INVESTIGATING THE FUNCTIONALITY OF METACOGNITIVE PROMPT DURING THE CIRCUIT ANALYSIS PROBLEM-SOLVING

Jyoti Shaha, Vishwas Badhe and Ramkumar Rajendran
Indian Institute of Technology Bombay, India

ABSTRACT

Metacognitive strategies play a crucial role in Computer-Based Learning Environments (CBLEs). However, students often struggle to apply these strategies spontaneously during learning. Research demonstrates that metacognitive prompts can effectively guide students' awareness and help them monitor their learning progress, leading to improved outcomes. While studies have shown the benefits of metacognitive prompting in various domains such as clinical reasoning, biology, educational psychology, and social science, most focus on reading and writing tasks. There is limited research on problem-solving tasks, particularly in the engineering domain. To address this gap, we developed MetaGuru, a learning environment designed to stimulate learners' metacognitive strategies using prompts in electrical engineering circuit analysis problem-solving. In this paper we investigate the functionality of metacognitive prompts in engineering problem-solving with five participants. Participants solved circuit analysis problems within MetaGuru. We examined the functionality of prompts by collecting screen recordings and conducting semi-structured interviews. The findings reveal that while the orientation and planning prompts were effective, the monitoring and evaluation prompts showed limited effectiveness, highlighting the need for improvement in these areas.

KEYWORDS

Metacognition, Metacognitive Prompts, Engineering Problem-Solving, Computer-Based Learning Environment, Electrical Engineering

1. INTRODUCTION

Computer-based learning environments (CBLEs) are designed for instructional purposes and to support learners in achieving goals across various disciplines (Lajoie, S.P., Naismith, L. 2012, Aballe, K. S., et al. 2022)). Most CBLEs provide learning content through multimedia, text, images, animation, simulations, graphs, and Audio-video representation with tools (Fielding I. Winters, 2008, Jeffrey A. 2011). In CBLE, learners are allowed to follow their instructional path and have access to multiple representations of information and opportunities to manipulate them (Fielding I. Winters 2008). To access such information-rich environments, learners must make decisions and make an effective plan for spending their time and accessing the information, constantly identify relevant information, track progress toward the goal and sub goals, and make judgments of their learning (Jeffrey A. 2011). This highlights the importance of metacognitive skills for decision-making during learning and using strategic learning approaches (E Pieger, M Bannert 2018). Metacognitive skills refer to the planning, monitoring, control, and evaluation processes involved in learning and problem-solving (P Güner 2021, Jumari, N. F. 2022). Where planning refers to choosing appropriate strategies for the task, monitoring is an awareness of an individual’s performance. Control and evaluation mean reviewing the process (Ochilova, V. R. 2021).

The underlying assumption is that learners know metacognitive skills. Still, they often struggle to recall or execute them spontaneously in a specific learning context. This phenomenon, a production deficit, can result in poorer learning outcomes (K Engelmann 2021). Educators often employ metacognitive prompting as an effective instructional strategy to address production deficits and promote self-regulated learning in CBLEs (M. Bannert. 2015; K Engelmann, 2021). Several Researchers have demonstrated that metacognitive prompts effectively guide students' awareness and facilitate self-monitoring during learning activities. This not only improves learners’ metacognitive skills but also contributes to better overall learning outcomes (E Pieger, M

Bannert 2018, K Engelmann, M Bannert, N Melzner 2021, M. Bannert, C Sonnenberg, C Mengelkamp, E Pieger 2015, L Guo 2022).

Although extensive research has examined the effects of metacognitive prompts in computer-based learning environments (CBLEs) within social science and science domains, there remains a notable gap in the engineering domain. Also, current studies on metacognitive prompts have largely focused on reading and writing tasks, neglecting the realm of problem-solving. This research gap emphasizes a need for further exploration and empirical studies evaluating metacognitive prompts' impact and effectiveness within engineering domains' problem-solving contexts.

Problem-solving is the most essential factor for engineering graduates in the 21st century (Khairiyah Mohd-Yusof 2014). However, students enrolled in basic electrical engineering courses face difficulties while solving circuit analysis problems (Niebler, C. 2023). Due to a lack of metacognitive abilities, students may struggle to reach the correct answer despite having the necessary knowledge and formulas while solving circuit analysis problems (Murata, A., Ohta, Y., & Hayami, T. (2013). Students must develop and enhance their metacognitive skills to improve performance in basic electrical circuit problem-solving (Murata, A., Ohta, Y., & Hayami, T. (2013).

Hence, we designed and developed a learning environment named MetaGuru to support learners in basic electrical circuits' problem-solving. In this environment, metacognitive prompts are embedded to stimulate metacognitive skills while learners interact with the learning environment.

The primary objective of this paper is to analyze the functionality of metacognitive prompting during problem-solving process in MetaGuru. through learners' initial responses to them. To achieve this goal, we conducted a pilot study involving five participants interacting with MetaGuru. Our data collection methods included computer-generated trace data, screen recording, and semi-structured interviews, providing a comprehensive view of learners' interactions and experiences.

The following research questions are addressed in the present study:

RQ 1. What are the learners' initial responses to the metacognitive prompts in the circuit analysis problem-solving?

RQ 2. How well do learners understand the meaning of the metacognitive prompts in circuit analysis problem-solving?

The following sections will describe the theoretical framework (section 2), MetaGuru context, and embedded metacognitive prompts, followed by the learner interactions captured (section 3). Further, we describe the research goal, study design, and data collection for analyzing the functionality of metacognitive prompting (section 4). Finally, we report results and discussion (section 5), followed by a conclusion and future work (section 6).

2. THEORETICAL FRAMEWORK

2.1 Metacognition and Problem-Solving

Flavell introduced the concept of metacognition in the 1970s. Flavell (1979) proposed a model of metacognition comprising four interacting classes, i.e., goals, experiences, knowledge, and Strategies. Schraw proposed that metacognition includes two distinct components: knowledge of cognition and regulation of cognition. Knowledge of cognition encompasses three types of metacognitive awareness: declarative knowledge, procedural knowledge, and conditional knowledge. Regulation of cognition involves three key processes: planning, monitoring, and evaluation (Schraw, G., & Moshman, D. 1995). Desoete (2008) conceptualized metacognition as consisting of metacognitive knowledge and skills. There are four metacognitive skills: prediction, planning, monitoring, and evaluation. Whereas Efklides proposed that metacognition is a multifaceted phenomenon, Metacognitive Experience (ME), Metacognitive knowledge (MK), and Metacognitive skills (MS) are the three facets (Efklides 2008). Metacognitive knowledge (MK) is defined as knowledge of self and others, knowledge of tasks, and knowledge of multiple strategies. Metacognitive knowledge is continuously enriched, updated, and differentiated. Metacognitive Experience (ME) is what a person is aware of and can easily feel when across a task and processing related information, feeling of knowing, familiarity, and confidence, how a person feels in the context of problem-solving, i.e., Judgement of learning, an estimate of effort expenditure, an estimate of time needed or spent, an estimate of solution correctness, where metacognitive skills (MS)/strategies comprise orientation, strategy planning, regulation of cognitive processing, monitoring the execution of planned activities, and evaluation of the outcome of task processing (Efklides 2008).

Metacognition plays an important role in problem-solving (Flavell J. 1979). Metacognitive skills support learners in regulating the problem-solving process and deciding when and how to use knowledge and cognitive resources (Güner, P. & Erbay, H. N. 2021). Polya (1985) defines four phases of problem-solving. These phases are parallel to the skills in metacognition (Ader, 2019; Whitebread et al., 2009).

Table 1. Problem-solving phases mapping to the metacognitive skills (Güner, P. & Erbay, H. N. 2021)

Four phases of problem-solving (Polya 1985)	Metacognitive skills (Ader, 2019; Whitebread et al., 2009)
Understanding the problem	Planning
Making a plan	Monitoring
Carrying out the plan	Monitoring
Checking out the solution	Evaluation

2.2 Metacognitive Prompting

To address production deficit and stimulate metacognitive skills, metacognitive prompting is an effective instructional strategy in CBLE (M. Bannert. 2015; K Engelmann, 2021). Several studies have explored prompting use in CBLEs. For example, MetaTutor is a hypermedia-based intelligent tutoring system that incorporates virtual agents to assist students in developing effective learning strategies and metacognitive monitoring skills in biology. (Azevedo et al., 2018). BioWorld, a CBLE designed to support medical students in clinical problem-solving, provides conceptual, strategic, and metacognitive scaffolding during problem-solving tasks (Lajoie et al., 2013). Bannert and colleagues developed a hypermedia learning environment focusing on educational psychology topics. The learning environment involves reading and writing tasks to analyze the impact of metacognitive prompts on learning outcomes (Bannert et al., 2009; Bannert & Mengelkamp, 2013; Azevedo et al., 2018). These studies demonstrate the growing interest in implementing prompting strategies within diverse digital learning contexts to enhance metacognitive skills and learning outcomes.

3. METAGURU: LEARNING ENVIRONMENT

The following section introduces MetaGuru, a computer-based learning environment designed to assist students in solving problems in electrical engineering circuit analysis.

3.1 MetaGuru: Learning Environment

Freshman students in introductory electrical engineering courses often encounter difficulties when solving circuit analysis problems (Niebler, 2023). Despite possessing the necessary knowledge and formulas, students may struggle to arrive at correct solutions due to underdeveloped metacognitive abilities (Murata et al., 2013).

To address this challenge and the research gap outlined in the introduction, we developed MetaGuru. The primary objectives of MetaGuru are:

1. To stimulate learners' metacognitive strategies during circuit analysis problem-solving tasks.
2. To collect log data of learners' interactions with the learning environment.
3. To analyze the impact of metacognitive prompts on problem-solving performance.

MetaGuru's theoretical foundation is rooted in the instructional design framework for computer-based interactive content, as Zhang (2022) and David (1997) proposed. This framework guides the design of metacognitive scaffolds specifically tailored for problem-solving instruction. By incorporating these principles, MetaGuru aims to provide effective metacognitive support within the context of circuit analysis problem-solving. Figure 1 shows the screenshot of the MetaGuru earning environment.

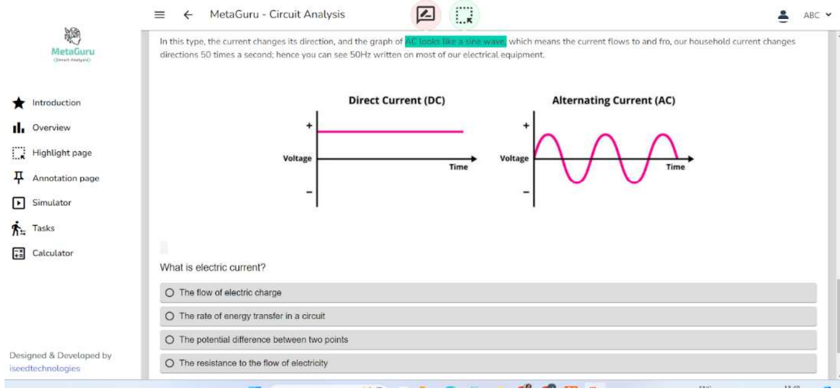

Figure 1. Screenshot of MetaGuru: Computer-based learning Environment

MetaGuru's learning materials encompass core topics in circuit analysis, including basic Concepts, DC circuits, and Circuit Theorems. These materials are presented through diverse media formats: Text, Videos, Pictures, and Solved examples. To promote self-assessment and comprehension, each sub-topic concludes with an assessment question that includes feedback. Additionally, assessment questions are integrated into the video content, reinforcing learning throughout the material. MetaGuru equipped users with a range of tools to support their learning. A countdown timer displays the remaining study time and begins to blink during the final ten minutes of the allocated period. This feature is designed to assist learners in efficiently managing their time during problem-solving tasks. The annotation tool enables learners to write interpretations of text by selecting specific passages. It allows them to enhance their comprehension by highlighting key points and appending their interpretations. The highlighter tool allows learners to emphasize text content by selecting specific passages and changing their background color. A MetaGuru incorporates a user-friendly circuit simulator called 'circuitjs1,' which allows learners to design and simulate electrical circuits. Learners can evaluate their solutions by comparing the simulated current with their calculated values. Metaguru allows learners navigation options to facilitate seamless movement through the learning content. By integrating these features, MetaGuru creates a comprehensive learning environment that addresses multiple facets of cognitive and metacognitive processes in circuit analysis problem-solving.

3.2 Metacognitive Prompts

Analyzing the existing literature, we curated a comprehensive list of metacognitive prompts that we integrated into our learning environment. The MetaGuru System employed a series of prompts strategically placed throughout the problem-solving journey. These prompts guided users towards effective strategies at each stage, enhancing their metacognitive strategies and problem-solving abilities.

Table 2 details the metacognitive prompts used in the MetaGuru and where they are placed. It shows the different steps of problem-solving mapped with metacognitive strategies and metacognitive prompts. Our system is structured around these five distinct prompts, each tailored to stimulate individuals through the orientation, planning, execution, and reflection phases of problem-solving

3.3 Log Data

This section describes the details of the interaction log data. The interaction log data of students using the MetaGuru provides a comprehensive overview of their engagement and activities within the system. This data captures a range of actions that detail how learners interact with different features and resources available in MetaGuru. Table 3 provides the details of the actions captured.

Table 2. Metacognitive prompts

Problem-solving process	Metacognitive skill	Metacognitive Prompts	Where they are placed
Represent Problem	Orientation	Think and write what specific concepts or techniques are needed to solve this problem successfully. (Q. Zang 2022)	On task page
Generate solution	Planning	What concepts or techniques do you think you need to revise or revisit to solve this problem? (Q. Zang 2022)	On task page
Generate solution	Monitoring	The information you are reading, is it relevant to solve this problem successfully? If yes, then write a summary of your understanding of the content you read. (Azevedo 2009)	On Every reading page
Present and evaluate	Evaluation	While working on your solution, have you thought about using a simulator to validate and confirm the accuracy of your answer? Think and write how you use a simulator to verify your answer.	On Solution page Before submitting solution
Reflect	Reflection	What did you gain as you worked through this problem? Write your understanding	On the solution page, after submitting the solution

Table 3. Problem-solving phases mapping to the metacognitive skills (Güner, P. & Erbay, H. N. 2021)

Actions captured	Metacognitive skill
System_access	Log in and log out to MetaGuru
Read	Course material is read
Video	Information about the video is played, paused, and seek
Highlight	Highlighting feature is used
Annotate	Highlighting feature is used
Highlight_View	The page where highlights are saved is viewed
Annotate_view	The page where annotations are saved is viewed
Calculator	Accessing calculator
Self_assessment_Question	Self-assessment question in video and text content is attempted
Prompt_Question	Metacognitive Prompt question is attempted
Simulator	Interacting with Simulator

4. METHODOLOGY

4.1 Study Design

Five learners (3 male, 2 female) first year of Engineering participated in the study voluntarily. The Institute Research Board (IRB) approved the study, and an informed consent form was obtained from all students. No monetary compensation was given to the students. The study was conducted in a lab setup to control the conditions wherein individual learners interacted with the MetaGuru for 120 min.

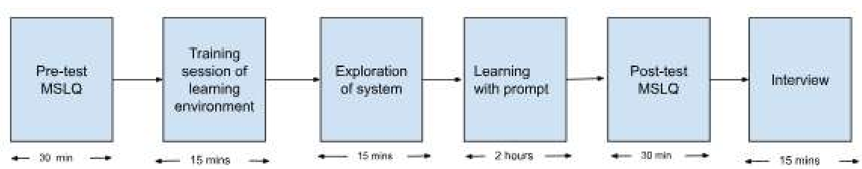

Figure 2. Design and procedure of research study

Figure 2 illustrates the study's detailed procedure. The learning activity took place over 2 hours, during which students interacted with the MetaGuru learning environment to solve three problems related to Thevenin's theorem. Students analyzed the circuits to find Thevenin's equivalent circuits, with the difficulty level increasing by the third problem. Students received different metacognitive prompts throughout this period to guide their problem-solving process.

4.2 Data Collection

Our study design incorporated three types of data collection methods to evaluate the overall experience with MetaGuru and the functionality of prompts. We collected interaction log data, screen recording, and semi-structured interview data. We captured interaction log data to investigate whether learners attempted the prompt. The screen recording is captured to analyze the learners' responses to the prompt. The final phase of the study involved individual interviews with the students, each lasting approximately 15 minutes. These semi-structured interviews aimed to gather students' perceptions of the MetaGuru learning environment and the prompts provided during the problem-solving session.

5. RESULT

This pilot study aimed to analyze learners' initial responses to the metacognitive prompts and the functionality of prompts through initial learner responses. We analyzed the initial response through log data and screen recording data.

Log data analysis revealed the following patterns in prompt attempts. The orientation prompt was attempted by 4 out of 5 learners. The reflection prompt was attempted by 3 out of 5 learners. The evaluation prompt was attempted by 2 out of 5 learners.

Screen recording analysis provided insights into learners' understanding and responses. 3 learners demonstrated understanding by providing expected answers to the orientation Prompt. These learners correctly outlined the steps to solve Thevenin's problem. Learner S1 correctly understood the evaluation Prompt and identified the use of the simulator for answer evaluation but did not use the simulator. Learner S2 suggested checking formulas and steps as an evaluation method. 3 out of 5 learners attempted the reflection prompt. These learners provided written reflections on their understanding of the problem-solving process.

To address RQ 2, first, we analyzed screen recording data capturing students' initial responses to the prompts. Second, we conducted semi-structured interviews to gather additional insights. Our analysis focused on assessing the functionality of the prompts.

Prompt functionality: We evaluated how well each prompt performed its intended metacognitive role. By combining data from screen recordings and interviews, we gained a comprehensive understanding of how students interacted with the prompts initially and how these interactions reflected the prompts' functionality. This approach allowed us to identify the strengths and potential areas for improvement in the MetaGuru system's metacognitive scaffolding.

To analyse the understanding of prompts, students were asked, "So this question is about prompts. Was the prompt helpful? How? Can you give an example?"

S5: "*The planning prompt was helpful to know how to solve the problem. Yes, after reading the prompt question, I started thinking of the answer that I have to do this, what will be the first step? What will be the second step? Before, I had an idea that yes we have to solve problems, But after this prompt question, I had a different idea that I have to go step-wise. Which step do we have to do first in the evidence Vth, Rth, Rl is the first one, So we solve it like that after reading the evaluation prompt*."

The response of student S3 to the interview question: *"Planning prompt, writing steps on how to solve of the first task was helpful, the steps are helped in next tasks."*

The response of student S2 to the interview question: "*Orientation prompt attempted, It helps in writing the steps needed to solve the task."*

The response of student S1 to the interview question: *"Monitoring prompt, questions were helpful but very repetitive. Like one question was repeated throughout a lot, so it was very tiring to answer the same questions again and again."*

S5 understood the evaluation prompt he reported *"I verified the answer, Whether the formulas were right or not, And Did I take any wrong steps. Not using a simulator to evaluate."*

S1 understood the evaluation prompt and reported, *"There was no time for me to go to the stimulator and check my answer. But yeah, I understood the prompt."*

Table 4. Overall functionality of prompts

Prompts	Overall Functionality of Prompt
Orientation	Effective for 4 out of 5 students
Planning	Effective, though ignored by S3
Monitoring	Needs improvement. All students ignored
Evaluation	Effective for some, but terminology (simulator) issues
Reflection	Effective though ignored by 2

Findings from the interview analysis shows that orientation and planning prompts generally worked well in helping students outline their steps for solving Thevenin's theorem, although there were cases of misunderstanding or ignoring. The monitoring prompt did not function as effectively as the others. All students ignored. There is need of improvement. The evaluation prompt helped some students verify their answer, but confusion about using a simulator. Needs Improvement. The reflection prompt worked well, encouraged students to think about their learning. Though two students ignored.

6. LIMITATIONS AND FUTURE PLAN

The limitation of this pilot study was the small sample size. Our next study aims to evaluate the revised MetaGuru version with a larger sample. Based on the insights from this pilot study, the future plan involves refining the prompts and the overall system to address the identified issues. Additionally, a more extensive study will be conducted to analyze the impact of these refined prompts on students' learning outcomes and metacognitive strategies.

7. CONCLUSION

This pilot study aimed to evaluate learners' initial responses to the metacognitive prompt and the functionality of prompts while problem-solving tasks. The findings reveal that the overall experience with MetaGuru was positive, with students, they attempted the prompts effectively. The effectiveness of the prompts varied significantly among participants. The planning and reflection prompts were generally well-received and provided valuable guidance in structuring the problem-solving process. Overall, the interactive and user-friendly nature of MetaGuru, coupled with well-designed planning and reflection prompts, can significantly enhance the learning experience. The prompts influenced the students' problem-solving strategies. However, prompt clarity, relevance, and design improvements are necessary to maximize their effectiveness. Based on the insights from this pilot study, the future plan involves refining the prompts and the overall system to address the identified issues. Additionally, a more extensive study will be conducted to analyze the impact of these refined prompts on students' learning outcomes and metacognitive strategies.

REFERENCES

Azevedo, R. et al. (2022). *Lessons Learned and Future Directions of MetaTutor: Leveraging Multichannel Data to Scaffold Self-Regulated Learning With an Intelligent Tutoring System*. *Frontiers in Psychology*, 13, p. 813632.

Bannert, M. and Reimann, P. (2012). *Supporting self-regulated hypermedia learning through prompts. Instructional Science*, 40, pp. 193-211.

Bannert, M. et al. (2015). *Short- and long-term effects of learners' self-directed metacognitive prompts on navigation behavior and learning performance*. Computers in Human Behavior, 52, pp. 293-306.

Brown, A.L. (1978). *Knowing when, where, and how to remember: A problem of metacognition. In: R. Glaser, ed. Advances in instructional psychology*. Erlbaum, Hillsdale, USA, pp. 77-165.

Efklides, A. (2008). *Metacognition: Defining its facets and levels of functioning in relation to self-regulation and co-regulation.* European Psychologist, 13(4), pp. 277-287.

Engelmann, K. et al. (2021). *Do self-created metacognitive prompts promote short- and long-term effects in computer-based learning environments? Research and Practice in Technology Enhanced Learning*, 16(1), p. 3.

Flavell, J. (1979). *Metacognition and Cognitive Monitoring A New Area of Cognitive—Developmental Inquiry*. American Psychologist, 34(10), p. 906.

Greene, J. et al. (2011). *Self-Regulation of Learning with Computer-Based Learning Environments. New directions for teaching and learning*, [online] Available at: https://doi.org/10.1002/tl449 [Accessed Date].

Guo, L. (2022). *Using metacognitive prompts to enhance self-regulated learning and learning outcomes: A meta-analysis of experimental studies in computer-based learning environments*. Journal of Computer Assisted Learning, 38(3), pp. 811-832.

Güner, P. and Erbay, H.N. (2021). *Metacognitive Skills and Problem-solving. International Journal of Research in Education and Science*, 7(3), pp. 715-734.

Hannafin, M. et al. (1999). *Open learning environments: Foundations, methods, and models. In: C. Reigeluth, ed. Instructional-Design Theories and Models: A New Paradigm of Instructional Theory. Lawrence Erlbaum Associates, Mahwah, USA, pp. 115-140.*

Jonassen, D.H. (1997). *Instructional Design Models for Well-Structured and Ill-Structured Problem-Solving Learning Outcomes*. Educational technology research and development, 45(1), pp. 65-94.

Jumari, N.F. et al. (2022). *Success factors in developing metacognitive skills among engineering students. In: AIP Conference Proceedings. AIP Publishing, 2433(1).*

Kim, Y.R. et al. (2013). *Multiple levels of metacognition and their elicitation through complex problem-solving tasks. The Journal of Mathematical Behavior, 32(3), pp. 377-396.*

Marra, R.M. et al. (2022). *Metacognition and the development of self-directed learning in a problem-based engineering curriculum*. Journal of Engineering Education, 111(1), pp. 137-161.

Mayer, C.W. et al. (2023). *Analysing domain-specific problem-solving processes within authentic computer-based learning and training environments by using eye-tracking: a scoping review*. Empirical Research in Vocational Education and Training, 15(1), p. 2.

Murata, A. et al. (2013). *Role of metacognition in basic electric circuit problem solving process*. In: HCI International 2013-Posters' Extended Abstracts: International Conference, HCI International 2013, Las Vegas, NV, USA, July 21-26, 2013, Proceedings, Part I 15. Springer Berlin Heidelberg, Berlin, Germany, pp. 442-446.

Niebler, C. (2023). *Overcome learning obstacles in circuit network analysis with flowcharts*. In: 2023 32nd Annual Conference of the European Association for Education in Electrical and Information Engineering (EAEEIE). IEEE, pp. 1-6.

Pieger, E. and Bannert, M. (2018). *Differential Effects of learners' self-directed metacognitive prompts. Computers in Human Behavior*, 86, pp. 165-173.

Schraw, G. and Dennison, R.S. (1994). *Assessing metacognitive awareness*. Contemporary educational psychology, 19(4), pp. 460-475.

Schraw, G. and Moshman, D. (1995). *Metacognitive theories. Educational psychology review*, 7, pp. 351-371.

Sun, L. et al. (2024). Review Flow: *Intelligent Scaffolding to Support Academic Peer Reviewing*. In: Proceedings of the 29th International Conference on Intelligent User Interfaces. pp. 120-137.

Van Der Graaf, J. et al. (2021). *Do Instrumentation Tools Capture SelfRegulated Learning?* In: LAK21: 11th International Learning Analytics and Knowledge Conference.

Wang, T. et al. (2023). *Computer-based scaffoldings influence learners' metacognitive monitoring and problem-solving efficiency in an intelligent tutoring system*. Journal of Computer Assisted Learning, 39(5), pp. 1652-1665.

Zhang, Q. and Lockee, B. (2022). *Designing a Framework to Facilitate Metacognitive Strategy Development in Computer-Mediated Problem-Solving Instruction*. Journal of Formative Design in Learning, 6, pp. 127-143.

Zheng, J. et al. (2023). *Supporting self-regulated learning in clinical problem-solving with a computer-based learning environment: the effectiveness of scaffolds*. Metacognition and Learning, 18(3), pp. 693-709.