Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #46525

BOARD # 251: Integrating Metacognitive Knowledge and Self-Regulation: Insights from Problem-Solving in Engineering Mathematics Courses

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IUSE: Integrating Metacognitive Knowledge and Self-Regulation: Insights from Problem-Solving in Engineering Mathematics Courses

This research examines the relationship between undergraduate students' task-related knowledge and self-regulation strategies during problem-solving, leading to a framework illustrating the combined use of metacognitive knowledge (MKT) and self-regulation (SR). Conducted with 20 students (7 females, 13 males) from two engineering mathematics courses (Engineering Statics and Ordinary Differential Equations), the study analyzed 40 problem-solving sessions through pre- and post-solution interviews and think-aloud protocols.

The study explored how the interplay between metacognitive awareness and self-regulatory strategies affects performance. Qualitative analysis identified seven distinct problem-solving episodes, highlighting the impact of cognitive and self-regulatory factors on outcomes. These findings offer insights into improving instructional practices and teaching strategies.

Keywords: knowledge about tasks, problem-solving, self-regulation, mathematics education, engineering education, learning episodes.

1. Background

Problem-solving is a persistent challenge in education, requiring integration of cognitive and metacognitive skills for success. Polya's framework—understanding the problem, devising a plan, implementing it, and reviewing the solution—remains central to problem-solving and mirrors self-regulation phases [1]. This study focuses on the cognitive dimensions of problem-solving, which are less explored, though external factors like abstraction and continuity also influence students' approaches.

Shin et al. [2] highlight the complexity of problem-solving in STEM, requiring cross-disciplinary integration. However, many STEM graduates struggle with cognitive processing and motivational regulation [3]-[5], limiting their problem-solving ability. Additionally, merely reviewing solutions post-task is often ineffective in enhancing understanding [6].

Metacognition, as Swanson notes, plays a key role in effective problem-solving by enabling students to regulate their cognitive strategies, leading to improved performance. This study explores the interplay between self-regulation, metacognition, and task complexity to inform educational interventions in STEM. Funded by the NSF under the IUSE program at Level 2, this research aims to advance STEM education.

1.1. Metacognitive Knowledge About Task

Students' problem-solving approaches are shaped by their metacognitive knowledge, which includes awareness of themselves, the task, and the strategies they use [7]. This knowledge, categorized as **person** (beliefs about their own and others' cognitive abilities), **task** (understanding of task demands and goals), and **strategies** (methods employed to achieve objectives), plays a crucial role in shaping how students approach and navigate academic challenges.

This study highlights the importance of metacognitive knowledge about tasks (MKT) in guiding students' interpretation and approach to problem-solving within self-regulation processes [8]. Tasks, or "problems," are defined by three key aspects:

- **Purpose:** Understanding the goals of solving the problem.
- **Structure:** How information is organized and interpreted.
- **Components:** The steps and processes required to solve the problem.

Effective problem-solving requires a clear grasp of these interconnected elements. With problems varying from simple to complex and well-structured to ill-structured, students must develop metacognitive tools to navigate challenges and adapt their strategies.

1.2. Self-Regulatory Process in Problem-Solving

Successful problem-solving requires students to continuously monitor and assess their engagement with tasks [9]. This self-regulation process [10] involves cycles of interpreting task requirements, planning, managing time, selecting strategies, processing information, tracking progress, evaluating outcomes, and refining methods [11].

Active engagement in this cyclical process helps students develop the skills to tackle complex problems and adapt to challenges. Constructing an accurate mental representation of a problem is essential, guiding solution development and strategy refinement. These skills, central to self-regulated learning (SRL), are crucial for open-ended problems in fields like engineering design [12].

Self-regulation, especially monitoring and evaluation, is key to problem-solving. Monitoring tracks progress and method effectiveness, while evaluation reflects on outcomes and refines strategies, improving problem-solving efforts.

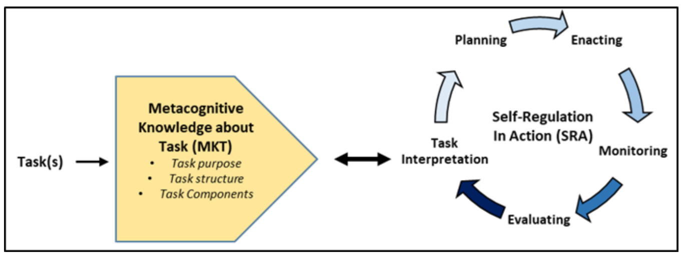

Figure 1. The interplay between MKT & SRA in a learning activity; Adopted from Butler & Cartier (2004)

2. The Study

2.1. Objectives and Research Questions

The aim of this study was to investigate how students engage with their metacognitive knowledge about tasks (MKT) and their approaches to monitoring and evaluation (ME) during problem-solving in mathematics and engineering contexts. Specifically, we analyzed how MKT interacts with ME by examining students' cognitive processes at various stages of problem-solving. A central goal was to develop a framework to elucidate these interactions.

The study addressed one main research question (RQ): *How does students' metacognitive knowledge about tasks interact with their self-regulatory monitoring and evaluation strategies during problem-solving?* To refine this inquiry, two sub-questions were posed: (a) *What specific instances illustrate the interaction between MKT and ME during problem-solving?* and (b) *How can these interactions be captured within a comprehensive framework?*

2.2. Study Context and Participants

The study was conducted in two second-year engineering courses: a mathematics course covering linear algebra and differential equations, and a foundational engineering statics course. These courses represent critical and complementary elements of the engineering curriculum and are mandatory for most students.

Participants consisted of 20 undergraduate students (7 females, 13 males) from a mid-sized public land-grant university in the western United States. Eleven students were enrolled in the mathematics course, and nine in the engineering course. Tasks were administered late in the semester to ensure participants had developed a solid understanding of the material. Institutional Review Board (IRB) approval was obtained prior to the study.

2.3. Data Collection and Analysis

Each participant completed an "easy" and a "difficult" task, classified by instructors and aligned with course objectives as either "story" or "rule" problems per Jonassen's typology [13]. Established rubrics [14][15] ensured consistency in difficulty.

Data collection occurred before, during, and after problem-solving. Beforehand, reflective interviews assessed metacognitive knowledge. During tasks, think-aloud protocols captured cognitive processes, categorized as Type 1 or Type 2 [16]. Afterward, exit interviews gathered reflections on performance, confidence, and solution quality.

The study aimed to map MKT-ME interactions. Qualitative data from think-alouds and interviews were transcribed, coded, and analyzed for self-regulatory patterns. Quantitative analysis categorized MKT levels using "hit" and "miss" percentages, while instructor evaluations classified performance as proficient (≥80%), average (21–79%), or below proficient (≤20%).

3. Findings

The study examined students' problem-solving strategies by analyzing two key components: Metacognitive Knowledge about Task (MKT) before problem-solving and Monitoring and Evaluation (ME) during the activity. By mapping 21 of 40 problem-solving events into quadrants based on MKT-ME alignment, distinct learning episodes emerged.

Quadrant 1, "Impeccable Learning," featured high MKT and effective ME, leading to success, while Quadrant 4, "Faulty Adaptive Learning," reflected strong ME undermined by insufficient MKT. Other categories included Fortuitous Learning (low MKT/ME with unexpected success), Oblivious Learning (low MKT/ME with poor outcomes), Routine Learning (high MKT, weak ME, acceptable results), and Non-Adaptive Learning (high MKT, ineffective adjustments, poor outcomes).

Analysis of seven episodes involving 20 students identified 16 distinct MKT-ME interaction patterns. Four students (25%) adapted their strategies based on task difficulty, two (12.5%) maintained consistent patterns, and nine varied their approach within a single problem.

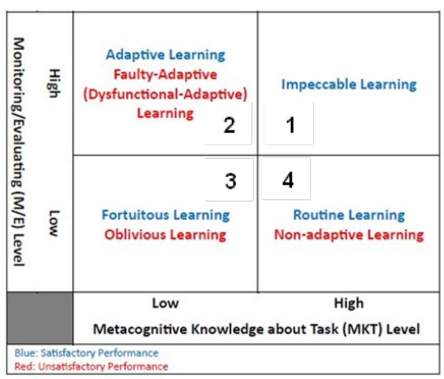

Figure 2. Seven Learning Episodes

Students' initial MKT levels and ME processes influenced their performance, with outcomes varying from high to low. Notably, students in Oblivious Learning episodes took longer to complete tasks than those who found solutions fortuitously. Of 21 problem-solving events, 14 were satisfactory, while seven were unsatisfactory.

3.1. Quadrant 1: Impeccable Learning Episodes

In Quadrant 1, problem-solving is highly effective due to the synergistic combination of high levels of Metacognitive Knowledge about Task (MKT) and Monitoring and Evaluation (ME). These levels range between 60% and 73%, with task interpretation informed by MKT reaching 96% of the recommended benchmark. Effective monitoring and evaluation strategies further support this process. Students in this category display high confidence before and after problem-solving and excel in managing both straightforward and complex tasks, particularly in statics. Outcomes in this quadrant are consistently favorable, with solution quality accurately assessed by both instructors and students. Of the 21 analyzed problem-solving events, four (19%) fell into this category, showcasing the hallmarks of Impeccable Learning.

3.2. Quadrant 2: Adaptive and Faulty-Adaptive Learning Episodes

Quadrant 2 captures varying levels of effectiveness in monitoring and evaluation during problem-solving, often influenced by limited metacognitive knowledge. Adaptive Learning episodes occur when students with low MKT (33%-35%) successfully compensate with strong monitoring and evaluation strategies (60%-67%), achieving satisfactory results efficiently. In contrast, Faulty-Adaptive Learning describes cases where, despite adequate monitoring (63%-83%), students fail to fully apply MKT (44% of the recommended amount), leading to less successful outcomes.

In Adaptive Learning episodes, students utilized 93% of the teacher-recommended MKT, resulting in successful problem-solving. Faulty-Adaptive episodes, however, were marked by slower task completion and lower performance, with metacognitive awareness ranging from 20%-39%. Of the five events in this quadrant, 40% were Adaptive Learning, while 60% were Faulty-Adaptive. Collectively, Adaptive episodes accounted for 10% of all events, and Faulty-Adaptive episodes made up 14%.

3.3. Quadrant 3: Fortuitous and Oblivious Learning Episodes

In Quadrant 3, success can arise unexpectedly through unconventional approaches, while failure results from inadequate knowledge and monitoring. Fortuitous Learning occurs when students, with limited MKT (26%-39%) and weak monitoring (9%-39%), increase task interpretation activities to 86%, often displaying high confidence. In contrast, Oblivious Learning involves students with even lower MKT (20%-25%) and monitoring (31%-33%), leading to task failure.

Fortuitous Learning was observed in easy statics and challenging math problems, while Oblivious Learning occurred mainly in difficult statics problems, requiring longer completion times. Of 21 events, 4 (19%) were Fortuitous Learning, and 3 (14%) were Oblivious Learning, representing 57% and 43% of Quadrant 3 events, respectively.

3.4. Quadrant 4: Routine and Non-Adaptive Learning Episodes

Quadrant 4 represents scenarios where metacognitive knowledge is adequate but monitoring and evaluation strategies vary. Routine Learning describes individuals with extensive MKT who achieve success through automatic, knowledge-based strategies, even with limited monitoring (15%-28%). This approach was prevalent in mathematics tasks, regardless of difficulty or confidence levels, but less common in engineering statics.

In contrast, Non-Adaptive Learning occurs when individuals with sufficient MKT (73%) fail to effectively monitor (22%) or apply their knowledge (58%), resulting in poor outcomes. Routine learners completed tasks more efficiently and accurately assessed their solutions compared to Non-Adaptive learners. Of the 21 events, four (19%) were Routine Learning, and one (5%) was Non-Adaptive Learning, with Routine episodes accounting for 80% of Quadrant 4 events.

4. Conclusions and Brief Discussion

The analysis identified seven distinct learning episodes shaped by the interplay between metacognitive knowledge and monitoring strategies. Statics tasks proved more challenging than mathematics, with higher instances of Fortuitous and Oblivious Learning (50% vs. 23%).

Students with strong MKT and proficient ME consistently succeeded, while those with dynamic ME but weak MKT often failed (60%). In contrast, adequate MKT without strong ME increased success rates

(80%). Developing metacognitive awareness and evaluation skills is crucial for fostering adaptive problem-solvers.

Educators can design targeted interventions to enhance monitoring and evaluation, helping students transition from Faulty-Adaptive to Adaptive Learning or Non-Adaptive to Routine Learning. Training students to recognize problem structures beyond surface details prevents Fortuitous or Oblivious Learning (Quadrant 3) and supports mastery of metacognitive knowledge about tasks. Prior research [17] highlights the importance of improved monitoring and evaluation in achieving these goals.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 2110769. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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