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Enhancing self-regulated learning and learning experience in generative AI environments: The critical role of metacognitive support

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The rapid development of generative artificial intelligence (GenAI) has brought opportunities and new challenges to higher education. Students need a high level of self-regulated learning to adapt to this change. However, it is difficult for students to persist in self-regulation without guidance. Metacognitive support has a significant advantage in enhancing self-regulated learning, but fewer studies have explored the effects of its role in GenAI environments. The purpose of this study was to investigate the impacts of metacognitive support on college students' self-regulated learning and learning experiences in a GenAI environment. A quasi-experiment was designed in which 68 college students were divided into two groups. The experimental group ($N=35$) received explicit metacognitive support, while the control group ($N=33$) did not receive any metacognitive prompts. The experiment lasted 4 weeks. The study measured students' academic performance, self-regulated learning ability and learning experiences (including cognitive load and technology acceptance). The results indicate that in the GenAI environment, metacognitive support, while not producing significant between-group differences in achievement, enhances students' self-regulated learning abilities particularly in terms of task strategy and self-evaluation, as well as optimizing their learning experience. The study also found that students were at risk of decreasing their level of self-regulated learning if they lacked metacognitive support in the GenAI environment. The conclusion points out that GenAI supports learners to accomplish learning tasks while potentially reducing self-regulated learning effectiveness, and that metacognitive support is key to supporting effective regulation in learners' GenAI environments. This study provides an important theoretical and practical basis for how to better support learners' learning in GenAI environments.

KEYWORDS

GenAI, learning experience, metacognitive support, self-regulated learning

INTRODUCTION

With the development of generative artificial intelligence (GenAI) technology, more and more researchers are trying to introduce chatbots, such as ChatGPT, Spark Desk and Bing Chat into the education field, creating GenAI learning environments to help students learn (Hwang & Chen, 2023; Jin et al., 2023). In this environment, students can get real-time feedback and learning suggestions provided by GenAI, which greatly improves their learning experience (how the learner feels about the learning process, eg, cognitive load) and academic success (eg, learning performance) (Lee et al., 2022). While GenAI tools have immense capabilities, their effectiveness largely depends on how students engage with and use these tools to cultivate and enhance their learning abilities (Sun & Zhou, 2024). It brings more convenience to students' independent learning. But they also place higher demands on learners' ability to self-regulate their learning. Despite the fact that GenAI can quickly answer students' questions, there is a growing concern that it may leave students with a lack of reflection, reducing their deep learning and creativity (Habib et al., 2024).

The core of effective learning is self-regulated learning (SRL). SRL refers to students' achievement of learning goals by analysing task objectives, planning, monitoring progress, adapting strategies, self-reflection and assessment (Pintrich, 2004; Zimmerman, 2002). SRL is a predictive variable in students' academic success (Khiat, 2022). In the GenAI environment, the importance of SRL is more prominent because students are given greater autonomy and can complete various tasks without teacher guidance (Chiu, 2024). This increased autonomy also brings challenges. Without sufficient guidance, students may lose their ability to think and self-regulate in this instant intelligent feedback, relying on artificial intelligence (AI) and becoming recipients of information rather than actively participating in learning and judging the received feedback (Aleven et al., 2016). This situation often worsens further within the GenAI environment.

To address the above challenges, introducing metacognitive support into the GenAI environment is a promising solution. Metacognition, the awareness and regulation of one's cognitive processes, has long been closely associated with improving SRL and academic success (Greene, 2021; Hooshyar et al., 2020; Schuster et al., 2020). In GenAI environments, where learners encounter large amounts of information, metacognitive support can help students process the information for effective learning (Urban et al., 2024). Metacognitive support (eg, prompts or scaffolding) can encourage students to engage in self-reflection, self-evaluation and improve learning performance. Researchers have found that metacognitive support significantly affects optimizing students' SRL, particularly in enhancing self-reflection and higher-order thinking (Pedrosa et al., 2021; Zohar & Ben-Ari, 2022). Moreover, metacognitive support can effectively contribute to academic success (McClellan et al., 2024).

Practitioner notes

What is already known about this topic

- SRL is vital for effective learning in digital environments.
- Generative AI tools, like ChatGPT, can enhance learning but require support.
- Learners often struggle to apply SRL strategies without guidance.

What this paper adds

- Metacognitive support improves SRL in Generative AI environments.
- It reduces cognitive load and increases the perceived usefulness of AI tools.
- Structured support leads to better academic outcomes.

Implications for practice and/or policy

- Teachers should integrate metacognitive support when using AI tools.
- Teacher training should focus on SRL strategies in tech-rich settings.
- Policies should promote ethical and effective AI use in education.

However, current research on metacognitive support has mainly considered traditional digital education platforms, such as online courses or intelligent tutor systems (Guo, 2022). Few studies have designed metacognitive support in GenAI-supported learning environments and explored its role. How students utilize metacognitive support in such environments and whether it affects students' academic success, SRL and learning experience is not clear. These gaps have resulted in GenAI being unable to be used to its full advantage in education to help students learn.

To address the gap, this study aims to investigate whether metacognitive support can improve academic success and SRL abilities in GenAI environments, and explore its impacts on learning experiences, including cognitive load and technology acceptance. The research questions are as follows:

Q1: Can metacognitive support enhance students' academic success in the GenAI environment?
Q2: Can metacognitive support improve students' SRL in the GenAI environment?
Q3: Can metacognitive support optimize students' learning experience in a GenAI environment?

LITERATURE REVIEW

Generative AI in education

The rapid development of GenAI has opened up new opportunities in education (Dwivedi et al., 2023). For example, ChatGPT and Bing Chat are able to generate contextualized and fluent responses instantly and have been integrated into various aspects of education (Chiu et al., 2023). This real-time, personalized feedback and support have changed teaching, evaluation, and students' learning experiences and habits (Baidoo-anu & Ansah, 2023; Rudolph et al., 2023). For example, ChatGPT can help students simplify complex tasks, reduce cognitive load or assist them in understanding unfamiliar concepts (Chiu, 2023). Learning performance and learning experience in AI environments are very important, as they are key factors for academic success and long-term retention of knowledge. These AI tools promote effective learning and empower learners by fostering more engaging and adaptive learning environments. These benefits help students achieve academic success and improve their learning experience.

The widespread application of GenAI in education also brings some risks. During the interaction between students and GenAI, they may develop a dependency on this instant response, no longer actively learning but passively accepting it, which reduces their critical thinking ability (Chan, 2023; Warschauer et al., 2023). Some studies have found that students, when confronted with a ChatGPT response, subconsciously follow its suggestions without thorough analysis and judgement, which reduces students' ownership of their learning (Chan & Lee, 2023; Horton, 2023).

However, GenAI is a tool, and whether it enhances learning or hinders students' skill development depends on how students interact with it (Kasneci et al., 2023; Yang et al., 2022). Therefore, students need to possess high SRL abilities to properly handle content generated by AI (Kong & Yang, 2024) rather than constraining the development of their abilities (Chiu, 2024). However, instantly generated answers can be a temptation for students, and how to get students to resist the temptation to strengthen their SRL is a current challenge that must be faced (Guan et al., 2025). Therefore, researchers need to consider how to cultivate students' SRL abilities to enhance their academic success and learning experience in the GenAI environment.

Self-regulated learning in digital learning environments

SRL is the process by which students set goals and plans for themselves, control and regulate their learning, and accomplish learning tasks (Zimmerman, 1989). To understand SRL, researchers have proposed different theoretical models. These models agree that SRL is a cyclical dynamic process consisting of planning, execution and assessment. In other words, SRL refers to the process in which learners, driven by learning tasks, spontaneously mobilize their own elements of metacognition, motivation and behaviour to plan, monitor, assess and reflect to select and use appropriate learning strategies to complete learning tasks. Researchers showed the critical impact of SRL ability on academic success (Broadbent & Poon, 2015; Ma & She, 2024). Moreover, learners with high SRL ability have good metacognitive strategies and are able to make full use of external resources during the learning process to learn effectively (Popham et al., 2020), especially in AI-supported online learning environments (Fan et al., 2024). Online learning spaces lack one-on-one guidance provided by teachers; students have more autonomy to manage their learning process (Khalil et al., 2024). That is to say, students' SRL ability is considered a key factor of student success in the digital learning environment (Li et al., 2024).

However, many studies have shown that students find it challenging to engage in SRL in complex digital environments (Khalil, 2022; Yang & Cao, 2018). Learners often encounter challenges in effectively planning, monitoring and adjusting their learning strategies. Researchers are focusing on how to provide support to facilitate learner engagement in SRL. Metacognition is an integral part of the SRL model. Metacognitive support plays an important role in addressing these challenges (van der Graaf et al., 2023). Wong, Baars, He, et al. (2021) explored the effects of prompted and unprompted conditions on SRL and showed that helping students clarify goals and make plans can improve their academic performance. Khiat (2022) proposed the conceptual framework of mobile multimodal learning analytics, and the study found that helping learners manage their learning time could improve their SRL ability. Guo (2022) explored the effects of metacognitive cues on learners' SRL and academic performance and found that metacognitive cues effectively enhanced

SRL and academic performance. These findings suggest that metacognitive support in digital environments is essential for enhancing SRL performance.

The role of metacognitive support

Metacognition is the understanding and use of an individual's cognitive processes, which involves planning, monitoring and evaluating learning under the individual's control (Flavell, 1979). As a central part of competence during learning, it helps students in making their minds about the content, revealing their knowledge gaps and readjusting their learning strategies (Avargil et al., 2018; Ku & Ho, 2010). Metacognition is closely related to SRL; it is an essential mechanism for learners to engage in effective self-regulation (Zimmerman, 2002). Through metacognition, learners can accurately assess the current state of knowledge and monitor the learning process to adjust strategies. Essentially, metacognition supports learners' participation in SRL. Therefore, metacognitive support refers to offering remedies in the form of learning and studying aid that helps in planning, guiding and monitoring the learning process.

Research has shown a close relationship between metacognitive support and SRL (Zhang & Zhang, 2019). It was evidenced in several empirical works that when students' strategies are supplied with metacognitive prompts, their ability to control their learning is expanded greatly (Daumiller & Dresel, 2019; van der Graaf et al., 2023). For example, academic research has shown that students prefer instructional designs that include metacognitive interventions, guiding them to think about the purpose of education or evaluate the success or failure of work. Therefore, metacognitive cues stimulate students' interest in learning and achieve better academic success (Ifenthaler, 2012). Through scaffolding instruction and personalized support, students can fully understand concepts and enhance their SRL abilities.

There are many examples of applying metacognitive support for SRL effectiveness in educational settings. In online learning environments, when students set self-regulatory goals, they are motivated to monitor their progress and reflect on their work, which will improve their SRL (Guethler, 2024; Wong, Baars, de Koning, & Paas, 2021). According to Moos and Bonde (2016), applying metacognitive prompts in a flipped classroom approach can increase student engagement in SRL and improve learning outcomes. Breitwieser et al. (2023) created a mobile application to help students develop SRL skills by facilitating scheduling and sending prompts. In AI learning environments, environmental complexity and dynamics, as well as the abundance of massive resources, make the need for metacognitive support to facilitate SRL even more evident. Although metacognitive help can connect SRL and learning in different environments, possible applications in GenAI environments require further research. Urban et al. (2024) conducted research and found that the GenAI environment reduced learners' perceived task difficulty, calibrated their self-assessment and decreased task effort, which is related to metacognition. However, their study did not specifically explore how to provide metacognitive support in such an environment. Fan et al. (2024) discovered that learners in the GenAI environment exhibited SRL processes related to GenAI tools, but there was a problem of metacognitive laziness. How to provide effective metacognitive support in this context needs further exploration. The impact of metacognitive support on the learning experience in AI environments also deserves further attention.

Given the higher demands on SRL in GenAI environments, such as deeper reflection and firm goals, we need to investigate how to design more targeted metacognitive supports. Whether these metacognitive supports can actually help students better interact with GenAI, improve academic success and their SRL abilities, and enhance their learning experience also needs to be further explored. This study aimed to explore these possibilities by designing effective metacognitive supports to enhance SRL performance and learning experiences in GenAI environments.

METHOD

Participants

A total of 71 sophomores (32 males, 39 females) from a university in China volunteered to participate in this research. The age range of the students was between 19 and 21 years old, with an average age of 19.44 (SD = 0.57). They were all from the same class, majoring in Educational Technology, and had the same academic background. Prior to the commencement of this task, we investigated whether learners had used GenAI tools while collecting basic information about them. Notably, none of them had previously used GenAI tools in classroom tasks. Based on the functionality and embeddability of ChatGPT, this study chose this tool to create an AI environment. The participants in our study used ChatGPT 4.0. Before the experiment, participants were informed that their data would be anonymized for research purposes only and would not affect their course grades. All participants were randomly divided into two groups: 36 students in the experimental group and 35 students in the control group. Because three students did not complete the final test, the final analysis included 35 students (20 females and 15 males) in the experimental group and 33 students (19 females and 14 males) in the control group. The study was approved by the institutional review board.

Research design

Procedure

This study was conducted in a course titled 'Instructional Technology and Media', which aims to develop participants' abilities to integrate various technologies and media resources into instructional design. To ensure participants fully engaged with ChatGPT to complete learning tasks, experienced teachers and researchers collaborated to meticulously design a challenging course assignment focused on interdisciplinary instructional design. This joint effort was aimed at creating an assignment that not only presented an appropriate level of challenge for participants but also effectively incorporated AI to enhance the learning experience. This task required participants to integrate knowledge from multiple disciplines (such as mathematics, information technology and biology) to create a lesson that fosters interdisciplinary application skills and higher-order thinking in K-12 students. All participants were provided with computer equipment capable of interacting with ChatGPT. The study adopted a quasi-experimental design, with the key variable being the presence or absence of metacognitive support. In this study, learners' learning performance and SRL performance before and after the experiment were collected. Additionally, after the experiment, the cognitive load and technology acceptance of the learners were investigated. The procedure is illustrated in Figure 1.

Phase 1 (Lesson 1): This phase investigates participants' initial level, encompassing both their prior knowledge and SRL performance, and completes the pretest. Participants were also trained to use ChatGPT and adapt to completing simple learning tasks with ChatGPT's assistance.

Phase 2 (Lessons 2–4): The formal experiment occurred during this phase, focusing on the impact of metacognitive support on participants' SRL and learning experiences in the

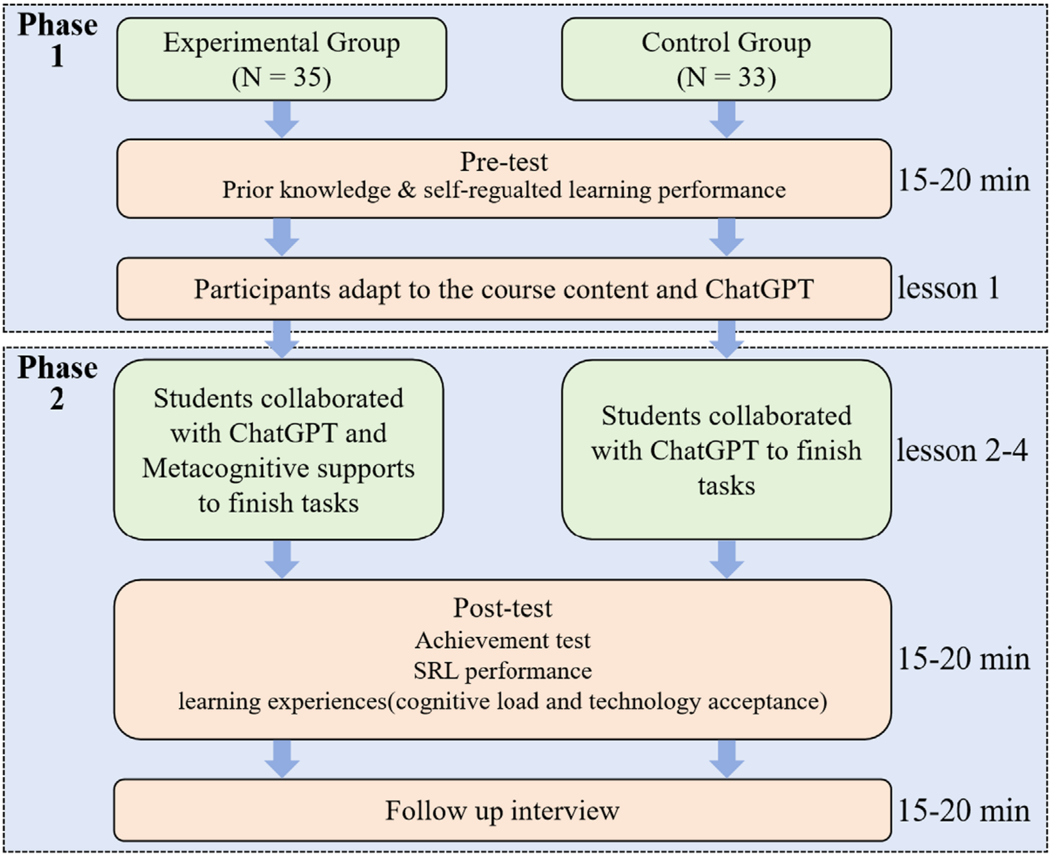

FIGURE 1 Experimental procedure.

GenAI environment. Participants in the experimental group completed the task with the help of metacognitive supports and ChatGPT; participants in the control group completed the task with the help of ChatGPT without any prompts.

Design of metacognition support framework

We designed a metacognitive support framework based on the SRL model and metacognitive theory (see Table 1). SRL is a cyclical and iterative process encompassing planning, execution and reflection. Its sequential and iterative nature provides a clear roadmap for the design of support tools, facilitating learners' active and effective engagement in SRL. Metacognitive theory focuses on an individual's awareness and regulation of their own cognitive processes, emphasizing conscious thinking, planning, monitoring and evaluation to optimize learning efficiency. Consequently, our framework centres on promoting learners' conscious participation in SRL, unfolding around four dimensions: planning, monitoring, assessing and reflecting, and each dimension corresponds to a specific stage of the student's interaction with the GenAI tools. We integrated these stages into the learning task to guide participants to reflect and make judgements at key points in their interactions with the GenAI tools. To enhance the robustness of this approach, the framework draws upon the experiences of previous courses and the expertise of educators, ensuring that the design is

TABLE 1 Metacognitive support framework.

Dimension of prompts	Examples
A. During the task initiation phase (planning)	
Identifying specific learning objectives	What is the main objective of this task?
Planning how to use the GenAI tools	What questions do I need to ask ChatGPT to get useful information?
Clarifying their prior knowledge	What prior knowledge will I rely on when interacting with GenAI?
B. During the task execution phase (monitoring and reflection)	
Assessing the relevance and accuracy of the AI responses	Is this information accurate and relevant to my task?
Summarizing their understanding of the content	Can I explain this concept in my own words?
Adjusting strategies as needed	Do I need to ask more specific questions or improve my methods?
C. Task completion phase (evaluation and reflection)	
Assessing the achievement of initial learning goals	Have I achieved my goals? What else can I improve next time?
Reflecting on GenAI tools' contribution to comprehension	How has ChatGPT helped me understand the topic?
Planning improvements for future learning	What strategies will I use next time to improve my learning outcomes?
[Participants can record their thoughts in the blank space.]	

grounded in established pedagogical practices. Furthermore, this framework is text-based and its effectiveness is tested through experimentation. The aim was to prompt participants to pay attention to the phases of planning, monitoring and evaluating learning tasks when using AI tools, such as ChatGPT. The focus was to promote active student participation, prompting them to clarify their learning goals, critically evaluate the feedback from ChatGPT and adjust their learning strategies accordingly.

Based on a predesigned metacognitive support framework, we integrated SRL into the task phase, which was carried out in conjunction with the task to facilitate learners' engagement in SRL. Teachers prompt learners to use the metacognitive support framework based on learners' progress in completing the K-12 interdisciplinary instructional design and SRL phases. During the task initiation phase (Planning), metacognitive supports prompt participants to develop clear learning objectives and strategies for using GenAI tools that promote critical thinking. These tips ensure participants complete tasks with purpose and planning, minimizing passive engagement when interacting with GenAI tools. During the task execution phase (Monitoring and Reflection), participants receive prompts that remind them to monitor their learning progress and reflect on the accuracy and relevance of GenAI tools' feedback. This support encourages participants to critically evaluate AI-generated content, follow task progress and continually gauge their own understanding. During the task completion phase (Evaluation and Reflection), metacognitive support guides participants in assessing their performance and reflecting on the role of GenAI tools in learning. These supports help participants develop self-reflection and continuous improvement abilities, enabling them to internalize the learning process and identify areas for improvement.

Although the support framework can be implemented digitally, this study provided the experimental group with a paper-based metacognitive support framework to learners by phase for several reasons. Firstly, it can reduce cognitive load. Interacting with GenAI tools already requires significant cognitive resources. Paper-based metacognitive support minimizes screen distractions and allows participants to perceive prompts more easily (Alemdag & Çağiltay, 2018). It also enables participants to write down thoughts at any time, promoting deeper cognition (Mueller & Oppenheimer, 2014). Finally, the format is more flexible. Participants have the flexibility to manage their learning progress and reflect at their own pace without being constrained by the system's prompts. And separating the paper and digital environments ensures that participants' metacognitive activities are not interrupted by instantaneous messages from GenAI tools.

Instruments

In this study, pre- and posttests were used to assess academic performance and SRL ability. A questionnaire was utilized after the experiment to investigate the cognitive load and technology acceptance of the two groups of participants. Semi-structured interviews were also conducted to gather participants' perceptions of GenAI and metacognitive support.

Academic achievement test

The academic achievement tests included theoretical questions and practical design tasks aiming at evaluating to what extent the participants understand and apply the interdisciplinary teaching strategies before and after the intervention. The prior knowledge test and achievement test examined the same competencies and course content. Experienced educators in the field of interdisciplinary teaching design were consulted in the design of the tests to ensure that the tests examined the skills and knowledge covered in the course. Two professors reviewed the content of the prior knowledge test and achievement test to confirm that the scope, structural content and difficulty of the tests were consistent.

The theory section was designed to assess participants' level of understanding of conceptual knowledge of interdisciplinary instructional design, such as core concepts, design principles and instructional strategies. The section was based on multiple-choice and short-answer questions, accounting for 40% of the total score. A sample short-answer question read: 'What principles are needed to implement interdisciplinary thematic instruction?'

The practical design section requires participants to complete a 45-minute interdisciplinary teaching design that combines information technology with other disciplines (eg, Mathematics, Foreign languages and Biology). The goal is to incorporate interdisciplinary teaching into the curriculum, which can cultivate K-12 students' higher-order thinking, problem-solving abilities and data literacy. A complete instructional design must include the following parts: teaching objectives, teaching methods, technology usage and evaluation types. This section accounts for 60% of the total score.

Moreover, all the tests underwent a pilot study to ensure their reliability before the main experiment. The feedback provided on the pilot research was used to improve the questions with the aim of making them more effective, achieving the key objectives of measuring competencies and providing a fair comparison on a pretest and posttest basis.

Questionnaires

This study used Barnard et al.'s (2008) online SRL questionnaire to measure participants' SRL performance. Before using it, we invited experts proficient in English and Chinese from our institution to translate the items into Chinese. In addition, all items were modified according to the characteristics of the GenAI environment in this study, but the dimensions of the measurements remained unchanged. For example, in the goal-setting dimension, the impact of personalized benchmarks and learning progress prediction provided by AI is emphasized. Some examples are shown below: '*I prepare my questions before communicating with GenAI tools such as ChatGPT*'. We invited three experts in the fields of education and AI applications to evaluate and improve the questionnaire, and also invited learners with experience in AI environment learning to provide feedback to ensure the scientific and effective nature of the questionnaire. In this study, Cronbach's alpha value of the questionnaire is 0.93. This instrument has been widely used to measure SRL in various educational settings with established reliability and validity (Xu et al., 2025).

We used the questionnaires to investigate student's learning experiences (including cognitive load and technological acceptance). We used the cognitive load scale validated by Hwang et al. (2013) to measure participants' cognitive load. This scale adopts a 7-point Likert scoring system, which includes mental load (five items) and mental effort (three items). To measure participants' technology acceptance, this study used Park's (2009) Technology Acceptance Scale. This scale also adopts a 7-point Likert scoring system, including perceived ease of use (three items) and perceived usefulness (three items). Based on our research background, we have made adjustments to the items. Examples of some items are as follows: '*GenAI tools would improve my learning performance*'. In this study, Cronbach's alpha values for cognitive load and technical acceptance were 0.82 and 0.90.

Interviews

We conducted interviews with participants in the experimental and control groups (see Appendices Semi-Structure Interview Protocol). The purpose of interviewing the control group was to understand their experience using the GenAI tools and what problems they had. The purpose of interviewing the experimental group was to investigate how their experience of using the GenAI tools with metacognitive support differs, and what problems they encountered. Open-ended questions were used for both control and experimental group interviews. Interviews in both groups lasted 20 minutes.

This study used thematic analysis to analyse the content of the interviews in order to understand learners' perceptions. The quantitative analysis results were further supplemented by identifying and analysing different themes. Two coding meta-analyses independently analysed all interview transcripts. The coding consistency between the two reached 0.83. Coding differences were resolved through face-to-face discussions.

Data analysis

First, we analysed participants' academic performance improvement by comparing pre- and posttest scores using the Wilcoxon signed rank test (response Q1). Before analysing, we conducted a normality test, and the results indicated that the academic achievement scores followed a normal distribution ($p = 0.10 > 0.05$). After the experiment, we used ANCOVA to measure differences in student learning outcomes between the experimental and control groups, with pretest scores as the covariate and posttest scores as the dependent variable. Second, we conducted an independent samples *t*-test to compare the SRL questionnaire scores of the experimental and control groups before and after the test (response Q2). Finally, we used an independent samples *t*-test to examine the differences between the experimental and control groups in terms of cognitive load and technology acceptance, and used thematic analysis to analyse the interview data to gain a deeper understanding of the participants' perceptions (response Q3).

RESULTS

Q1: Can metacognitive support enhance students' academic success in the GenAI environment?

The pretest results indicated mean and standard deviation scores of ($M=76.31$, SD$=4.43$) for the experimental group and ($M=76.36$, SD$=5.57$) for the control group (see Table A1). Additionally, the t-test results ($t=-0.041$, $p=0.968>0.05$) confirmed that there was no significant difference between the groups. These suggested that both groups possessed similar knowledge levels before the experiment began.

Table 2 shows the ANCOVA analysis results. The homogeneity test ($p=0.105>0.05$) confirmed that posttest scores were homogeneous for each group, allowing for the application of ANCOVA. The posttest mean scores were recorded as ($M=86.91$, SD$=5.30$) for the experimental group and ($M=84.97$, SD$=5.34$) for the control group. The improvement in the experimental group's performance was higher than that of the control group, but the effect was not significant ($F=3.939$, $p=0.051$). Additionally, we calculated the effect size for both groups, indicating a medium effect improvement level (Cohen's $d=0.36$).

The above results answer Q1. The findings indicate that while metacognitive support did not lead to a statistically significant enhancement in students' academic success in the GenAI environment, a medium effect size suggests a potential positive impact on learning outcomes that warrants further consideration.

Q2: Can metacognitive support improve students' SRL in the GenAI environment?

We examined the questionnaire data to assess the impact of metacognitive support on SRL abilities in a GenAI environment. An independent samples t-test conducted on the pretest results revealed no significant differences in SRL performance between the experimental and control groups before the experiment (see Table A2). This finding indicated that both groups started with similar levels of SRL.

Table 3 shows the independent samples t-test for SRL posttest results. The significant differences were observed between the two groups in task strategy ($t=2.833$, $p=0.006<0.01$) and self-evaluation ($t=2.172$, $p=0.033<0.05$). However, no significant differences were found in the other four dimensions. We also calculated the effect sizes and found that metacognitive support had a small effect on goal setting (Cohen's $d=0.29$), time management (Cohen's $d=0.29$) and help seeking (Cohen's $d=0.34$).

Figure 2 provides a more intuitive comparison of the differences in SRL performance between the two groups before and after the experiment. The findings showed that the

TABLE 2 Descriptive data and posttest scores ANCOVA analysis.

	Group	*N*	Mean	SD	Adjusted mean	Std. error	*F*	Cohen's *d*
Achievement	EG	35	86.91	5.30	86.93	0.997	3.939 ($p=0.051$)	0.36
	CG	33	84.97	5.34	84.95	0.997		

Abbreviations: CG, control group; EG, experimental group.

TABLE 3 Independent samples *t*-test for self-regulated learning posttest.

	Group	*N*	Mean	SD	*t* (*p*)	Cohen's *d*
Goal setting	EG	35	5.32	0.87	1.168 ($p=0.247$)	0.29
	CG	33	5.08	0.78		
Environmental structure	EG	35	5.46	0.99	0.110 ($p=0.913$)	0.02
	CG	33	5.44	0.87		
Task strategy	EG	35	4.98	0.98	2.833 ($p=0.006$)**	0.69
	CG	33	4.36	0.79		
Time management	EG	35	4.88	1.14	1.181 ($p=0.242$)	0.29
	CG	33	4.57	1.02		
Help seeking	EG	35	5.40	1.02	1.402 ($p=0.166$)	0.34
	CG	33	5.09	0.77		
Self-evaluation	EG	35	5.44	0.88	2.172 ($p=0.033$)*	0.53
	CG	33	4.99	0.82		

Abbreviations: CG, control group; EG, experimental group.
*$p<0.05$; **$p<0.01$.

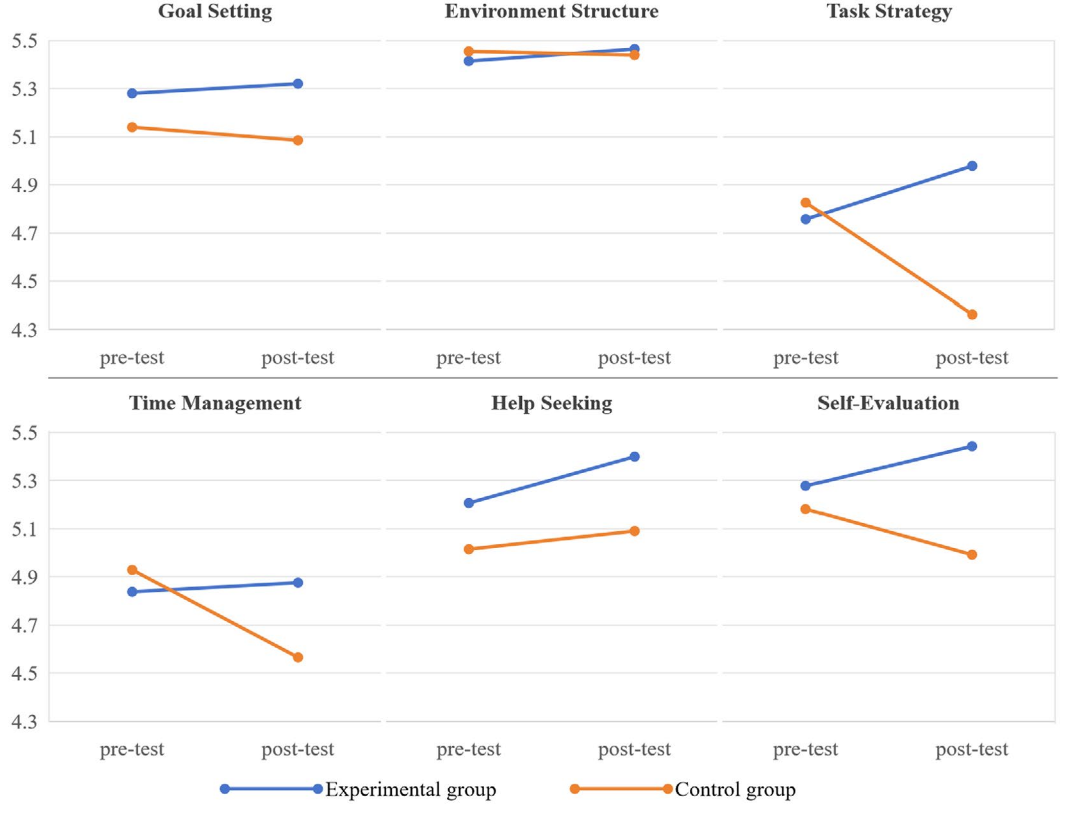

FIGURE 2 Comparison of SRL before and after for the experimental and control groups.

experimental group demonstrated improvement across all six dimensions of SRL, with the most pronounced gains in task strategy, help seeking and self-evaluation. In contrast, the control group exhibited declines in five dimensions of SRL (goal setting, environment

TABLE 4 Independent samples *t*-test of learning experience.

	Group	*N*	Mean	SD	*t* (*p*)	Cohen's *d*
Mental load	EG	35	3.69	1.08	−1.990 ($p=0.052$)	−0.47
	CG	33	4.09	0.52		
Mental efforts	EG	35	3.90	1.12	−1.293 ($p=0.201$)	−0.30
	CG	33	4.18	0.66		
Perceived usefulness	EG	35	5.85	0.91	1.695 ($p=0.095$)	0.42
	CG	33	5.49	0.80		
Perceived ease of use	EG	35	5.67	0.78	−1.714 ($p=0.091$)	−0.41
	CG	33	5.99	0.77		

structure, task strategy, time management and self-evaluation), with the most significant reductions occurring in task strategy, time management and self-evaluation.

The above results answer Q2, metacognitive support significantly improved task strategy and self-evaluation within the GenAI environment, and the overall enhancement across multiple dimensions underscores the potential of metacognitive support to foster SRL among students.

Q3: Can metacognitive support optimize students' learning experience in a GenAI environment?

After the experiment, we investigated participants' mental load, mental efforts, perceived usefulness and perceived ease of use and interviewed some participants. This helped us get insights into their learning experiences in the GenAI environment. We compared these variables between the two groups using independent samples *t*-tests (see Table 4). Although no significant differences were found, the effect size results indicated some noteworthy trends. Specifically, the experimental group had lower mental effort and mental load than the control group, and the difference in mental load was not significant ($p=0.052$). In terms of effect size, the experimental group showed a medium effect (Cohen's $d=-0.47$) in mental load compared with the control group and a small effect (Cohen's $d=-0.30$) in mental effort.

There were also some differences in technology acceptance between the two groups. On the one hand, the perceived usefulness of the GenAI tool was higher in the experimental group than in the control group. Although the *t*-test results showed no significant difference between the two groups ($t=1.695$, $p=0.095$), there was a medium effect difference between the two groups (Cohen's $d=0.42$). This indicates that the experimental group found the GenAI tools more useful in interdisciplinary tasks. On the other hand, the experimental group had lower perceived usefulness of GenAI tools than the control group. Although the *t*-test results indicated that there was no significant difference between the two ($t=-1.714$, $p=0.091$), the effect size results likewise showed a medium effect difference (Cohen's $d=-0.41$). This indicated that the control group participants believe that GenAI tools are easier to use.

This was found by analysing interview data from the control and experimental groups on how to use the GenAI tool with metacognitive support:

First, both groups expressed that GenAI aided them in completing tasks and conveyed a strong interest in the tool. They believed that compared with traditional web search resources, ChatGPT could help them solve problems more quickly. For instance, Student A from the experimental group said, ‘This is my first time using ChatGPT, and it's amazing. I tell it my questions, and it provides many solutions, some of which I hadn't even considered.

However, sometimes I wonder if these answers are really accurate, so I occasionally check other sources to verify'. Student D from the experimental group added, 'ChatGPT is great, but I'm cautious. I noticed that its answers seem to be based on common knowledge it has gathered. I'm thinking about how I can use its responses as a starting point, but then build on it with my own understanding'. In contrast, Student C from the control group stated, 'ChatGPT has been extremely helpful for me in completing interdisciplinary teaching designs. When I share my questions with it, it responds immediately and offers systematic solutions, allowing me to quickly complete tasks. It's truly a fantastic learning assistant, or rather, a homework helper'. Student F from the control group simply said, 'I just use it to get the job done. It gives good answers, and I can finish my assignments faster'. These statements indicate that both groups of participants highly recognized the value of GenAI. However, it is evident that participants in the experimental group exhibited deeper reflection and critical thinking while engaging with ChatGPT's responses.

Next, we analysed the experimental group's experiences with metacognitive support. Participants in this group felt that metacognitive support prompted them to question themselves each time they received a response from ChatGPT, helping them clarify their objectives and assess whether the answers met their requirements. For example, Student D stated, 'Even though ChatGPT's answers often seem impressive, I still remind myself of my goals and think about how to elicit better responses'. Additionally, several participants noted that enhanced metacognition made using ChatGPT more cumbersome, as they needed to reflect repeatedly on how to complete tasks more effectively. For instance, Student O remarked, 'Metacognitive support makes me not fully trust ChatGPT. I try asking in different ways and consider whether its responses genuinely solve my problems. For example, when I asked how to improve teaching evaluations, it provided a comprehensive range of suggestions like classroom quizzes, surveys, and process data collection. However, I believe that teaching evaluation is not just about data collection; it requires clarity of evaluative perspectives. Therefore, I had to reiterate my goals, and only then did it provide a response that I found more acceptable. However, this process took more time'. Overall, while receiving support from ChatGPT, the experimental group participants also recognized the need to clarify their own dominant position and persist in reflection and self-regulation.

The above results answered RQ3; the questionnaire results indicated that metacognitive support had no significant effect on cognitive load and technology acceptance, and the interview results indicated that fostering deeper reflection and critical thinking could be found to optimize the students' learning experience in the GenAI environment.

DISCUSSION

This study investigated the impact of metacognitive support on SRL performance and learning experience in a GenAI environment. Previous studies have mostly focused on the role of metacognitive support in traditional digital learning environments, leaving a gap in understanding its effectiveness in GenAI environments. To address this gap, we provided metacognitive support to the experimental group participants and analysed the results from three aspects: academic achievement, SRL performance and learning experience.

Regarding the first research question, we found that the experimental group showed a greater degree of improvement in academic achievement than the control group. The effect size results indicate that in the GenAI environment, metacognitive support had a medium effect improvement in participants' academic achievement. Some research has shown that participants' metacognitive level is key in helping them achieve academic success (Daumiller & Dresel, 2019; Wong, Baars, de Koning, & Paas, 2021). Unlike Darwin et al. (2024), this study suggests that providing metacognitive support while using the GenAI tool can improve academic performance, but the effect was not significant. Other studies report similar results (Pieger & Bannert, 2018; Zeitlhofer et al., 2023). This may be related to the shorter duration of this experiment, as research indicates that metacognition improvement needs time to positively impact academic performance (Efklides, 2014). Furthermore, using only classroom tests to assess academic performance may also have influenced the results (Ohtani & Hisasaka, 2018).

Although the results did not reach the significant level, the moderate effect size suggests that metacognitive support has potential applications for enhancing learning performance in an AI environment. Our metacognitive support is expected to reduce participant's mindless reliance on real-time generated feedback, thereby improving their academic success.

Regarding the second research question, participants who received metacognitive support had better SRL performance. Findings suggest learners can better control learning with metacognitive cues (van der Graaf et al., 2023), and this study further reveals this is especially true for task strategies and self-evaluation. In addition, participants who received metacognitive support showed a medium effect improvement in SRL's goal setting, time management and help seeking. Metacognitive support has different effects on SRL dimensions in a given setting, consistent with Urban et al. (2024). However, participants without metacognitive support showed a decreasing trend in SRL performance. Studies have shown that in digital or GenAI environments, participants find it difficult to spontaneously use SRL strategies without prompts (Wong & Viberg, 2024). This is consistent with our finding of decreased SRL performance in the control group. The improvement in SRL performance in the experimental group suggests that metacognitive support is the way to address this issue. With metacognitive support, participants are more likely to use the GenAI tools rationally and scientifically, rather than relying on them and gradually losing control of their learning, resulting in a decrease in SRL performance (Chan, 2023).

Furthermore, delving into this case, we concluded that the metacognitive support exerted the most significant influence on task strategies and self-assessment. This is because metacognition helps guide participants to perceive the learning process, adjust learning strategies, and self-reflect and evaluate in a timely manner (Guethler, 2024). In this study, metacognitive support reminded participants to maintain independent thinking when communicating with AI and to view responses to GenAI tools with a critical eye. In this process, participants actively assess the amount of work to be accomplished, set goals within a given time frame, monitor their progress and adjust their learning methods based on the feedback received. Therefore, in GenAI environments where direct instruction from the instructor is limited, metacognitive support allows participants to develop more SRL, which improves learning outcomes (Daumiller & Dresel, 2019).

Regarding the third research question, we investigated the impact of metacognitive support for learners on learning experience in the GenAI environment, from the perspectives of cognitive load and technology acceptance. This gives us a clearer assessment of metacognitive support in the GenAI environment. The control group had a higher cognitive load than the experimental group, but the results were not significant. Because metacognitive support guides participants to engage in more focused assessment and reflection, which may simplify the cognitive process and improve the efficiency of processing GenAI feedback (López-Vargas et al., 2017). It also reduces mental effort in terms of setting goals, identifying instructions, monitoring progress and self-assessment (Chang & Yang, 2023). Therefore, participants can focus more on the task itself in the GenAI environment without being distracted by the real-time information generated by GenAI tools. The study found through interviews that, in contrast to the metacognitive laziness that exists in unsupported situations (Fan et al., 2024), the provision of metacognitive support prompted learners to better utilize metacognition for SRL. Consistent with the findings of Avargil et al. (2018), learners adapted their learning strategies to the solution based on the cue to discover the gap between the solution provided by the AI tool and their individual knowledge, while adapting their learning strategies to the solutions.

The technology acceptance analysis discovered that the perceived usefulness of GenAI tools in the experimental group was greater among participants than in the control group. For the participants in the experimental group, the effectiveness of GenAI tools assisted learning was more prominent, as they could see the benefits of this assistance with metacognitive support. A study has found that metacognitive support positively impacts participants' understanding of how to use information technology more effectively (Avargil et al., 2018). We also noticed that the perceived ease of use of the control group was better than the experimental group. This situation may be due to the fact that, in the experimental group, the metacognitive support guided participants to critically judge the accuracy of the AI-generated content, increasing the difficulty of interacting with ChatGPT. On the contrary, the control group more frequently and actively utilized ChatGPT's feedback and suggestions, believing them to be accurate without thinking twice. This resulted in higher usability ratings. The results of the interviews in this study similarly corroborate this view.

IMPLICATIONS, LIMITATIONS AND CONCLUSION

Implications

Through this study, we have demonstrated from a practical perspective how to utilize metacognitive support to enhance SRL performance in GenAI environments. Based on the findings of this study, guidance can be provided to researchers and educators in the field of GenAI education, both theoretically and practically.

Considering the theoretical implications, this study proposes a metacognitive support framework that can be applied to GenAI environments and integrated into teaching methods. The results of the study suggest that metacognitive support can effectively enhance participants' SRL ability and improve the learning experience to some extent. Through interviews, the study further found that the provision of metacognitive support can promote learners' critical thinking about AI feedback, reduce their direct reliance on machines, and form enhanced cognition through self-assessment and strategy adjustment in the process of receiving metacognitive support. These insights may prompt researchers to delve deeper into the exact nature and theoretical basis of metacognitive support in practical AI environments.

Regarding practical implications, we found that while GenAI tools have the ability to automate learning tasks and improve overall efficiency, their application should promote active learning. Educators should institutionalize metacognitive support within teaching practices, enabling students to critically evaluate their use of GenAI tools. Instructional designers should also prioritize task strategies and self-evaluation, developing AI tools that promote SRL. Such tools can help learners engage more purposefully in SRL while critically analysing GenAI feedback, thereby mitigating the risks and challenges associated with using ChatGPT. Furthermore, during the implementation of GenAI tools, educators should provide regular support and timely assessments of students' needs to offer necessary assistance.

Limitations and future research

This study is subject to several limitations that may affect the generalizability and robustness of the findings. Firstly, the entire experimental process only took several weeks. Although this offered preliminary insights into metacognitive support within GenAI environments, the complete impact of such support may not have materialized in such a short period.

Consequently, the study results might not precisely reflect long-term or more intricate learning situations, thereby restricting their generalizability to extended learning periods. Future research can increase the duration of experiments to better understand long-term impacts. Additionally, we will delve deeper into using AI-powered tools for personalized metacognitive support, seeking to uncover new insights in this area. Research focused on exploring digital implementations of the framework also warrants further inquiry to optimize the use of prompts and further enhance the learning experience. Second, our research sample came from a university in China, and all of them majored in educational technology. In other words, they have similar cultural backgrounds and professional knowledge. This may limit the generalizability of research conclusions in a broader or global educational and cultural context. Future research can include participants from different cultural backgrounds and disciplinary fields, increase the sample size and representativeness, and achieve more generalizable findings. Third, our research mainly relies on questionnaire and interview data. Previous studies have shown that the two can mutually verify and enhance the reliability of the results (Flick, 2022). But it must be acknowledged that using more diverse data is beneficial for analysis. Future research can incorporate data, such as logs and conversations, into analysis to improve the accuracy of evaluations. Finally, while our study provides valuable insights into the role of metacognitive support in a ChatGPT-based learning environment, future research should explore the application of metacognitive support in other Gen AI tools to fully understand its potential and limitations across different platforms.

Conclusion

This study designed a metacognitive support framework suitable for a GenAI environment and analysed their importance for college participants' SRL performance and learning experience through quasi-experiments. The research found that our metacognitive support framework significantly enhancing their SRL abilities and optimizing their learning experience (reducing cognitive load and improving perceived usefulness). However, the study found no significant effect of metacognitive support in improving academic performance, suggesting that although metacognitive support has a potential impact on academic performance, it may take longer to become apparent. The study also found that providing metacognitive support can promote deeper thinking and reduce learners' direct reliance on AI tools. This study effectively reveals the impact of metacognitive support on SRL in AI environments, providing a theoretical framework and practical guidance for promoting SRL in AI environments. The impact of digital forms of metacognitive support on SRL processes can be further explored in depth in the future.

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CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the paper/supplementary material; further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

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APPENDIX

TABLE A1 Independent samples *t*-test for the academic achievement pretest.

	Group	*N*	Mean	SD	*t* (*p*)
Achievement	EG	35	76.31	4.43	−0.041 (*p*=0.968)
	CG	33	76.36	5.57	

Abbreviations: CG, control group; EG, experimental group.

TABLE A2 Independent samples *t*-test for SRL pretest.

SRL dimensions	Group	*N*	Mean	*SD*	*t* (*p*)
Goal setting	EG	35	5.28	0.95	0.625 (*p*=0.534)
	CG	33	5.14	0.90	
Environmental structure	EG	35	5.41	0.94	−0.178 (*p*=0.859)
	CG	33	5.45	0.92	
Task strategy	EG	35	4.76	1.11	−0.283 (*p*=0.778)
	CG	33	4.83	0.87	
Time management	EG	35	4.84	0.99	−0.398 (*p*=0.692)
	CG	33	4.93	0.89	
Help seeking	EG	35	5.21	0.90	0.918 (*p*=0.362)
	CG	33	5.02	0.82	
Self-evaluation	EG	35	5.28	0.90	0.459 (*p*=0.648)
	CG	33	5.18	0.83	

Abbreviations: CG, control group; EG, experimental group.

Semi-Structure Interview Protocol

1. What are your feelings about using GenAI tools?
2. How do GenAI tools assist you in completing your learning tasks?
3. What problems have you encountered when using GenAI tools, such as inaccurate results, misunderstandings or misleading information? And how did you solve these problems?
4. In which aspects does metacognitive support help you the most in completing tasks? [The experimental group ONLY]
5. Do you think that metacognitive support has changed the way you use GenAI tools? If so, in what specific aspects has it changed? [The experimental group ONLY]