during curriculum implementation, especially in the initial year.

6. Curriculum pacing must be flexible and responsive to classroom needs. Although the curriculum was originally designed to fit within eight weeks, implementation required approximately three months due to the student characteristics, classroom context, and school schedule. We recommend using a modular curriculum structure that allows teachers to adapt lesson timing and sequencing to better align with student needs and school schedules.

6.2. Implications for Designing Engineering Design AI-Powered Robotics PBL

Robotics kits such as mBot offer block-based coding and AI/ML capabilities that can make complex AI concepts accessible even to novice CS learners. However, to leverage these technologies for teaching AI to novices, a carefully designed curriculum is essential. In our curriculum, AI/ML was one of the final modules, introduced after foundational topics such as algorithms and basic mBot functionalities. To deepen students' understanding of AI/ML, we incorporated a real-world scenario into our robotics engineering design challenge, where students learned about object recognition through the context of detecting trash and recyclable items. The findings across multiple dimensions of student learning suggest several implications for designing effective AI-powered robotics engineering design PBL experiences.

1. Embedding robotics projects within the EDP is critical. The structured stages of the EDP supported students' engagement, computational thinking, and troubleshooting skills. This scaffolding was particularly valuable for navigating the uncertainties inherent in AI-enabled robotics, such as sensor inaccuracies, misclassifications, and unexpected system behaviors. Designers of AI-robotics PBL should ensure that EDP stages are explicit, sequenced, and reinforced to help students interpret technical challenges as part of the learning process. To better facilitate the EDP, students need to be formally introduced to the EDP and encouraged to use tools, e.g., design journals, engineering notebooks, and worksheets, that help students document each phase of their EDP and reflect on their learning.
2. Attention should be given to creating authentic engineering design robotics challenges that are personally meaningful to students. For instance, researchers recommend focusing on topics that emphasize people-oriented tasks (Alshahrani et al., 2018), promote students' understanding of the societal impacts of CS (Share & Pender, 2018), and allow students to express themselves artistically (McChesney et al., 2022).
3. Personalization of robotics projects emerged as a powerful motivator that reinforced enjoyment, confidence, and ownership. Allowing students to create costumes for their robots as part of a robotics engineering design challenge can sustain engagement and support deeper coding practices, as students connect their creative ideas to their robot's AI-driven behaviors. Curriculum designers should intentionally incorporate opportunities for physical and computational design to enhance motivation, confidence, and sustained effort.
4. Collaborative, hands-on project work appeared to facilitate social interactions and CS confidence. Assigning roles, fostering peer interaction, and structuring teamwork allowed students to contribute uniquely, build social skills, and step outside their comfort zones. AI-robotics PBL should therefore be designed to balance individual responsibilities with team problem-solving, enabling students to gain confidence in both their technical abilities and collaborative competencies.
5. Integrating AI-related challenges as authentic learning opportunities supports CS learning and early AI literacy. Exposure to system limitations, debugging needs, and iterative refinement helped students develop practical problem-solving strategies and an understanding of AI constraints. Curricula should intentionally incorporate

structured troubleshooting, reflection prompts, and scaffolding to help students navigate AI unpredictability while maintaining agency and confidence.

7. Limitations and Conclusions

Given that limited research has examined AI-enabled learning experiences within educational robotics PBL contexts, this study contributes important insight into how students engage with engineering design, computational practices, and AI-related challenges during AI-robotics PBL. Engineering design robotics education offers an effective framework for structuring robotics PBL and fostering reflection, the autonomy of learning, and creativity in students. In addition, it exposes students to real-world engineering design practices. Nevertheless, several limitations should be acknowledged. Although the study used a mixed-methods research design with rigorous qualitative research, employing a pre-/posttest, single-group research design with a small sample size from one CS high school classroom limits the generalizability of the study findings. Experimental research with a larger sample size that investigates the added value of engineering design in educational robotics can help better understand how engineering design robotics education impacts student EDP practices, robotics knowledge, and other educational outcomes.

Moreover, future research should attempt to investigate how to integrate an EDP into various robotics curricula with different student populations, as well as best practices for integrating and supporting the EDP in robotics PBL. Equally important is to investigate how robotics education can be leveraged to make AI/ML concepts accessible to learners without an extensive technical background. One of the challenges of implementing AI robotics in K–12 is a lack of CS teachers who are knowledgeable about AI-robotics. Providing CS teachers with professional development in AI-enabled robotics can improve their AI/ML knowledge and skills, contributing to broader and more sustainable implementation of K–12 AI robotics education.

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Appendix A. Attitudes Toward Computing (Wanzer et al., 2019)

Computing Confidence

1. I have a lot of self-confidence when it comes to computing.
2. I am sure I could do advanced work in computing.

3. I think I could handle difficult computing problems.
4. I'm not good at computing. (R)

Computing Enjoyment

1. I enjoy computing.
2. Computing makes me nervous. (R)
3. Computing is difficult. (R)
4. I feel comfortable computing.

Computing Importance and Perceived Usefulness

1. I will be able to get a good job if I learn computing.
2. I will use computing in many ways throughout my life.
3. Computing is of no relevance to my life. (R)
4. Taking computing classes is a waste of time. (R)

Computing Identity and Belongingness

1. I feel like I "belong" in computer science.
2. I consider myself a scientist, technologist, engineer, or mathematician.
3. I take pride in my computing abilities.

Appendix B. Codes, Themes, and Exemplar Data Excerpts Developed Through Reflexive Thematic Analysis

Theme	Code Name	Code Description	Exemplar Quotes from Qualitative Data Sources
RQ1. How did high school students' CS confidence, enjoyment, career aspirations, and belongingness in CS change after participating in engineering design AI-robotics PBL?			
1. CS Enjoyment and Positive Experience	Joyful and engaging hands-on experience	Students describe the project as fun, cool, interesting, or engaging without further elaboration.	• *"It was really fun. It's a really good experience. And I had a really good time, like learning how to code and like build it together with my group."* • *"Our project's been going well so far. And, I mean, it looks nice and, you know, so far I think we're going to do pretty good and it's been a fun project to work on."*
	Enjoyment of tangible artifact and physical outcome	Students describe enjoyment as connected to seeing their code result in a working robot.	• *"It's really nice to build actually something and see it physically in front of me and not just on the computer screen."* • *"When they actually had the, okay, here's your challenge, and you need to build this and coded, that's when they were completely engaged."* (teacher interview)
	Variety of tasks sustaining engagement	Students describe alternating activities (e.g., designing components versus coding) as making the experience more engaging.	• *"I think to get to learn all of that and like how to work within like we're all together again and stuff, it was really fun."* • *"It was very interesting to try and figure out how to make certain functions work with the coding. So that was very fun."*
	Satisfaction from overcoming persistent challenges	Students describe enjoyment as connected to seeing their robot work after facing errors, debugging, or earlier frustration.	• *"I would say I am happy with how our mbot turned out. The design is nice and it works pretty well."* • *"Yes, because we put out hard labor into it and seeing it work and the codes moving from computer to an actual robot is pretty cool."*

Theme	Code Name	Code Description	Exemplar Quotes from Qualitative Data Sources
2. Building CS Confidence and Belongingness Through Teamwork	Role specialization and task division	Students describe how team members took on specific roles (coder, builder, designer, painter) in the project.	• *"I did the coding for the robot. I helped develop the code and paint Rosie's main structure. I helped compose and produce Rosie's structure using the design process."* • *"I did most of the coding because I'm kind of bad with like art stuff."*
	Peer collaboration and friendship making	Students and the teacher describe collaborating with peers they would not normally interact with.	• *"They never voluntarily [worked in groups]. But once they worked on this challenge together, they became friends, like really good friends. And it was really cool to see those relationships develop."* (teacher interview) • *"It was nice to see them, actually collaborating. Because it's hard sometimes in a computer science class."* (teacher interview)
	Confidence Development	The teacher and students describe confidence development across the curriculum.	• *"He just was shining. In this project, he developed confidence, he was talking to everyone in the class, which he hadn't done before."* (teacher interview) • *"She likes computer science so much now that she's going to stay at the high school and keep taking our classes, and now she's talking about majoring in it."* (teacher interview)
3. Differentiated CS Career Aspirations	Pre-existing CS interest	Students with existing CS interest describe the project as strengthening existing career intention.	• *"Yeah, I definitely think that at least for me that this helped me. . . well, I already wanted to go into computer science but this helped strengthen that idea."* • *"I think this strengthened my bond with like computer science because you're building something like out of your imagination from this."*
	Increasing interest in CS and CS-connected fields	The teacher describes students as becoming interested in pursuing CS as a result of the curriculum; students describe wanting to use CS to address a specific application area.	• *"I want to build a product for like diabetic patients. And this kind of helped me like understand how to do that and like do like prototypes and demos of it and trying to figure out what is wrong and fixing the bugs with it. This really like strengthened a lot of it for me."* • *"She was thinking about going to a Career Center, but she likes CS so much now that she's going to stay at the high school and keep taking our classes, and now she's talking about majoring in it"* (teacher interview)
	Provisional or emerging CS interest	Students are uncertain about pursuing CS but express positive attitudes.	• *"I'm still thinking about it. I really do like computer science. It's fun and everything, but like, I don't know all the fields of it, but like, I would like to get into it whenever I get older."* • *"I don't know about like [going to] a career in computer science. But I think it's fun. I really liked the class and I had a good experience."*
	Informed non-CS career plan	Students described enjoying the project but having a pre-existing non-CS career path; CS framed as a useful skill or backup option.	• *"I think it's really interesting. I personally probably wouldn't pursue a career because I already have what I would like to do in mind. But it is really fun and it definitely [would] be a good backup."* • *"I don't know about like a career in computer science. But I think it's fun. I really liked the class and I had a good experience."*

Theme	Code Name	Code Description	Exemplar Quotes from Qualitative Data Sources
RQ2. How did engineering design AI-robotics PBL influence high school students' learning experiences?			
1. Engagement in Authentic Engineering Design Practices	Defining problems and brainstorming solutions	Students define the design problem and requirements, and brainstorm solutions for the robot's functionality.	• *"Step one, identify the need for a smart robot. Our team built a smart robot that can collect and identify trash as well as recognize what is trash and what is recycling."* • *"[requirement:] make a training model for human–robot interaction (human, 5 recyclables, 5 landfill trash)"*
	Sketching and planning robot designs	Students describe creating initial sketches and plans for their robots' costumes, structure, and behaviors before programming.	• *"Yes and no, when we were sketching a design we were imagining something similar but different."* • *"We were trying the build the trashcan and making like a little script for the coding, basically a concept for the robot."*
	Iterative redesign in response to constraints	Students describe revising designs when initial plans failed to meet functional or material constraints.	• *"First we tried to use the rubber band to pull the lid up, but when it wasn't suiting our needs we changed our plan to the second option which was to put the servo motor inside the can and to have it push the lid up from the inside."* • *"We made the design for Gunter the penguin from Adventure Time and then we changed the code from automatic movement to remote control movement so we can maneuver it ourselves since it wouldn't stop moving."*
	Troubleshooting and debugging as design work	Students describe troubleshooting code and hardware as part of the design cycle.	• *"we were troubleshooting the code because the mobility started not working while it was trying to detect the objects, it wouldn't stop while detecting/opening the correct door and then it wouldn't stop at all."* • *"There were a lot of issues with the code at first and we learned a lot like how to fix it and everything and how to like go through it and like find that problem."*
	EDP applicability beyond the robotics task	Students describe the EDP as applicable to other projects and contexts, not only the current robotics challenge.	• *"Think the design process was pretty fun, because now I can use it on different projects, not just in here. So I know the different steps and how to focus on one step first. And how I collaborated together to come up with our final idea in the code."* • *"Creating complex things takes a lot of time."*
	Documenting and externalizing the design process	Participants describe writing down steps and brainstorming explicitly as part of the design process.	• *"Yeah, I thought the design process is really cool. And how we like wrote down all the steps and stuff and brainstormed, and I think it worked out really good for the robot in the end."* • *"Um, I learned a lot about the design process. And like teamwork and everything."*
	Teacher application of EDP as practical pedagogy	The teacher describes the curriculum as enabling practical application of the EDP.	• *"Just the whole process from the beginning to designing it, and then coding it and troubleshooting and then presenting it to an authentic audience."* (teacher interview) • *"That's when they were completely engaged in trying to figure [it out], I think that's when it really started coming together."* (teacher interview)

Theme	Code Name	Code Description	Exemplar Quotes from Qualitative Data Sources
2. Personalization as a Catalyst for Ownership, Motivation, and Programming Growth	Character- or theme-based robot design	Each team selected a pop-culture character or theme for their robot.	• *"To make a big Pac-Man but then we came up with the arcade machine design."* • *"On Thursday, we made the design for Gunter the penguin from Adventure Time."*
	Character and design choices caused technical constraint	Character choices and design ideas limited the students and led to technical challenges.	• *"[we would] make more room for the infrared light sensor to make the mbot easier to control because the box is kind of blocking it. The remote stutters but that's fine."* • *"When recycling and trash opens up to a recognition window, it slides instead of like opening up like this [vertical], it slides like this [horizontal]"*
	Programming growth from single-function to multi-function code	Students progressed from simple single-function code at the project start to multi-function programs for the final robot.	• *"Devices tab code works when testing individually, but the messages are not being received from the sprites tab."* • *"Started code for mbot functions, like sensing, continued to add to the design."*
	Ownership and pride in their project	Students express pride in and ownership of their design and are happy to show it to others.	• *"It would be really fun to share with people like what we've created together as teamwork with the design process and everything."* • *"It would be fun to share because we did work really hard on it."*
3. Technical/AI-Related Challenges as Productive Learning Opportunities	Object recognition errors	Students describe object recognition error (misclassifying objects) as unexpected algorithmic behaviors that they needed to understand and figure out.	• *"Well, we were having some issues with the detection. Like it was detecting like the wrong thing. Like if we would put recycle in front of it, it would think it was like trash."* • *"The detection didn't work the best; sometimes it would detect the wrong thing or nothing at all."*
	ML training-model adjustment	Students describe adjusting ML training data or model parameters as part of troubleshooting.	• *"We changed the required confidence for the robot to open and we changed some of the items it detected."* • *"It was kind of nice to see the training model, . . . and how it [bias] can, in an unintended way, enter into the training model. . .The students got to see like, the kinds of issues that can happen when you're trying to do that."* (teacher interview)
	Hardware troubleshooting	Students describe troubleshooting hardware issues (wiring, motors, sensors).	• *"2 white wire combo didn't work so we switched to a blue combo and it worked."* • *"It recognized Rosie and volume was over 50. Even when it recognized these things, the robot did not respond. It did respond when we just pulled a move block over and ran it."*
	Training-data bias awareness	Students and the teacher describe when bias in the ML training data became visible.	• *"It recognized him as a marker, because he was wearing black on top and white on the bottom, it looked like the marker they trained it on."* (teacher interview) • *"Seeing those sorts of things. For me, and for them, I think was good to learn those sorts of things."* (teacher interview)
	Step-by-step troubleshooting practice	Students describe step-by-step troubleshooting with the help of team members and mentors.	• *"Looking through the code step by step to see what the issue was. And finding the exact point the door got stuck and giving it support."* • *"We talked to Brayan and Sara [mentors] and figured out the problems, and we looked at the code [from] before."*

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