Designing Emotionally Supportive Blended Labs: Evidence-Based Insights from Situated Learning Research

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Abstract

This evidence-based practice full paper examines how engineering instructors can design emotionally supportive blended laboratory environments that help students engage with authentic engineering practice. Blended laboratories that integrate hands-on and online components often evoke strong emotions such as frustration, uncertainty, and excitement, which shape students' engagement and persistence. Designing laboratory environments that maintain cognitive challenge while supporting students' emotional experiences remains a critical instructional challenge. This paper presents an instructional approach informed by qualitative evidence from a multi-modal engineering laboratory learning environment that integrated in-person experimentation, online collaboration, and take-home laboratory kits. Student focus groups were used to examine how learners experienced and navigated emotional challenges during open-ended laboratory work. These insights were interpreted using a situated learning perspective that views learning as participation in authentic, socially mediated practice. Drawing on this evidence, the paper articulates three instructional design principles for emotionally supportive blended laboratories: (1) structured autonomy that balances flexibility with clarity of purpose, (2) reflective scaffolding that helps students reinterpret challenges as learning opportunities, and (3) inclusive collaboration that normalizes help-seeking and peer support. The paper discusses how these principles were enacted in practice and how they can be adapted across laboratory contexts. By translating qualitative evidence into actionable design guidance, this work contributes to evidence-based practice in engineering education and offers instructors practical strategies for balancing cognitive challenge with emotional support in blended and experiential laboratory environments.

Keywords: Blended learning, Emotional regulation, Cognitive engagement, Experiential learning, Instructional methods.

1. Introduction

Laboratory courses play a central role in engineering education by providing students with opportunities to apply theoretical knowledge, develop experimental skills, and engage in authentic engineering problem solving [1]. In response to evolving instructional needs and technological advances, many engineering programs have expanded beyond traditional, fully in-person laboratory formats to include blended, virtual, and take-home laboratory experiences [2] [3]. While these approaches increase flexibility and authenticity, they also introduce new instructional challenges: how students navigate uncertainty, troubleshoot independently, and persist through open-ended experimental tasks. These conditions frequently evoke strong emotional responses, including frustration, anxiety, curiosity, and excitement, which shape how students engage with laboratory work, collaborate with peers, and respond to experimental failure.

These emotional experiences shape how students engage with laboratory tasks, collaborate with peers, and respond to experimental failure [4] [5] [6]. Research in STEM education has shown that academic emotions influence motivation, cognitive engagement, and persistence, particularly in challenging learning contexts [7]. Yet despite their importance, emotional experiences and regulation strategies remain underexamined in the design of engineering labs [5]. When emotional demands are insufficiently supported, students may disengage or misinterpret struggle as a sign of inability rather than a normal feature of engineering work [8]. Despite growing recognition that emotions are integral to learning in experiential and problem-based environments, instructors have limited evidence-based guidance for designing laboratory experiences that intentionally support students' emotional engagement while maintaining cognitive rigor. This challenge is especially salient in blended and take-home laboratories, where students often work independently with reduced immediate feedback yet are expected to engage in authentic engineering problem solving.

Drawing on qualitative evidence from student focus groups, this paper identifies how students experienced and regulated emotions during laboratory work and translates these insights into three actionable design principles: structured autonomy, reflective scaffolding, and inclusive collaboration. These principles are grounded in a situated learning perspective and offer engineering educators practical, adaptable guidance for designing blended laboratory environments that maintain cognitive rigor while intentionally supporting students' emotional engagement.

2. Design Rationale and Conceptual Framing

The instructional practice examined in this paper was informed by prior research demonstrating that learning in laboratory and experiential environments is shaped by both cognitive and emotional processes. Studies in engineering and STEM education have shown that emotions such as frustration, confusion, excitement, and satisfaction influence students' motivation, persistence and engagement, particularly when tasks involve uncertainty and open-ended problem solving [7] [9]. Importantly, negative emotions do not inherently undermine learning; their impact depends on how instructional environments structure support, feedback, and opportunities for sense-making [8]. Recent syntheses in engineering education further emphasize that emotions are a core component of engineering learning and professional formation, rather than peripheral affective states [5]. However, much of the existing literature focuses on describing emotional experiences or documenting their relationships with learning outcomes, with less attention to how the instructional environment, particularly laboratory settings, can be intentionally designed to support productive emotional engagement. This gap is especially evident in blended and distributed laboratories, where students must navigate experimentation across physical, digital, and social contexts [2]. To guide instructional design decisions, this work draws on Situated Learning Theory as a conceptual lens, which conceptualizes learning as participation in authentic, socially mediated practices within a community, rather than the acquisition of abstract, context-free knowledge [10] [11]. From this perspective, laboratory learning involves not only mastering technical procedures but also learning to engage with uncertainty, collaborate with peers, and persist through iterative problem-solving, hallmarks of professional engineering practice.

This perspective is particularly relevant for engineering laboratory environments because it foregrounds how emotional experiences emerge through participation in authentic practice rather than as reactions to it. Laboratory tasks that resemble professional engineering work naturally evoke emotional responses, such as uncertainty, frustration, and satisfaction, as students engage in troubleshooting and iterative problem-solving [12]. These emotional experiences are not solely individual reactions; they are shaped by social and environmental context, including interactions with peers, instructors, and established norms for collaboration and help-seeking [13]. Moreover, affective experiences are intertwined with students' developing sense of competence and belonging, as emotions such as confidence, anxiety, or discouragement inform how students interpret their participation and identity as emerging engineers [14]. Within blended laboratory environments, emotional regulation emerges through interaction with task structure, feedback mechanisms, and collaborative norms. It is not an isolated individual skill but an outcome of how the learning environment is designed.

Accordingly, the design rationale for the instructional practice examined in this paper treats emotional regulation not as an individual skill deficit, but as an emergent outcome of instructional design. By intentionally structuring autonomy, reflection, and collaboration, laboratory environments can support students in navigating emotional challenges while maintaining the cognitive demands essential to authentic engineering learning. This rationale informed the development of the instructional design principles presented in the following sections.

3. Description of Educational Practice

The educational practice examined in this paper was a multi-modal engineering laboratory designed to engage undergraduate engineering students in authentic, open-ended experimentation while supporting their emotional and cognitive engagement. The learning environment was implemented as a short, intensive laboratory experience that combined in-person experimentation, online collaboration, and take-home laboratory activities. The instructional intent was to approximate key features of professional engineering practice, including iterative problem solving, troubleshooting under uncertainty, and collaborative sense-making, while providing structures that support persistence and learning.

3.1 Instructional Context and Participants. The learning environment was designed for undergraduate engineering students from multiple majors and academic levels. Participation occurred within an academic laboratory context and complemented existing coursework rather than replacing a traditional laboratory course [15]. Students engaged in the learning environment voluntarily after they provided consent. The instructional design emphasized participation, exploration, and reflection rather than performance-based grading. This context allowed instructors to focus on supporting learning processes, including how students navigated uncertainty, collaboration, and emotional challenges during experimentation.

3.2 Structure of the Learning Environment. As part of a larger instructional intervention (see paper [16]), it is important to situate the implementation's duration and structure to fully understand its impact. The intervention spanned 5 weeks, enabling sustained student engagement with the learning environment and iterative exposure to key design challenges. Building on this broader context, the activities integrated three interconnected instructional components:

a) In-person laboratory sessions: Students participated in an initial in-person orientation session, followed by hands-on experimentation in a traditional laboratory setting. These sessions introduced core experimental concepts, familiarized students with equipment and safety protocols, and established expectations for collaborative problem solving. Instructors emphasized that uncertainty and iteration were expected aspects of the learning process.

b) Take-home laboratory experiment: Students were provided with kits that allowed them to continue experimentation outside the physical laboratory. These kits were intentionally designed to support exploration, iteration, and troubleshooting without continuous instructor supervision. Working independently or in small, informal groups, students collected data, encountered unexpected outcomes, and decided how to proceed. This component increased autonomy and authenticity while also surfacing emotional challenges related to ambiguity, failure, and responsibility for learning.

c) Online collaborative sessions: Synchronous online sessions were held throughout the learning activities to support collaborative troubleshooting and peer interaction. During these sessions, students discussed experimental challenges, shared strategies, and reflected on their experiences. Instructors facilitated discussion by prompting students to articulate their reasoning, describe challenges encountered, and normalize difficulty as part of engineering practice. These sessions functioned as a social and emotional support structure that connected distributed learning experiences.

3.3 Instructional Design Features. Table 1 summarizes the intentional instructional design features that shaped the learning experience and guided how students engaged cognitively and emotionally with laboratory tasks. Together, these design features created a learning environment in which emotional experiences were treated as an expected and supported part of authentic engineering practice, reflecting a situated learning perspective that views learning as participation in authentic, socially mediated engineering practice, where emotional experiences emerge through interaction with tasks, peers, and instructional structures.

Table 1. *Instructional Design Features of the Learning Environment*

Emphasis on Authenticity and Open-Endedness	Structured Opportunities for Reflection	Norms for Collaboration and Help-Seeking
Tasks were designed to resemble real engineering problems, with multiple possible solution paths and no single “correct” outcome. This authenticity was intended to promote deeper engagement while exposing students to the emotional realities of engineering work.	Reflection was integrated informally through instructor prompts and group discussions, encouraging students to examine both technical decisions and emotional responses to challenges. Rather than treating emotions as separate from learning, reflection emphasized how frustration, uncertainty, and success informed problem-solving strategies.	Instructors explicitly encouraged peer support, shared troubleshooting, and open discussion of challenges. Collaborative norms were established early to reduce stigma around difficulty and to position emotional expression as a normal and productive part of learning.

3.4 Role of Instructors and Peer Mentors. The instructor adopted a facilitative role throughout the activities, focusing on guiding learning processes rather than providing immediate solutions. During laboratory activities and collaborative sessions, instructors used questioning strategies, prompted reflection, and supported students in interpreting setbacks as opportunities for learning. Instructional decisions emphasized maintaining cognitive challenge while preventing prolonged, unproductive struggle. Peer mentors were also incorporated into the instructional support structure. These mentors, students with prior experience in similar laboratory contexts, supported participants by sharing strategies, modeling problem-solving approaches, and normalizing uncertainty during experimentation. Rather than serving as sources of answers, peer mentors helped create a supportive learning climate in which help-seeking, collaboration, and emotional expression were expected aspects of engineering practice. Together, instructors and peer mentors contributed to an instructional environment that supported students’ emotional regulation through environmental design rather than direct intervention. By distributing support across multiple roles, the learning environment leveraged social and instructional structures to help students navigate cognitive and emotional challenges while engaging in authentic engineering problem solving.

3.5 Intended Outcomes of the Practice. The primary instructional goal of the activities was to support students in developing technical competence through authentic experimentation while also fostering productive emotional engagement. The practice was designed to help students navigate uncertainty and experimental failure, collaborate effectively with peers, and integrate engineering theory with practical experimentation. The evidence presented in subsequent sections examines how students experienced and navigated this learning environment and how these experiences informed the instructional design principles articulated in this paper.

4. Design Principles

The design principles presented in this section are grounded in a situated learning perspective and reflect how instructional environments can be intentionally structured to support students' emotional engagement in authentic engineering practice. Figure 1 illustrates the conceptual alignment between key perspectives from Situated Learning Theory, the resulting designable learning conditions in blended laboratory environments, and the instructional design principles derived from this work. Rather than representing a prescriptive model or causal pathway, the figure is intended to clarify how theoretical perspectives informed instructional decisions that shaped the learning environment examined in this study. Drawing on qualitative evidence from students' experiences in the blended laboratory, we identified three instructional design principles that support productive emotional engagement in laboratory learning environments. Table 2 summarizes how key perspectives from Situated Learning Theory informed instructional design decisions and how these decisions were operationalized as instructional design principles. These principles synthesize how students navigated uncertainty, collaboration, and reflection during authentic experimentation and translate those insights into guidance that instructors can adapt across laboratory contexts. Rather than prescribing specific activities, the principles articulate design orientations that can inform instructional decision-making in blended, experiential, or take-home laboratory settings.

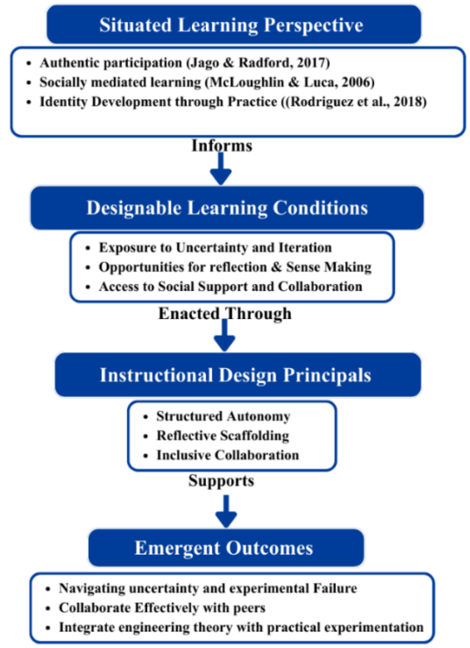

Figure 1. *Conceptual alignment between SLT perspectives and the design principles*

Table 2. *Alignment Between Situated Learning Perspectives and Design Principles.*

Situated Learning Perspective	Design Implication for Labs	Resulting Design Principle
Learning occurs through participation in authentic practice	Students must engage with ill-structured, open-ended tasks that resemble real engineering work	**Structured Autonomy**
Meaning-making is socially mediated	Students benefit from opportunities to discuss challenges, share strategies, and normalize difficulty	**Inclusive Collaboration**
Identity development is intertwined with affective experience through participation	Students need support to interpret struggle and uncertainty as part of becoming an engineer	**Reflective Scaffolding**

By grounding instructional decisions in a situated learning perspective, the resulting principles emphasize how laboratory environments can be intentionally structured to support students' emotional engagement as they navigate uncertainty, collaboration, and reflection in blended learning contexts. The following describes each design principle and illustrates how it can be adapted across engineering laboratory settings.

Principle 1: Structured Autonomy. Blended laboratories present students with the distinctive challenge of fostering their decision-making, iterating on experimental designs, and troubleshooting independently, often without immediate instructor support. When this autonomy is paired with clear learning goals and accessible guidance, students are more likely to experience uncertainty as a productive feature of engineering work rather than as a source of overwhelming frustration. In practice, this means providing clear objectives and success criteria, offering multiple pathways for task completion, and building in checkpoints that help students recalibrate without removing ownership of the problem. The key insight is not that students need less independence, but that independence works best when students understand the purpose of what they are doing and know where to turn when they get stuck.

Principle 2: Reflective Scaffolding. Frustration, confusion, and uncertainty are inevitable in open-ended laboratory work. The question is whether students interpret these experiences as signs of failure or as informative signals that are part of the engineering process. Reflective scaffolding creates the conditions for the latter. By embedding structured opportunities for reflection into laboratory sessions, online discussions, or post-lab activities, instructors help students slow down, articulate their reasoning, and examine how their emotional responses shape their problem-solving decisions. These moments do not require extensive curricular redesign. A well-placed instructor prompt, a brief group discussion, or an invitation to explain what went wrong can meaningfully shift how students relate to difficulty and support more adaptive responses to challenge over time.

Principle 3: Inclusive Collaboration. Students rarely navigate the emotional demands of laboratory work on their own. Instead, they rely on peers, mentors, and instructors to validate their thinking, share strategies, and remind them that struggle is shared rather than individual. Inclusive collaboration means designing laboratory environments where help-seeking is expected and normalized, not treated as a sign of weakness. In practice, this involves establishing collaborative norms early, structuring opportunities for shared troubleshooting, and incorporating peer mentors where feasible. In blended and take-home laboratory settings, where students may work in isolation for extended periods, these social structures are especially important. When students feel that asking for help is a normal part of engineering practice, they are more likely to persist through challenges and remain emotionally engaged with the work.

4.1 Using the Design Principles in Practice. These principles are not tied to a specific disciplinary context, technology, or laboratory setup. Instead, they identify instructional levers that educators can adapt based on course goals, student populations, and available resources. By treating emotional experiences as an integral part of learning rather than as obstacles to be minimized [5], they support laboratory designs that more closely reflect the realities of professional engineering practice. The following section describes the evidence base that informed their development.

5. Methods

5.1 Evidence Sources and Analytic Approach. The instructional design principles presented in this paper were informed by qualitative evidence collected during the implementation of the instructional activities described earlier. The purpose of this evidence collection was not to evaluate the effectiveness of the intervention or to generate generalizable claims, but to gain insight into how students experienced and navigated emotional challenges within an authentic laboratory learning environment. These insights were used to inform instructional design decisions and refine principles that could support emotionally productive engagement in blended laboratory contexts.

5.2 Evidence Sources and Context. Qualitative evidence was collected through a series of semi-structured focus groups with undergraduate engineering students. A total of eleven students volunteered to participate in three focus group sessions, each lasting approximately 60-75 minutes. Participants represented multiple engineering majors and academic levels, providing diverse perspectives on the laboratory experience. Focus groups were selected as the primary source of evidence to capture the socially mediated nature of emotional regulation in laboratory settings. Group discussions allowed students to articulate shared challenges, compare strategies, and reflect collectively on moments of uncertainty, frustration, and success. This approach aligned with the situated learning perspective guiding the instructional design, which emphasizes learning as participation in social practice. Focus group prompts invited students to reflect on their emotional experiences across different phases of laboratory work, the strategies they used to navigate frustration, confusion, and uncertainty, their perceptions of instructional and peer support, and moments that felt authentic, overwhelming, motivating, or affirming. All sessions were audio-recorded and transcribed to support systematic analysis.

5.3 Analytic Approach. An interpretive thematic analysis approach was used to examine the focus group transcripts [16]. Analysis focused on identifying recurring patterns in how students described emotional experiences, regulation strategies, and interactions with instructional structures and peers during laboratory work. Rather than treating emotions as isolated psychological states, analysis attended to how emotional experiences were embedded within task design, collaboration, feedback, and opportunities for reflection. Transcripts were reviewed multiple times to develop familiarity with students' accounts. Guided by CVT, deductive coding was employed, yielding segments on emotional responses, coping strategies, and learning interactions. Codes were then clustered into broader patterns that captured how students navigated emotional challenges across different components of the learning experience. Through an iterative process, analytic discussions among the research team were used to refine interpretations and to ensure that insights remained grounded in participants' accounts. The resulting insights were interpreted through the lens of Situated Learning Theory, with attention to participation in authentic practice, social mediation, and identity development. These interpretations informed the synthesis of evidence into the instructional design principles presented earlier. The analytic goal was not to exhaustively represent all student experiences, but to identify meaningful patterns that could inform the design of emotionally supportive blended laboratory environments. This study was reviewed and approved by the institutional review board. All participants provided informed consent prior to participation in the focus groups, and their names were changed to pseudonyms. Participation was voluntary, and no academic credit was offered. Students were offered a small incentive for their time in the focus groups.

6. Evidence-Informed Insights

The following insights, drawn from focus group data, illustrate how students' emotional experiences were shaped by the instructional design features described in Section 3.

Insight 1: Autonomy Was Productive When Paired with Clear Purpose and Access to Support *(Informing Structured Autonomy)***:** Students described open-ended laboratory tasks as both motivating and emotionally demanding. Opportunities to make decisions, explore multiple solution paths, and troubleshoot independently contributed to a sense of authenticity and ownership. One participant, Paul, noted that having individual fluid kits allowed students to be accountable for their own performance while still engaging in peer interaction. As Paul explained, "Everyone had their own fluid kit…*no one is responsible for your performance besides yourself*… this was overall a much more enjoyable team collaboration because *you were the one responsible for your work*, and your teammates were there if I had any questions, I asked them" (Paul). Many participants described moments of frustration during setup or data collection but recognized that these struggles contributed to a deeper understanding of the experiment rather than hindering progress. These emotions often became integral to the learning process when students perceived them as challenges to overcome. When autonomy was paired with a clear task purpose and sufficient instructional structure, students reframed stress as productive. For example, Paul reflected: *"*While I was doing it*, it was a little stressful…. but I consider them good side effects*. Cause it did work, and I think I got pretty good results" (Paul).

However, students also noted that autonomy became frustrating or overwhelming when task goals were unclear or when they were unsure when or how to seek support. Overall, participants described the blended laboratory experience as enjoyable because it provided a greater sense of ownership and personal responsibility. Students were more likely to persist through uncertainty when they understood the task's purpose and knew that guidance was available if needed. Moments of difficulty were described as manageable when instructional structures, such as checkpoints, peer discussion opportunities, or instructor prompts, helped students recalibrate without taking ownership of the problem away. These accounts informed the principle of **structured autonomy,** highlighting the importance of balancing flexibility with clarity and accessible support.

Insight 2: Reflection Helped Students Reframe Emotional Responses as Part of Learning: Participants frequently described initial feelings of frustration, anxiety, and uncertainty during the early stages of the blended laboratory activities. However, through reflection on their experiences, these emotional responses were often reframed as expected and productive components of the learning process. Maria's account illustrates how pausing to reflect helped transform frustration into deeper understanding. After her kit failed to work as expected, she noted: *"At first, I got really frustrated when my kit didn't work, but then I reminded myself that this is part of the process. Once I calmed down and started troubleshooting step-by-step, I actually learned more about how the system functions."* Her experience suggests that reflection created a shift, not in the difficulty of the task, but in how she related to it. Omar's account speaks to a different but related dimension: persisting through uncertainty that could not be fully resolved. Rather than waiting for a definitive answer, he described learning to move forward with partial understanding: *"It was frustrating when my results looked off, but once a document helped us diagnose part of the issue, I realized you sometimes just have to accept uncertainty and keep moving forward."* Together, Maria and Omar's reflections illustrate how structured pauses for sense-making helped students reinterpret difficulty as a normal and informative aspect of engineering problem-solving rather than as personal failure.

Informal reflection opportunities, such as guided discussion during online sessions or instructor prompts that invited students to explain their reasoning, supported both sense-making and emotional regulation. These moments allowed students to extract learning from mistakes and recognize growth over time, reinforcing the principle of **reflective scaffolding** as a mechanism for supporting emotional engagement in open-ended laboratory contexts.

Insight 3: Emotional Regulation Was Socially Mediated Through Collaboration and Peer Support: Participants described how emotional regulation during challenging moments was rarely a solitary process. Rather than working through frustration in isolation, students leveraged collaborative dialogue to validate their understanding, reduce uncertainty, and develop confidence in troubleshooting. Instructor guidance played a particularly important role in helping students move from uncertainty to diagnostic competence. Omar described how a shared problem-solving exchange with his instructor reshaped not just his immediate understanding but his approach to subsequent trials*: "We're both seeing the issue but he had more background knowledge than I did, so he would tell me what to do, and of course he'd tell me the reason why to do it and then after I gained that insight, I kept applying it to every other trial that I did… and that actually did help a lot."*

Peer interaction served a complementary function, offering reassurance and a sense of shared progress rather than expert guidance. Priya captured this dynamic clearly: *"I felt mostly in control… it helped to talk with my team about my results to check if they were on track, and I think that helped me understand what to fix and how to move forward."* What Priya's account highlights is that collaboration did not need to resolve the problem to be valuable, rather the act of checking in with peers was itself a form of emotional regulation, reducing isolation and restoring a sense of forward momentum.

Across both instructor and peer interactions, a consistent pattern emerged: emotional regulation in blended laboratory environments is socially mediated. Collaborative troubleshooting sessions, informal peer exchanges, and the presence of peer mentors who modeled help-seeking and normalized uncertainty all contributed to students' persistence and engagement. These social interactions helped normalize frustration and reduced feelings of isolation, supporting students' persistence and engagement. This insight informed the principle of **inclusive collaboration**, underscoring the importance of designing laboratory environments that intentionally promote peer interaction and normalize emotional expression.

7. Implications for Engineering Education Practice

The design principles presented in this paper offer actionable guidance for engineering educators seeking to design laboratory environments that support both cognitive challenge and emotional engagement. While the instructional practice examined here was implemented within a blended laboratory environment, the principles are intentionally articulated at a level that allows adaptation across engineering disciplines, course formats, and institutional contexts. First, the principle of **structured autonomy** suggests that instructors can preserve the benefits of open-ended, authentic laboratory tasks while reducing unproductive frustration by making learning goals, expectations, and support pathways explicit. In practice, this may involve clarifying the purpose of laboratory activities, offering multiple pathways for task completion, and providing checkpoints or prompts that help students recalibrate when they encounter difficulty. These strategies can be incorporated into traditional, blended, or take-home laboratories without reducing rigor or independence. Second, **reflective scaffolding** highlights the value of integrating reflection into laboratory instruction as a means of supporting sense-making and emotional regulation. Instructors can embed brief reflective moments within laboratory sessions, online discussions, or post-lab activities to encourage students to articulate both technical reasoning and emotional responses to challenge. Such reflection does not require extensive curricular redesign and can be adapted to align with course goals, class size, and available instructional time. Third, the principle of **inclusive collaboration** underscores the importance of designing laboratory environments that normalize help-seeking and peer support. Establishing norms for collaboration, structuring opportunities for shared troubleshooting, and incorporating peer mentors or more advanced students where feasible can help reduce isolation and support persistence, particularly in blended or distributed laboratory settings. These approaches are especially relevant in contexts where students work independently for extended periods, such as take-home or remote laboratories.

Emotionally supportive laboratory environments are not achieved through isolated interventions but through intentional design of tasks, reflection opportunities, and social structures. Engineering educators can use these principles as a framework for examining how existing laboratory designs support or hinder students' emotional engagement and persistence, adapting each one based on local constraints, resources, and student populations.

8. Limitations and Scope of Applicability

Several limitations should be considered when interpreting the design principles presented in this paper. The instructional practice and evidence base are situated within a specific educational context with a small number of voluntary participants. As such, the insights presented here are not intended to be generalizable to all laboratory settings or student populations. The qualitative evidence informing the design principles is based on students' self-reported experiences and reflections, and the study did not examine learning outcomes, performance measures, or long-term persistence. The focus of this work is on informing instructional design rather than evaluating effectiveness.

Features of this context, including its short duration, non-graded structure, and use of peer mentors, may not be present in all laboratory courses. Instructors seeking to adapt the design principles should consider how differences in course structure, assessment practices, class size, and institutional support may shape students' experiences. Accordingly, the design principles presented in this paper should be understood as evidence-informed guidance rather than prescriptive solutions. Their applicability depends on thoughtful adaptation to local contexts and instructional goals. Future work could explore how these principles are enacted across different laboratory formats and examine their influence on learning and persistence over longer time scales.

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10. Author Contributions

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