



Effects of Scaffolding Project-Based Learning on Metacognitive Skill Development: A Quantitative Study in Undergraduate Engineering Education

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ABSTRACT

BACKGROUND & CONTEXT

Metacognitive skills are essential in engineering education to strengthen students' problem-solving, adaptability, and lifelong learning capacities. Project-Based Learning promotes active engagement, but many students struggle to develop self-regulated learning strategies without additional instructional support.

PURPOSE OR GOAL

This study investigates how integrated scaffolding strategies, including Phased Guidance, Timely Feedback, and Reflective Activities, influence metacognitive skill development among undergraduate engineering students. The research aims to determine which scaffolding components contribute most significantly to metacognitive growth and provide empirical guidance for instructional design in engineering curricula.

APPROACH OR METHODOLOGY

A 12-week quasi-experimental pretest-posttest study involved 44 first-year electrical engineering students engaged in scaffolded project-based learning. Metacognitive awareness was assessed using the Metacognitive Awareness Inventory before and after the intervention, while Peer Evaluations (PE) captured scaffold engagement. Data analysis employed paired-sample t-tests and Spearman correlation analyses.

OUTCOMES

Significant improvements were observed in Declarative Knowledge, Information Management Strategies, and Evaluation, with moderate to large effect sizes. Timely Feedback strongly correlated with gains in Debugging and Evaluation, while Reflective Activities supported early conceptual understanding. Phased Guidance provided task structure but limited direct metacognitive impact.

CONCLUSIONS

The study provides quantitative evidence that integrated scaffolding enhances metacognitive skills in engineering education. Timely feedback and reflective practice are critical to promoting self-regulated learning during complex project work.

KEYWORDS

Metacognition; Scaffolding; Project-Based Learning; Engineering Education.

Introduction

Metacognitive skill development, defined as the awareness and control of one's cognitive processes, has become increasingly central in engineering education due to its proven role in enhancing students' problem-solving abilities, adaptability, and lifelong learning competencies (Stanton et al., 2021). Metacognition encompasses both knowledge about cognitive strategies, such as understanding which methods best facilitate learning, and regulation of cognition, including planning, monitoring, and evaluating one's learning process (Schraw & Dennison, 1994). These capabilities are particularly critical for undergraduate engineering students who regularly encounter complex, interdisciplinary challenges that demand effective self-directed learning strategies (Dunlosky et al., 2013; Stanton et al., 2021).

Project-Based Learning (PjBL) has emerged as a pedagogical strategy uniquely suited to fostering deeper cognitive engagement and skill development among engineering students. However, evidence suggests that students often require additional instructional support, known as scaffolding, to maximize their metacognitive gains within PjBL contexts (Belland et al., 2017). Scaffolding involves structured educational supports, such as explicit guidance, timely feedback, and reflective prompts, that progressively build student autonomy and mastery over complex tasks. While scaffolding techniques have shown promise in various educational settings, rigorous quantitative evaluations specific to engineering education remain limited, and the overall effectiveness of scaffolding strategies within PjBL in promoting metacognitive skill development is not thoroughly quantified (Dawood et al., 2021; *The Effect of Project-Based Learning on the Metacognitive Skills of Students in Vocational High Schools* | IJSAR, n.d.).

Therefore, the purpose of this study is to quantitatively examine the overall effects of Scaffolding Project-Based Learning (SPjBL) on undergraduate engineering students' metacognitive skill development. Unlike previous investigations that have primarily focused on specific phases or mechanisms within scaffolding interventions, this research provides an overarching assessment using robust statistical methods, namely paired-sample t-tests and correlational analyses. Through a systematic evaluation of pre- and post-intervention data, this study aims to identify whether and to what extent scaffolding strategies contribute to improvements across various metacognitive subdimensions, such as Declarative Knowledge, Procedural Knowledge, Information Management, and Evaluation.

Literature Review

Metacognition in Engineering Education

Metacognition has been extensively studied as a crucial educational outcome linked directly to improved academic performance and effective lifelong learning strategies. In engineering education, strong metacognitive skills are essential given the complexity and interdisciplinarity inherent to engineering problems. Stanton emphasized that enhancing students' metacognitive awareness significantly improves their problem-solving effectiveness, academic outcomes, and long-term professional adaptability (Stanton et al., 2021).

Metacognition includes both knowledge of cognition (awareness of one's learning processes and strategies) and regulation of cognition (planning, monitoring, and evaluating one's learning activities) (Schraw & Dennison, 1994). Students with strong metacognitive abilities are more likely to select effective study strategies, monitor their understanding accurately, and adjust their learning approaches when facing challenges (Dunlosky et al., 2013).

Project-Based Learning and the Role of Scaffolding

Project-Based Learning (PjBL) has been widely adopted in engineering curricula to provide authentic, problem-centered learning experiences. PjBL enables students to engage in collaborative tasks, apply theoretical knowledge to real-world problems, and develop critical thinking and problem-solving skills. However, without sufficient guidance, some students may

struggle to fully develop the metacognitive skills required to navigate complex projects effectively (Belland et al., 2017).

Scaffolding has thus been proposed as a supportive instructional approach within PjBL to guide students' cognitive and metacognitive processes. Scaffolding strategies such as Phased Guidance (PG), Timely Feedback (TF), and Reflective Activities (RA) serve to systematically assist students in planning their tasks, monitoring their progress, and evaluating their learning outcomes. Scaffolding represents instructional strategies that provide temporary cognitive supports tailored to learners' needs, gradually withdrawn as students gain autonomy (Belland et al., 2017). This gradual fading of supports allows students to internalize cognitive and metacognitive strategies over time, eventually fostering independent learning regulation.

Through these structured supports, scaffolding interventions aim not only to prevent students from becoming overwhelmed by complex project tasks but also to actively cultivate metacognitive processes that are essential for effective project execution and deeper learning. As such, scaffolding plays a pivotal role in maximizing the potential of PjBL environments to support the comprehensive development of metacognitive skills among undergraduate engineering students.

Quantitative Evidence of Scaffolding's Effects on Metacognition

A growing body of quantitative research supports the efficacy of scaffolding interventions in enhancing metacognitive awareness among engineering students. For instance, Poh observed significant improvements in multiple metacognitive subdimensions among Malaysian engineering students after scaffolded instructional interventions, although some subskills, such as debugging, remained challenging to improve (Poh et al., 2016). Similarly, Dawood demonstrated that first-year engineering students exhibited substantial gains in metacognitive awareness following a structured scaffolding intervention combining workshops, reflective exercises, and planning activities (Dawood et al., 2021).

Other studies have further confirmed that scaffolded interventions positively impact students' abilities in specific subdimensions of metacognition, such as planning, monitoring, and evaluation, with moderate to large effect sizes typically reported (Devika & Singh, 2019; *The Effect of Project-Based Learning on the Metacognitive Skills of Students in Vocational High Schools* | IJSAR, n.d.). Nguyen also found positive correlations between higher metacognitive awareness scores and improved academic performance, supporting the notion that scaffolding not only enhances self-regulation but also translates into better learning outcomes (Nguyen et al., 2023).

Research Gaps and Current Study Focus

Despite accumulating evidence, several important gaps remain in the literature. Many previous studies have either targeted individual scaffolding components or employed purely qualitative assessments, limiting the understanding of scaffolding's overall quantitative impact on metacognitive skill development in engineering contexts. Moreover, limited attention has been given to comprehensive evaluations that capture the combined effects of multiple scaffolding strategies across diverse metacognitive subdimensions.

The present study addresses these gaps by systematically examining the cumulative effects of Scaffolding Project-Based Learning (SPjBL) on undergraduate engineering students' metacognitive skill development. Employing a quantitative pretest-posttest design with paired-sample t-tests and correlation analysis, this study provides a holistic assessment of SPjBL's effectiveness across key metacognitive subdimensions. The findings aim to offer practical insights to engineering educators regarding the integration of scaffolding strategies into project-based curricula to better support students' metacognitive growth.

This study advances knowledge by quantitatively linking specific scaffolding components to distinct metacognitive facets in undergraduate engineering. Timely Feedback relates most to

debugging and evaluation, Reflective Activities align with early conceptual understanding, and Phased Guidance primarily structures tasks rather than directly elevating metacognition. The phase-specific operationalization in an electrical engineering context clarifies which MAI subscales are most sensitive to these supports and addresses the scarcity of comprehensive quantitative mappings between scaffolds and metacognitive outcomes (Belland et al., 2017; Guo et al., 2020; Schraw & Dennison, 1994).

This study provides component-level quantitative evidence that maps Phased Guidance, Timely Feedback, and Reflective Activities to distinct MAI subscales in undergraduate electrical engineering. It specifies phase-contingent links, with feedback aligning most with debugging and evaluation and reflection aligning with declarative knowledge, while phased structuring primarily organizes task work. It also surfaces measurement considerations for the 52-item true or false MAI by indicating which facets are most sensitive under a one-semester implementation (Belland et al., 2017; Guo et al., 2020; Schraw & Dennison, 1994).

Methodology

Research Design and Analytical Procedure

A quantitative quasi-experimental one-group pretest-posttest design was employed to examine the effects of Scaffolding Project-Based Learning (SPJBL) on undergraduate engineering students' metacognitive skill development. The 12-week intervention was embedded in a practical design project integrated across two core engineering courses: Circuit Design and Analysis and Sustainable Engineering Practices. The instructional design incorporated three scaffolding components: Phased Guidance (PG), Timely Feedback (TF), and Reflective Activities (RA), each mapped to planning, monitoring, and evaluation processes in metacognitive regulation. The project was divided into three phases: Project Proposal, Project Demonstration, and Final Report. Table 1 presents the phase-specific implementation of the scaffolds (PG, TF, RA), including the core tasks and deliverables, the concrete PG elements used, how TF was delivered, and the reflective peer-review prompts used at the end of each phase. While no control group was included in this design, the one-group pretest-posttest approach remains a widely accepted method in educational intervention studies when preliminary effectiveness and internal changes within participants are of primary interest.

Table 1 Phase specific implementation of scaffolds (PG, TF, RA)

Phase	Core tasks and deliverables	Phased Guidance (PG)	Timely Feedback (TF)	Reflective Activities (RA)
P1 Proposal	Needs analysis; design objectives; written proposal including problem definition, circuit design principles, and preliminary resource planning	Project decomposed into sub goals with a needs analysis template provided for the proposal stage	Written feedback on proposals from instructors and peers	Reflective peer review questions at the end of the phase (e.g., challenges faced; strategy adjustments)
P2 Demonstration	TinkerCad based testing; oral presentation of preliminary outcomes	Structured guidance continued with a simulation design checklist for the demonstration stage	Oral feedback during presentations to address issues observed in simulations	Reflective peer review questions at the end of the phase
P3 Final Report	Design refinement based on feedback; development of	Continued structured milestones for	Iterative prototype evaluation with	Reflective peer review questions

physical prototypes; comprehensive project report	completing and reporting results (phase deliverables clarified)	instructor and peer feedback during refinement	at the end of the phas
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Note. Peer Evaluations at P1, P2, and P3 included ratings and short written responses; they indexed engagement with PG, TF, and RA and were not treated as a fourth scaffold.

Students' metacognitive awareness was measured using the Metacognitive Awareness Inventory (MAI) both prior to the intervention (Week 1) and following its completion (Week 12). The MAI has been widely used in engineering education research to assess both metacognitive knowledge and regulation (Dawood et al., 2021; Schraw & Dennison, 1994; *The Effect of Project-Based Learning on the Metacognitive Skills of Students in Vocational High Schools* | IJSAR, n.d.).

Additionally, scaffold engagement was captured through structured Peer Evaluations (PE) administered at each project milestone. Only students with complete pretest and posttest data were included in the final analysis.

Two statistical procedures were applied to analyze the data. First, paired-sample t-tests were conducted to evaluate significant differences across the eight MAI subscales, thereby assessing the extent of metacognitive improvement. Second, Spearman's rank-order correlation was utilized to explore associations between students' scaffold engagement levels and their corresponding metacognitive gains.

The study was implemented according to a structured timeline. In Week 1, the MAI pretest was administered to the participants. This was followed by the implementation of the SPjBL approach with integrated scaffolding components: Phased Guidance (PG), Timely Feedback (TF), and Reflective Activities (RA), which took place from Weeks 2 to 12. To monitor scaffold engagement, Peer Evaluations (PE) were conducted at three intervals during Weeks 4, 8, and 12. At the end of the intervention, in Week 12, the MAI posttest was administered. The collected data were then analyzed using paired-sample t-tests and Spearman correlation analyses; PE served as an engagement/fidelity measure indexing exposure to PG/TF/RA rather than a fourth scaffold.

Participants and Learning Context

We applied a census sampling strategy using an intact cohort to support analytic generalization to comparable first year electrical engineering populations. Sampling steps were as follows: define the sampling frame as all students concurrently enrolled in two required first year courses (Circuit Design and Analysis; Sustainable Engineering Practices) in the intervention semester; invite all frame members during class time; obtain informed consent; apply inclusion criteria of enrollment in both courses and completion of the MAI pretest and posttest, with exclusion for missing either test; retain the 44 students meeting these criteria; and randomly assign students to 12 project teams of 3–4 to reduce team level confounds. We targeted this group because novice stage metacognitive regulation in design intensive, project based contexts is especially responsive to structured scaffolding, and because intact cohort sampling minimizes self-selection and contamination while maintaining implementation fidelity (Dawood et al., 2021; Guo et al., 2020; Schraw & Dennison, 1994; Stanton et al., 2021).

The participants consisted of 44 first-year undergraduate students enrolled in an electrical engineering program at a Malaysian public university. Students were randomly distributed into 12 project teams of 3 to 4 members each. The project-based coursework was delivered entirely in English, and all participants engaged with the same scaffolding protocols, project structures, and instructional content.

The learning environment was intentionally designed to simulate authentic engineering project scenarios while embedding consistent scaffolding opportunities at critical stages. Weekly instructor consultations, peer feedback cycles, and structured reflective assignments were implemented to support scaffolded learning throughout the intervention.

Instrumentation

Metacognitive Awareness Inventory (MAI)

The Metacognitive Awareness Inventory (Schraw & Dennison, 1994) contains 52 dichotomous True/False items distributed across eight subdimensions of metacognition: Declarative Knowledge (8 items), Procedural Knowledge (4 items), Conditional Knowledge (5 items), Planning (7 items), Comprehension Monitoring (7 items), Information Management Strategies (10 items), Debugging Strategies (5 items), and Evaluation (6 items). Raw scores were calculated for each subdimension to capture students' metacognitive profiles before and after the intervention.

Peer Evaluation (PE) Rubric

To measure scaffold engagement, Peer Evaluations (PE) were conducted at each project phase, with students rating themselves and their teammates across six items (4-point scale) capturing perceived engagement with PG, TF, and RA. These items corresponded to engagement with the three scaffolding components: Phased Guidance, Timely Feedback, and Reflective Activities. Composite scores were computed for each student based on peer evaluation averages, providing scaffold engagement indicators for correlation analyses.

Results and Discussion

Overall Effects of SPjBL on Metacognitive Skill Development

The effectiveness of Scaffolding Project-Based Learning (SPjBL) on metacognitive skill development was examined through pretest-posttest analysis using the Metacognitive Awareness Inventory (MAI) (Schraw & Dennison, 1994). To avoid redundancy, representative subdimensions with significant improvements are highlighted in Table 2.

Table 2: Selected Pre–Post MAI Subscale Analysis Results

MAI Subscale	t-value	p-value (2-tailed)	Cohen's d
Declarative Knowledge	-3.936	0.0003	0.593
Information Management Strategies	-4.153	0.0002	0.626
Evaluation	-2.537	0.0149	0.382

The paired-sample t-tests revealed statistically significant gains in Declarative Knowledge, Information Management Strategies, and Evaluation. Beyond these three subscales, we also examined the remaining MAI dimensions. Procedural Knowledge, Conditional Knowledge, Planning, Comprehension Monitoring, and Debugging Strategies did not show statistically significant pre–post changes. The mean pre–post deltas for these five subscales were small and mixed in direction. The observed effect sizes ranged from moderate to large, aligning with previous findings in scaffold-supported metacognitive research in engineering education (Dawood et al., 2021; Poh et al., 2016).

Improvements in Declarative Knowledge reflect students' strengthened conceptual understanding, enabling more effective application of theoretical principles in project planning and execution. Gains in Information Management Strategies suggest enhanced abilities to organize and apply technical information when addressing complex engineering problems (Guo et al., 2020). The increase in Evaluation indicates that students became more proficient

at critically assessing their own work, identifying weaknesses, and modifying design approaches accordingly (Flavell, 1979).

These results provide empirical evidence that scaffolded interventions embedded within PjBL foster multidimensional growth in metacognitive regulation, supporting prior theoretical models of scaffolded learning (Belland et al., 2017). The absence of statistically significant change for Procedural Knowledge, Conditional Knowledge, Planning, Comprehension Monitoring, and Debugging is interpretable given the 12-week one-group pre–post design and the 52-item true/false MAI, which can limit sensitivity to small gains. The intervention most directly targeted evaluation and information management through rubric-anchored feedback and end-of-phase reflections, while planning and debugging received fewer opportunities for iterative rehearsal. Consequently, Evaluation and Information Management Strategies improved, whereas the other facets showed small, heterogeneous shifts.

Correlations Between Scaffolding Engagement and Metacognitive Gains

To further explore how scaffold engagement influenced students' metacognitive development, Spearman's rank-order correlations were calculated between changes in MAI subscale scores and scaffold participation levels, as assessed through Peer Evaluations (PE) across project phases (Cohen, 2013).

The observed correlation coefficients ranged from -0.20 to +0.15, reflecting generally weak but informative associations that characterize the complex, distributed nature of scaffolded metacognitive development in engineering project work (Dawood et al., 2021; Poh et al., 2016). It is important to note that the heatmap presented in Figure 1 is scaled to reflect these observed correlation ranges, rather than the full theoretical Spearman coefficient interval of $[-1, +1]$, in order to emphasize the actual variation present in the collected data. While the observed correlation coefficients were modest in magnitude, they reveal meaningful directional patterns that warrant further investigation through larger-scale, longitudinal, or multi-cohort studies to capture more stable scaffold–metacognition relationships.

Declarative Knowledge exhibited moderate positive correlations with Timely Feedback (TF) during both the Demonstration (P2) and Final Report (P3) phases ($r = 0.11$), suggesting that real-time formative feedback reinforced students' conceptual understanding during increasingly complex design tasks (Flavell, 1979; Guo et al., 2020). Reflective Activities (RA) demonstrated a weaker but still positive correlation with Declarative Knowledge during P2 ($r = 0.07$), while Phased Guidance (PG) showed minimal correlation ($r \approx 0.02$) for this dimension.

For Debugging Strategies, TF displayed the strongest observed correlations, with $r = 0.20$ during P2 and $r = 0.15$ during both P1 and P3, highlighting the role of timely feedback in supporting error diagnosis and correction as students engaged in iterative circuit simulations. RA also contributed to Debugging improvements, with a positive correlation of $r = 0.10$ observed during P1, suggesting that early reflective practice may have facilitated error anticipation and procedural monitoring (Guo et al., 2020; Schraw & Dennison, 1994).

Evaluation demonstrated consistent positive correlations with TF across all phases, ranging between $r = 0.15$ and $r = 0.20$, underscoring the importance of dynamic feedback in strengthening students' capacity for self-evaluation and performance judgment (Flavell, 1979). In comparison, RA and PG exhibited comparatively weaker correlations with Evaluation ($r \approx 0.05$), suggesting that while they may contribute indirectly, their direct effects on evaluative metacognition were more limited in this study.

The remaining subdimensions, including Procedural Knowledge, Conditional Knowledge, Planning, Comprehension Monitoring, and Information Management Strategies, exhibited negligible correlations ($|r| < 0.05$) across all scaffolding strategies. These results suggest that these aspects of metacognition may be less directly responsive to scaffold engagement under the conditions studied.

Collectively, these results emphasize the differentiated effects of the three scaffolding strategies. Taken together, the findings advance theory by identifying scaffold-to-subscale linkages that are precise enough to be tested in future controlled comparisons of scaffold bundles and durations (Belland et al., 2017; Schraw & Dennison, 1994). The pattern of effects specifies plausible pathways: feedback near performance supports monitoring and evaluation that underlie debugging and self-checking; end-of-phase reflections consolidate conceptual knowledge that aids planning and transfer; phased structuring reduces task complexity and opens opportunities for regulation rather than directly increasing metacognitive activity. These mechanisms refine accounts of how scaffolding supports regulation of cognition in project settings (Belland et al., 2017; Schraw & Dennison, 1994). Timely Feedback (TF) was most strongly associated with improvements in Debugging and Evaluation, particularly during complex design execution phases where cognitive load was highest. Reflective Activities (RA) contributed meaningfully to conceptual consolidation and early-stage procedural awareness. Phased Guidance (PG), although supportive in task structuring, showed limited direct association with metacognitive growth unless paired with additional cognitive scaffolds (Vygotsky, 1978; Wood et al., 1976).

These findings align with prior evidence that dynamic feedback and structured reflection are central drivers of metacognitive development in scaffolded project-based learning environments (Dawood et al., 2021; Nguyen et al., 2023).

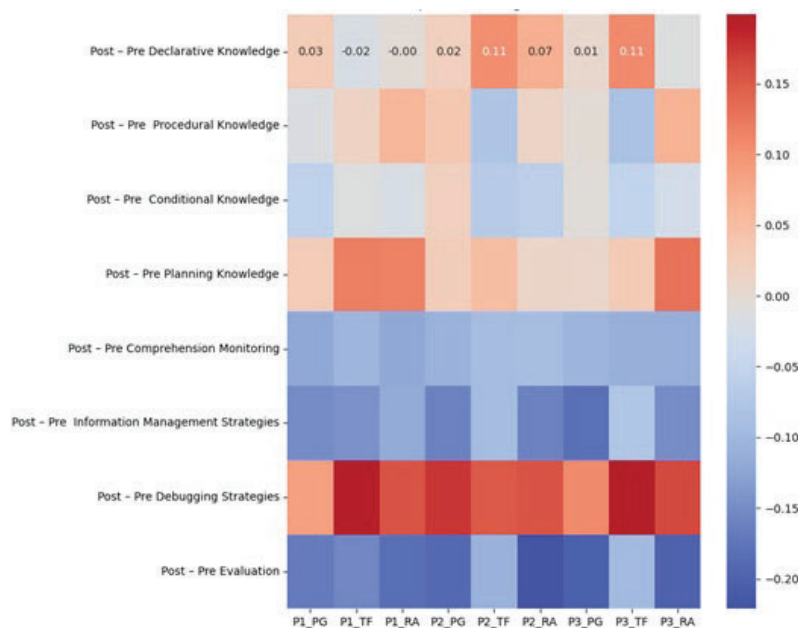


Figure 1: Heatmap of *PE-derived* Spearman correlations between scaffold engagement (PG, TF, RA) at each project phase (P1–P3) and MAI subsdimension gains

Note. Colors are displayed on a full -1 to $+1$ scale; the observed range in this dataset is -0.20 to $+0.15$. Engagement with PG/TF/RA was indexed via Peer Evaluations (PE) at each milestone.

Instructional Implications

The findings of this study offer several instructional insights for enhancing scaffolded project-based learning in undergraduate engineering education. Timely Feedback should be prioritized during high-cognitive-load design phases where iterative revision and rapid adjustment are required. Reflective Activities are most effective when introduced early, facilitating conceptual understanding and anticipatory self-regulation as students transition from planning to execution. Phased Guidance, while useful for organizational structure, should be

supplemented with explicit metacognitive prompts to better support self-directed regulation throughout project work.

Taken together, these findings provide empirical support for scaffolded interventions as effective mechanisms for promoting metacognitive growth in undergraduate engineering students. By strategically integrating multiple scaffolding components across different project phases, instructors can better equip students to engage in complex, self-regulated learning processes essential for success in professional engineering practice (Dawood et al., 2021; Nguyen et al., 2023).

Conclusion

This study investigated the effects of Scaffolding Project-Based Learning (SPjBL) on the development of metacognitive skills among undergraduate engineering students. Using a quasi-experimental pretest-posttest design combined with scaffold engagement data, the results demonstrated significant improvements in several metacognitive subdimensions, particularly Declarative Knowledge, Information Management Strategies, and Evaluation. Among the scaffolding strategies, Timely Feedback (TF) consistently showed the strongest positive associations with metacognitive gains, especially in Debugging and Evaluation. Reflective Activities (RA) also contributed positively, particularly in enhancing Declarative Knowledge and supporting early error anticipation, while Phased Guidance (PG), though useful for structuring tasks, demonstrated weaker direct effects on metacognitive development. These findings underscore the importance of combining cognitive, reflective, and procedural scaffolds to optimize metacognitive growth. Beyond practice, the study contributes to knowledge by mapping scaffold components to metacognitive subscales and indicating which dimensions are detectably affected within a one semester MAI application (Belland et al., 2017; Guo et al., 2020).

The present study contributes to the growing body of research on scaffolding and metacognition by offering a holistic, data-driven evaluation of scaffolded interventions in undergraduate engineering education. Whereas previous studies have often examined isolated scaffolding components or phase-specific interventions, this study provides an integrated assessment of multiple scaffolding strategies implemented concurrently throughout an entire project-based learning cycle. The findings align with key theoretical frameworks, including metacognitive regulation models (Flavell, 1979; Schraw & Dennison, 1994), cognitive apprenticeship theory (Collins et al., 1989), and scaffolding frameworks (Belland et al., 2017; Vygotsky, 1978). The observed correlation patterns between specific scaffolds and metacognitive subdimensions offer refined empirical insights into how various instructional supports differentially contribute to knowledge acquisition, procedural regulation, and reflective evaluation within authentic engineering project contexts.

In terms of practical implications, the study emphasizes the importance of providing timely, context-sensitive feedback during cognitively demanding stages of project work, alongside structured reflective activities introduced early in the learning process. Procedural guidance alone appears insufficient for fostering deeper metacognitive engagement, highlighting the need for a comprehensive scaffolding approach that integrates metacognitive prompts, reflective checklists, and opportunities for critical self-evaluation throughout the project lifecycle.

Despite its contributions, the study has several limitations, including a relatively small sample size from a single institution, which may constrain the generalizability of its findings. These methodological choices, including census sampling of a single-institution first-year cohort, the one-group pretest-posttest design, reliance on the 52-item true or false MAI and perception-based PE indices, and a one-semester timeline, prioritize feasibility and internal change but necessarily bound external validity and the generality of the knowledge claims (Dawood et al., 2021; Poh et al., 2016; Schraw & Dennison, 1994). Future research should consider larger, more diverse populations, incorporate multimodal data sources such as observational data

and learning analytics, and employ longitudinal or experimental designs to better understand the complex, interacting effects of various scaffolding strategies on metacognitive development.

Overall, this study provides empirical evidence that strategically implemented SPjBL can meaningfully enhance metacognitive skills among engineering students, thereby equipping them with essential self-regulation, problem-solving, and reflective practices critical for success in professional engineering practice and lifelong learning.

Beyond practice, the study contributes to knowledge by establishing a reproducible mapping between scaffold components and MAI facets in undergraduate electrical engineering and by showing which facets demonstrably shift within a 12-week implementation (Belland et al., 2017; Guo et al., 2020).

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