NEXUS RESEARCH PUBLISHING

International Journal of Educational Innovation & Pedagogy
Volume X, Number X, Year
P-ISSN: xxxx-xxxx E-ISSN : xxxx-xxxx
Open Access: https://journal.nexuspublishing.co.id/ijeip

Metacognition as the Regulatory Foundation of AI Competency Development in AI-Supported K–12 Learning: A Systematic Review and Thematic Synthesis

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Article Info

Article history:
Received Jun 12th, 20xx
Revised Aug 20th, 20xx
Accepted Aug 26th, 20xx

Keyword:
Artificial intelligence; AI competency; Metacognition; AI-supported learning; K–12 education; Systematic review.

ABSTRACT

Artificial intelligence (AI) is increasingly integrated into K–12 education, creating new learning opportunities while increasing learners' cognitive and regulatory demands. Although metacognition is widely recognized as essential for self-regulated learning, its role in developing AI competency within AI-supported learning remains fragmented. This systematic review synthesized empirical evidence on the role of metacognition in developing AI competency within AI-supported K–12 learning. Following the PRISMA 2020 guidelines, a systematic search of the Scopus database identified 13 empirical studies published between 2024 and 2026. The studies were analyzed using thematic synthesis, including paper-level coding, code consolidation, descriptive theme development, and analytical theme generation. Three analytical themes emerged. First, metacognition enables learners to appropriate AI-supported scaffolding through monitoring, strategy regulation, reflection, and affective regulation. Second, metacognition extends beyond regulating learning toward the emerging regulation of human–AI interaction by supporting evaluation and strategic control of AI-generated information. Third, metacognition supports regulated knowledge construction, providing a foundation for AI competency-related development. However, direct evidence of AI-specific metacognitive regulation remains limited. This review proposes AI-specific metacognitive regulation and metacognitively regulated AI competency development as complementary conceptual propositions, arguing that metacognition is the regulatory foundation through which AI competency develops and is enacted in AI-supported K–12 learning.

INTRODUCTION

The rapid advancement of artificial intelligence (AI), particularly generative AI, is transforming teaching and learning across K–12 education (Guilbault et al., 2025; Jauhiainen & Guerra, 2024; Kim, 2025; Marzano, 2025). AI-powered tools are increasingly being integrated into classrooms to support personalized learning, problem solving, assessment, and knowledge construction (Hönigsberg et al., 2025; Hristova & Donchev, 2025; Ram, 2025; Said et al., 2025). As AI becomes embedded in everyday learning activities, students are expected not only to operate AI tools but also to understand their capabilities and limitations, critically evaluate AI-generated information, and use AI responsibly and ethically (Anjum et al., 2023; Coppin, 2025; Jayaweera, 2025; Matthews & Wang, 2026; Selim & Ali, 2025). Consequently, developing AI competency has emerged as an important educational goal that prepares students to learn effectively and participate responsibly in AI-rich learning environments (Caspari-Sadeghi, 2026; Chee et al., 2024; Chiu et al., 2024; Long & Magerko, 2020). Recent educational frameworks have expanded the concept of AI literacy into AI competency, emphasizing that students require more than conceptual knowledge about AI (Lee & Lee, 2025). AI competency encompasses the ability to understand AI principles, critically evaluate AI-generated outputs, collaborate effectively with AI systems, make informed decisions, and apply AI responsibly in authentic learning contexts (UNESCO, 2024). Rather than treating AI as a technological tool alone, these

P-ISSN: xxxx-xxxx E-ISSN : xxxx-xxxx

frameworks position AI competency as a multidimensional capability integrating cognitive, ethical, and practical dimensions of learning.

Developing AI competency requires students to engage in continuous metacognitive processes while interacting with AI systems (Odugbesan et al., 2026). Students need to plan how AI will be used to accomplish learning goals, monitor the quality and relevance of AI-generated responses, evaluate the credibility and limitations of AI outputs, and reflect on how AI influences their own thinking and decision making (Odugbesan et al., 2026; Wang et al., 2025). These planning, monitoring, evaluation, and reflection processes represent core dimensions of metacognition, suggesting that metacognitive regulation may function as a key mechanism supporting AI competency development in AI-supported learning environments.

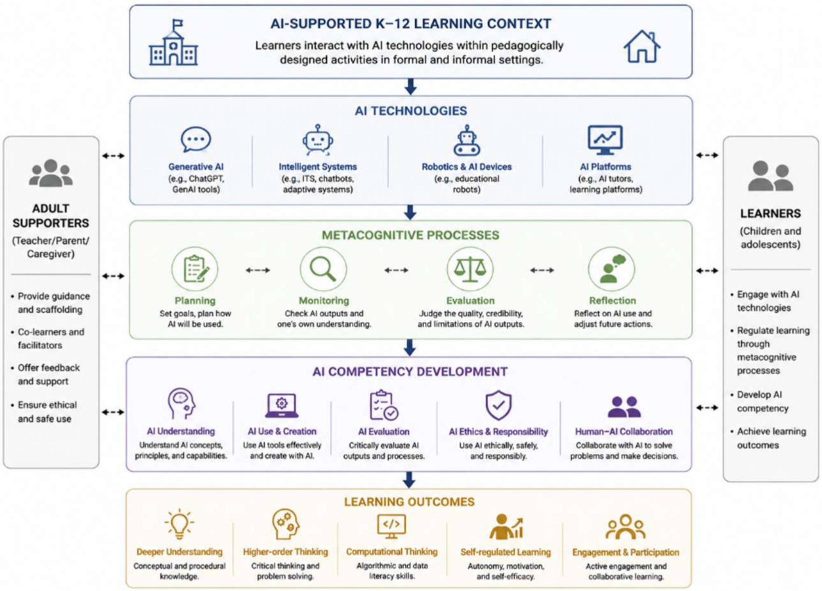

Figure 1 Conseptual Rationale

Although empirical studies have increasingly investigated AI-supported learning in K–12 education, the existing evidence remains fragmented. Previous studies have reported improvements in computational thinking, self-regulated learning, critical thinking, motivation, engagement, and academic achievement through various AI-supported interventions (Hao et al., 2025; Hwang, 2022; Meyrambaykyzy & Maratuly, 2025; Wonganu et al., 2026). However, these studies differ considerably in their educational contexts, AI technologies, and conceptualization of metacognitive processes. More importantly, the literature primarily emphasizes learning outcomes or AI applications rather than explaining how metacognitive processes contribute to the development of AI competency. Consequently, a coherent synthesis of the relationship between metacognition and AI competency within AI-supported K–12 learning is still lacking.

To address this gap, this systematic literature review synthesizes empirical evidence on the role of metacognition in developing AI competency within AI-supported K–12 learning. Following the PRISMA 2020 guidelines, fourteen empirical studies published in Scopus-indexed journals were systematically analyzed using a hybrid deductive–inductive thematic synthesis approach. The review addresses the following research question: By integrating evidence across diverse AI-supported educational contexts, this review proposes a conceptual understanding of how metacognitive processes facilitate AI competency development and identifies directions for future research and educational practice.

RESEARCH METHODS

Research Design

This study employed a systematic literature review (SLR) to synthesize empirical evidence on the role of metacognition in developing AI competency within AI-supported K–12 learning. A systematic literature review was selected because it provides a rigorous and transparent approach for identifying, evaluating, and integrating findings from existing empirical studies while minimizing selection bias and enhancing the reproducibility of the review process. Given the rapidly growing body of research on artificial intelligence in education, an SLR enables the identification of recurring patterns, research trends, and conceptual gaps that may not be evident from individual studies. The review was designed to address the following research question:

RQ1: What AI-supported learning contexts and AI technologies have been investigated in K–12 education?

RQ2: What metacognitive processes are reported to support AI competency development?

RQ3: How do the identified metacognitive processes contribute to AI competency development and student learning outcomes?

The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines, which provide internationally recognized standards for documenting the identification, screening, eligibility assessment, and inclusion of relevant studies. The review process comprised four main stages: literature identification, study screening, eligibility assessment, and qualitative synthesis. To improve the efficiency of the initial screening, Elicit was employed as an AI-assisted evidence discovery tool to filter potentially relevant studies based on the predefined inclusion criteria. However, all eligibility decisions and final study selections were determined through manual full-text assessment by the researchers to ensure methodological rigor and alignment with the review objectives.

To answer the research question, the included studies were analyzed using a hybrid deductive–inductive thematic synthesis approach adapted from Thomas and Harden (2008). Deductive coding was guided by established theoretical frameworks on AI competency and metacognition, whereas inductive coding allowed new concepts and relationships to emerge from the empirical evidence. Through iterative coding and constant comparison across studies, descriptive themes were progressively synthesized into higher-order analytical themes that explain the role of metacognition in AI competency development within AI-supported K–12 learning. The overall methodological workflow is presented in Figure 2, while the subsequent coding and thematic synthesis procedures are described in Sections 2.5–2.7.

Research Design

A systematic literature search was conducted using the Scopus database, which was selected due to its extensive coverage of high-quality, peer-reviewed journals across education, computer science, and interdisciplinary educational technology. Scopus is widely recognized as one of the most comprehensive bibliographic databases for educational research and provides reliable indexing of internationally recognized journals. To ensure the quality and relevance of the retrieved evidence, the search was restricted to journal articles published in Scopus Quartile 1 (Q1), Quartile 2 (Q2), and Quartile 3 (Q3). Only articles published in English were included to facilitate consistency in the review process and ensure the accessibility of internationally disseminated empirical evidence.

The search strategy was developed to align with the objective of this review, which was to synthesize empirical evidence on the role of metacognition in developing AI competency within AI-supported K–12 learning. Accordingly, four conceptual dimensions were identified: Artificial Intelligence, Metacognition, K–12 Education, and Educational Context. For each dimension, multiple synonymous and related terms were identified from previous systematic reviews, international AI education frameworks, and empirical studies. Within each conceptual dimension, keywords were combined using the Boolean operator OR, while the four dimensions were connected using AND to maximize retrieval sensitivity without compromising specificity. The complete search query employed in the Scopus database is presented in Table 1.

Table 1. Systematic Search Query for Studies on The Role Of Metacognition in Developing AI Competency Within AI-Supported K–12 Learning

Search Dimension	Search Query (TITLE–ABS–KEY)
Artificial Intelligence (AI)	("artificial intelligence" OR AI OR "generative AI" OR GenAI OR "large language model*" OR LLM* OR ChatGPT OR "GPT-4" OR "GPT-4o" OR "AI chatbot*" OR "AI tutor*" OR "intelligent tutoring system*" OR "AI robot*" OR robotics OR

Search Dimension	Search Query (TITLE–ABS–KEY)
	"AI literacy" OR "AI competence*" OR "AI competency" OR "AI education" OR "AI-assisted" OR "AI-supported")
Metacognition	(metacognition OR metacognitive* OR "self-regulation" OR "self-regulated learning" OR "self-monitoring" OR planning OR monitoring OR evaluation OR reflection OR "metacognitive strateg*" OR "critical thinking" OR "deep learning" OR "problem solving" OR "self-efficacy")
K–12 Education	("K–12" OR kindergarten OR preschool OR "primary school" OR "elementary school" OR "middle school" OR "junior high school" OR "secondary school" OR "high school" OR "school student*")
Educational Context	(education OR learning OR classroom OR teaching OR instruction OR curriculum OR pedagogy OR "technology-enhanced learning" OR "digital learning")
Exclusion Criteria	NOT ("higher education" OR universit* OR undergraduate* OR postgraduate* OR "college student*" OR "tertiary education" OR "adult education")
Combined Search Strategy	(Artificial Intelligence) AND (Metacognition) AND (K–12 Education) AND (Educational Context) NOT (Exclusion Criteria)

Rather than limiting the search to the term AI competency, broader AI-related terminology was intentionally incorporated. Previous empirical studies frequently describe AI competency using diverse concepts such as AI literacy, AI education, AI-assisted learning, AI-supported learning, intelligent tutoring systems, and generative AI. Similarly, metacognitive processes are often operationalized using constructs such as self-regulated learning, planning, monitoring, evaluation, reflection, and critical thinking. Therefore, the search strategy was designed to capture conceptual diversity while allowing AI competency to emerge as a synthesized analytical construct during the thematic analysis rather than functioning solely as a search keyword. The operationalization of each search concept is summarized in Table 2.

Table 2. Operationalization of Search Concepts

Search Dimension	Purpose in the Review
Artificial Intelligence	To identify studies involving AI technologies or AI-supported learning environments.
Metacognition	To identify studies examining metacognitive regulation and related cognitive processes.
K–12 Education	To limit the review to formal school education.
Educational Context	To ensure the retrieved studies focused on teaching and learning activities.

The literature search was performed using the TITLE–ABS–KEY search field in Scopus to identify studies explicitly addressing the four conceptual dimensions. Following the database search, all retrieved records were exported in RIS format and imported into Elicit, an AI-assisted literature screening platform, to facilitate the preliminary organization and relevance screening of the identified studies. It is important to note that Elicit was employed solely to support the efficiency of the initial screening process. All inclusion and exclusion decisions, as well as the final determination of eligible studies, were conducted through manual full-text assessment by the researchers based on the predefined eligibility criteria. This combined AI-assisted and researcher-led approach enhanced both the transparency and methodological rigor of the study selection process, which is illustrated in the PRISMA flow diagram presented in Figure 2.

Eligibility Criteria

To ensure the relevance, methodological quality, and consistency of the evidence included in this review, explicit inclusion and exclusion criteria were established prior to the screening process. These criteria were developed in alignment with the review objective, which was to synthesize empirical evidence on the role of metacognition in developing AI competency within AI-supported K–12 learning. By defining the eligibility criteria in advance, the review minimized selection bias and ensured that only studies directly relevant to the research objective were included in the thematic synthesis.

Studies were considered eligible if they met the following criteria: (1) published as peer-reviewed journal articles indexed in Scopus Quartile 1 (Q1), Quartile 2 (Q2), or Quartile 3 (Q3); (2) written in English; (3) conducted within formal K–12 educational settings, including kindergarten, primary, elementary, middle, or secondary schools; (4) investigated AI-supported learning, AI-assisted educational technologies, AI education, AI literacy, or related AI-based instructional interventions; (5) examined at least one metacognitive construct or closely related process, such as metacognition, self-regulation, self-regulated learning, planning, monitoring, evaluation, or reflection; (6) reported empirical evidence on student learning and/or AI competency-related outcomes; and (7) employed empirical research designs, including quantitative, qualitative, mixed-methods, experimental, quasi-experimental, or longitudinal studies.

Studies were excluded if they: (1) focused exclusively on higher education, vocational education, teacher education, or adult learning; (2) were conference proceedings, review articles, editorials, book chapters, dissertations, or other non-peer-reviewed publications; (3) primarily addressed AI from a technical or engineering perspective without investigating its educational application; (4) examined AI implementation for administrative, institutional, or teacher-management purposes without focusing on student learning; or (5) lacked sufficient methodological information or full-text availability for comprehensive assessment.

The eligibility criteria were intentionally designed to capture the diversity of AI-supported learning research while maintaining a clear focus on the intersection of artificial intelligence, metacognitive processes, and student learning within K–12 education. Notably, studies were not required to explicitly use the term "AI competency" for inclusion. Instead, studies investigating related constructs—such as AI literacy, AI education, AI-assisted learning, or AI-supported instructional interventions—were considered eligible when they provided empirical evidence relevant to the development of students' AI-related competencies. This broader conceptualization reflects the evolving terminology in the AI education literature and enables AI competency to emerge as a synthesized analytical construct during the thematic analysis rather than serving solely as a predefined search term. The complete inclusion and exclusion criteria are presented in Table 3.

Table 3. Inclusion and Exclusion Criteria

Category	Specific Criteria
Publication Period	Articles published between 2019–2026
Inclusion Criteria	1. Published as peer-reviewed journal articles indexed in Scopus Q1, Q2, or Q3. 2. Conducted within formal K–12 educational settings, including kindergarten, primary, elementary, middle, or secondary schools. 3. Investigated AI-supported learning, AI-assisted educational technologies, AI education, AI literacy, or related AI-based instructional interventions. 4. Examined at least one metacognitive construct or related process (e.g., metacognition, self-regulation, self-regulated learning, planning, monitoring, evaluation, or reflection). 5. Reported empirical evidence on student learning outcomes and/or AI competency-related outcomes. 6. Employed an empirical research design, including quantitative, qualitative, mixed-methods, experimental, quasi-experimental, randomized controlled trials, or longitudinal studies. 7. Full-text article available for review.
Exclusion Criteria	1. Studies conducted exclusively in higher education, teacher education, vocational education, or adult learning contexts. 2. Conference proceedings, review articles, editorials, book chapters, dissertations, theses, or other non-peer-reviewed publications. 3. Studies focusing primarily on technical AI development, algorithm design, or engineering applications without an educational context. 4. Studies examining AI for administrative, institutional, or teacher-management purposes without reporting student learning outcomes. 5. Studies that did not investigate any metacognitive construct or related learning regulation process. 6. Studies lacking sufficient methodological information or with inaccessible full-text versions.

Selection Methods

The study selection process was conducted following the PRISMA 2020 guidelines to ensure a transparent and systematic identification of relevant studies. After applying the predefined search strategy in the Scopus database, all retrieved records were exported in RIS format and imported into Elicit, an AI-assisted literature screening platform. Elicit was employed to facilitate the preliminary organization of the retrieved records and to assist in identifying studies that potentially met the predefined eligibility criteria. However, all screening decisions and final study selections were independently verified through manual assessment by the researchers to ensure methodological rigor and consistency with the review objective.

The screening process consisted of four sequential stages: identification, screening, eligibility assessment, and study inclusion. During the identification stage, 1,000 records were retrieved from the Scopus database. Following AI-assisted relevance screening in Elicit, 32 studies were identified as potentially eligible for full-text assessment. These studies were subsequently evaluated manually against the predefined inclusion and exclusion criteria. Studies were excluded if they did not meet the required educational context, population, research focus, or methodological criteria. Following the full-text eligibility assessment, 14 empirical studies satisfied all inclusion criteria and were retained for the qualitative thematic synthesis. These studies constituted the final evidence base for data extraction, coding, and thematic analysis. The complete study selection process is illustrated in the PRISMA 2020 flow diagram (Figure 2).

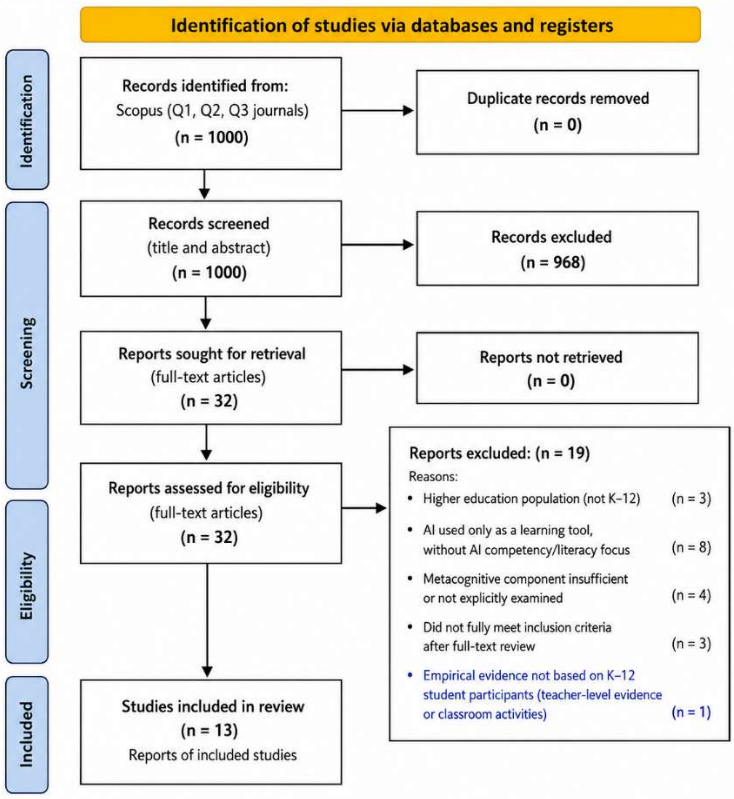

Figure 2 The PRISMA Flow Diagram of The Study.

Development of the Analytical Coding Framework

Following the study selection process, the full texts of the 14 included studies were systematically examined to identify evidence relevant to the review objective. Rather than treating evidence extraction as a separate analytical stage, the identification and organization of relevant information were integrated into the coding process. This approach enabled the researchers to iteratively organize empirical evidence while simultaneously developing analytical categories that addressed the review question concerning the role of metacognition in developing AI competency within AI-supported K–12 learning.

The analytical coding framework was developed using a theory-informed hybrid deductive–inductive coding approach (Fereday & Muir-Cochrane, 2006). The initial coding structure was established deductively based on the conceptual foundations underpinning this review, including theories and frameworks related to metacognition, AI competency, and AI-supported learning. These predefined concepts provided an initial analytical lens for organizing the evidence and ensured alignment between the coding process and the review objective. Simultaneously, inductive coding was employed to identify concepts, relationships, and emerging patterns that were not explicitly represented within the initial framework but consistently appeared across the included studies. This iterative process allowed the analytical framework to remain theoretically grounded while remaining sufficiently flexible to accommodate the evolving nature of AI-supported educational research.

Each included study was examined line by line to identify meaningful units of evidence related to the review objective. Relevant information describing AI-supported learning contexts, AI technologies, metacognitive processes, AI competency-related concepts, pedagogical characteristics, learning outcomes, and key empirical findings was assigned initial codes. Similar codes were continuously compared, refined, merged, and reorganized throughout the analytical process until conceptual consistency was achieved across all included studies. This iterative refinement reflects the principle of constant comparison commonly adopted in qualitative evidence synthesis and enhanced the coherence of the resulting analytical framework.

The final analytical framework consisted of two complementary levels of coding. Descriptive codes captured the methodological and contextual characteristics of the included studies, such as educational level, AI technologies, instructional approaches, and research design. Analytical codes, in contrast, represented higher-order concepts explaining how metacognitive processes contributed to AI competency development within AI-supported learning environments. These analytical codes subsequently served as the foundation for generating descriptive and analytical themes through the thematic synthesis procedure proposed by (Thomas & Harden, 2008). The resulting coding framework is presented in Table 4.

Table 4. Analytical Coding Framework

Analytical Domain	Representative Codes	Purpose in the Analysis
AI-supported Learning	AI chatbot, intelligent tutoring system, AI robot, AI-assisted learning, AI classroom	Identify AI-supported learning contexts
Metacognitive Processes	Planning, monitoring, evaluation, reflection, self-regulation, self-assessment	Identify metacognitive mechanisms reported across studies
AI Competency-related Concepts	AI literacy, AI competency, responsible AI use, AI understanding, prompt design, AI evaluation	Identify dimensions of AI competency emerging from the literature
Learning Outcomes	Computational thinking, critical thinking, deep learning, engagement, motivation, self-efficacy, academic achievement	Compare reported educational outcomes
Pedagogical Characteristics	Project-based learning, collaborative learning, scaffolding, inquiry-based learning, direct instruction	Examine instructional approaches supporting AI competency

RESULTS AND DISCUSSION

Characteristics of the Included Studies

The The final synthesis included 13 empirical studies published between 2024 and 2026 that examined metacognitive processes within AI-supported K–12 learning contexts. The studies represented diverse educational levels, ranging from kindergarten (Gu & Yan, 2025), primary education (Qiu & Ishak, 2025; Rivero Galeano et al., 2020; G. Zhao et al., 2025; Y. Zhao, 2026), and junior secondary education(Wang et al., 2025) (Wang et al., 2025; Ye et al., 2025; Zhang et al., 2026) to senior secondary school contexts (Makransky et al., 2025; Okada et al., 2025; Serik et al., 2026; Shi et al., 2025; Wan et al., 2026). Geographically, the evidence base was concentrated predominantly in China and other Asian educational contexts (Dong et al., 2025; Qiu & Ishak, 2025; Shi et al., 2025; Wan et al., 2026; Zhang et al., 2026; G. Zhao et al., 2025), although several studies broadened the geographical representation through research conducted in Hong Kong (Su et al., 2024), Kazakhstan (Serik et al., 2026), Denmark (Makransky et al., 2025), cross-national contexts involving the United Kingdom, Greece, and Brazil (Okada et al., 2025).

The included studies employed heterogeneous methodological approaches. Experimental and quasi-experimental designs were prominent across the evidence base, including randomized interventions, controlled pretest–posttest comparisons, and multi-group experimental studies (Dong et al., 2025; Makransky et al., 2025; Su et al., 2024; Ye et al., 2025; Zhang et al., 2026; G. Zhao et al., 2025). Other methodological approaches included longitudinal quantitative research (Shi et al., 2025), cross-national longitudinal mixed-methods research (Okada et al., 2025), structural equation modelling (Qiu & Ishak, 2025), psychometric scale development and validation (Zhang et al., 2026), quasi-experimental AI curriculum research (Wan et al., 2026), and school-based STEM and AI project investigations (Serik et al., 2026). Sample sizes varied considerably, ranging from small classroom-based studies involving approximately 60 participants (Dong et al., 2025; Wan et al., 2026)to large-scale investigations involving more than 2,000 students across multiple samples (Zhang et al., 2026). This methodological diversity enabled the synthesis to examine metacognitive processes across controlled interventions, longitudinal learning trajectories, authentic project-based environments, and AI-integrated classroom settings.

The educational role of AI also varied substantially across the included studies. AI technologies functioned as adaptive learning environments and intelligent tutoring systems (Qiu & Ishak, 2025; Zhang et al., 2026), AI robots supporting early learning activities (Su et al., 2024), generative AI chatbots supporting learning and sense-making (Makransky et al., 2025; Ye et al., 2025; G. Zhao et al., 2025), AI-based interactive scaffolding systems (Dong et al., 2025) and AI-supported mentoring environments (Y. Zhao, 2026). Other studies examined AI as curricular content or as part of authentic AI-related learning activities, including AI curricula (Wan et al., 2026), open-schooling projects integrating AI competencies and sustainability education (Okada et al., 2025), and robotics, machine-learning applications, and school-based STEM projects (Serik et al., 2026). Accordingly, the evidence base encompassed both learning with AI and learning about AI, providing different contexts for examining the role of metacognitive processes in students' engagement with artificial intelligence.

Metacognitive constructs and related regulatory processes were operationalized heterogeneously across the studies. Self-regulation and self-regulated learning were explicitly examined in several studies(Shi et al., 2025; Su et al., 2024; Wan et al., 2026; Y. Zhao, 2026), while other studies focused on goal setting and self-evaluation (Dong et al., 2025), self-explanation and generative sense-making (Makransky et al., 2025), critical thinking and regulation of cognitive engagement (G. Zhao et al., 2025), knowledge organization and self-monitoring (Wan et al., 2026), and reflective problem-solving and strategy regulation within programming and project-based environments (Serik et al., 2026; Ye et al., 2025). Affective and motivational dimensions of learner regulation were also represented through constructs such as self-efficacy, motivation, engagement, persistence, enjoyment, and affective regulation (Dong et al., 2025; Qiu & Ishak, 2025; Zhang et al., 2026; Y. Zhao, 2026). These variations indicate considerable conceptual diversity in how metacognition and metacognition-related processes have been represented within AI-supported K–12 learning research.

A similar heterogeneity was observed in the operationalization of AI competency-related outcomes. Only a subset of the included studies explicitly investigated AI competencies, AI literacy, or AI curriculum-related knowledge (Okada et al., 2025; Serik et al., 2026; Wan et al., 2026), whereas other studies examined computational thinking (Su et al., 2024; Ye et al., 2025), programming performance (Ye et al., 2025), deep learning and self-efficacy (Qiu & Ishak, 2025), conceptual knowledge and generative sense-making (Makransky et al., 2025), language learning performance and learner regulation (Dong et al., 2025), engagement and self-regulated learning (Shi et al., 2025; Zhang et al., 2026; Y. Zhao, 2026), and affective development in AI-integrated classrooms (Zhang et al., 2026). Consequently, the evidence base provided broader and more consistent empirical evidence concerning the role of metacognition in regulating learning within AI-supported environments than direct evidence linking metacognitive processes to the development of explicitly measured AI competency. The characteristics of the included studies are summarized in Table 5.

Table 5. Characteristics of The Studies Included in The Thematic Synthesis

ID	Study	Country / Educational Context	Participants	AI Context / Technology	Research Design	Metacognitive Focus	Main Outcomes
P1	Su et al. (2024)	Hong Kong; kindergarten	90 children aged 5–6 years	AI robots; cooperative play and direct instruction	Randomized three-group intervention study	Self-regulation	Computational thinking, sequencing, self-regulation, theory of mind
P2	Zhao et al. (2025)	China; Grade 6	126 students in final analysis	GenAI-supported learning using ERNIE Bot	Three-group quasi-experimental study	Critical thinking and regulation of cognitive reliance	In-depth learning, knowledge transfer, critical thinking
P3	Ye et al. (2025)	China; Grade 7	111 students	GPT-4-based GenAI chatbot combined with mind mapping	Three-group quasi-experimental study	Critical thinking, problem-solving, and metacognitive regulation	Programming performance, computational thinking, self-efficacy, critical thinking, problem-solving
P4	Li et al. (2026)	China; primary education	383 students	AI self-study rooms, intelligent tutoring, adaptive pathways, and AI feedback	Quasi-experimental pretest–posttest study	Self-regulation / self-regulated learning	Motivation, self-regulation, enjoyment, engagement
P5	Okada et al. (2025)	UK, Greece, and Brazil; secondary education	330 students	Open schooling, AI-supported STEM and sustainability projects	Cross-national longitudinal mixed-methods study	Reflection, self-assessment, and socially mediated learning	AI competencies, transversal skills, problem-solving, scientific citizenship, STEM for sustainability
P7	Shi et al. (2025)	China; secondary EFL education	334 students	AI-assisted EFL learning environments	Longitudinal quantitative study using latent growth curve modelling	Self-regulated learning	SRL trajectories and task engagement
P8	Qiu and Ishak (2025)	China; primary education	387 students	AI-assisted mathematics learning	Quantitative correlational study using SEM	Learning self-efficacy and regulation-related processes	Deep learning, self-efficacy, mathematics performance

ID	Study	Country / Educational Context	Participants	AI Context / Technology	Research Design	Metacognitive Focus	Main Outcomes
P9	Wan et al. (2026)*	China; middle/secondary education	60 students	AI curriculum with activity-enhanced scaffolding and knowledge representation	Quasi-experimental study	Self-monitoring, self-assessment, and knowledge organization	AI knowledge acquisition, concept mapping, learning attitudes, higher-order thinking
P10	Zhang et al. (2026)	China; Grades 7–9	2,083 students across two samples	AI-integrated classrooms, intelligent tutoring systems, and AI agents	Mixed-methods scale-development and psychometric validation study	Affective regulation	Affective development in AI-integrated classrooms
P11	Makransky et al. (2025), Study 2	Denmark; high school	234 students	ChatTutor and standard GenAI systems	Between-subjects experimental study	Self-explanation and generative sense-making	Conceptual knowledge, self-efficacy, trust, enjoyment, behavioral intentions
P12	Serik et al. (2026), K–12 component	Kazakhstan; senior secondary education	96 students	Robotics, machine learning, YOLOv8, LSTM, and school-based STEM projects	Embedded multiple-case study with quasi-experimental component	Error interpretation, monitoring, strategy revision, and reflective problem-solving	AI literacy, computational thinking, engineering thinking, digital competencies
P13	Wang et al. (2025)	China; Grade 7	60 students aged 12–13	AI-based interactive scaffolding in informal digital English learning	Two-group quasi-experimental study	Goal setting and self-evaluation	Speaking performance, goal setting, self-evaluation, motivation
P14	Zhao (2026)	China; socioeconomically disadvantaged K–12 learners	Exact analytic sample pending final verification	GPT-4-supported e-mentoring	Cluster randomized controlled trial with follow-up	Self-regulated learning	SRL, academic performance, engagement, persistence

Descriptive Synthesis of Metacognitive Processes in AI-Supported Learning

The thematic synthesis identified four descriptive themes representing recurrent patterns of metacognitive processes across the 13 included studies. These themes concerned (1) the potential role of AI-supported learning environments as scaffolds for metacognitive regulation, (2) learners' regulation of cognitive, strategic, and affective processes during AI-supported learning, (3) metacognitive evaluation and controlled interaction with AI, and (4) reflection and regulated knowledge construction. The themes differed in the breadth and directness of their empirical support. Learner regulation and metacognitive monitoring were represented most consistently across the evidence base, whereas direct evidence concerning learners' critical control of AI interaction was comparatively limited.

AI-Supported Learning Environments as Potential Scaffolds for Metacognitive Regulation

Across the included studies, AI-supported learning environments were frequently designed to provide external structures that could support learners' regulation of learning. These structures included adaptive learning pathways, intelligent feedback, conversational guidance, visual knowledge representation, interactive scaffolding, and personalized mentoring. AI self-study environments provided adaptive learning pathways and feedback alongside opportunities for students to regulate their learning behaviors (Li et al., 2026), while AI-supported curricula combined structured learning activities with knowledge representation to support self-monitoring, self-assessment, and organization of conceptual knowledge (Wan et al., 2026). Similarly, interactive AI scaffolding provided feedback that was associated with students' goal setting and self-evaluation (Wang et al., 2025), whereas GPT-4-supported e-mentoring embedded AI assistance within activities involving planning, monitoring, strategy adjustment, and reflection (G. Zhao et al., 2025).

Generative AI systems also provided dialogic and representational support for metacognitive activity. The combination of a GenAI chatbot and mind mapping created opportunities for learners to externalize thinking, organize knowledge, and engage in reflective problem-solving (Ye et al., 2025). ChatTutor prompted learners to generate explanations and actively process learning content rather than merely receive AI-generated information (Makransky et al., 2025). In project-based contexts, structured AI and STEM activities supported iterative problem solving, error interpretation, and strategy revision (Serik et al., 2026), while open-schooling projects provided socially mediated opportunities for reflection and self-assessment (Okada et al., 2025).

However, the evidence did not indicate that the availability of AI scaffolding automatically resulted in metacognitive development. The studies varied in whether metacognitive regulation was explicitly measured, embedded within the instructional design, or inferred from students' learning activities. Moreover, associational evidence concerning AI-assisted learning, self-efficacy, and deep learning should not be interpreted as demonstrating that AI support caused the development of metacognitive regulation (Qiu & Ishak, 2025). Overall, the studies indicated that AI-supported environments can provide external conditions and learning structures within which metacognitive activity may be elicited or supported, although evidence concerning the internalization and transfer of such regulation remained limited.

Cognitive, Strategic, and Affective Regulation During AI-Supported Learning

The most consistently represented descriptive pattern concerned learners' regulation of their own learning processes. Across the included studies, students engaged in monitoring understanding and progress, setting goals, adjusting learning strategies, regulating effort and engagement, and managing affective and motivational states. Self-regulation and self-regulated learning were explicitly investigated in studies involving AI robots, AI self-study environments, AI-assisted language learning, and AI-supported mentoring (Li et al., 2026; Shi et al., 2025; Su et al., 2024; Y. Zhao, 2026). Other studies identified related processes through goal setting, self-evaluation, reflective problem-solving, and strategy adjustment (Serik et al., 2026; Wang et al., 2025; Ye et al., 2025).

Metacognitive monitoring was particularly prominent across the evidence base. Learners monitored their understanding, progress, performance, and emerging difficulties while participating in AI-supported activities. Monitoring was represented through self-assessment and knowledge organization in AI curricula (Wan et al., 2026), reflective and strategic problem-solving in programming environments (Ye et al., 2025), self-explanation during GenAI-supported learning (Makransky et al., 2025), and error interpretation and iterative strategy revision in AI- and robotics-based projects (Serik et al., 2026). These findings indicate that monitoring functioned as a recurring regulatory process across diverse AI technologies, subjects, and educational levels.

The evidence base also demonstrated that metacognitive regulation was intertwined with affective and motivational processes. AI-supported learning contexts involved regulation-related outcomes such as motivation, engagement, enjoyment, self-efficacy, and persistence (Li et al., 2026; Qiu & Ishak, 2025; Wang et al., 2025; Y. Zhao, 2026). Affective regulation was also explicitly conceptualized and measured within AI-integrated classroom environments (Zhang et al., 2026). However, because this study focused on construct development and psychometric validation, its findings support the identification of affective regulation as a relevant dimension of AI-supported learning rather than demonstrating that AI integration caused affective development. Taken together, these studies showed that metacognitive activity in AI-supported learning extended beyond cognitive monitoring alone. Learners' regulation involved interconnected cognitive, strategic, behavioral, motivational, and affective processes that supported sustained and deliberate engagement with AI-supported learning activities.

Reflection and Regulated Knowledge Construction

The fourth descriptive theme concerned the role of reflection and metacognitive regulation in learners' construction and reorganization of knowledge. Across multiple studies, learners were not positioned merely as recipients of AI-generated information. Instead, AI-supported activities involved self-explanation, reflection, knowledge organization, conceptual mapping, error interpretation, and strategy revision.

Generative learning activities prompted students to explain their understanding and actively construct meaning from AI-supported learning materials (Makransky et al., 2025). The integration of GenAI chatbots with mind mapping supported the organization and representation of knowledge during programming learning (Ye et al., 2025), while activity-enhanced scaffolding and knowledge representation supported students' conceptual organization and higher-order thinking within an AI curriculum (Wan et al., 2026). Project-based learning environments further involved iterative problem solving, reflection on errors, and revision of technical strategies (Serik et al., 2026).

Reflective processes were also represented within open-schooling and AI-supported mentoring contexts. Students engaged in reflection, self-assessment, and socially situated learning during AI-supported sustainability projects (Okada et al., 2025), whereas personalized e-mentoring incorporated planning, monitoring, adjustment, and reflection within self-regulated learning cycles (Y. Zhao, 2026). Other studies connected monitoring and strategic regulation with broader outcomes such as computational thinking, critical thinking, engagement, and learning performance (Li et al., 2026; Shi et al., 2025; Su et al., 2024; G. Zhao et al., 2025).

Collectively, the studies indicated that reflection and metacognitive regulation were recurrently associated with learners' active organization, interpretation, and reconstruction of knowledge within AI-supported environments. However, only a subset of studies explicitly linked these processes to AI competency, AI literacy, or AI-related knowledge outcomes (Okada et al., 2025; Serik et al., 2026; Wan et al., 2026). Therefore, the evidence was stronger for the role of metacognition in supporting regulated knowledge construction than for demonstrating a direct relationship between metacognitive processes and the development of explicitly measured AI competency.

Analytical Themes Explaining the Role of Metacognition in AI Competency Development

Building on the descriptive synthesis, three analytical themes were developed to explain the role of metacognition in AI-supported K–12 learning. These themes represent higher-order interpretations generated by comparing recurrent metacognitive processes across the included studies. The evidence was strongest for metacognition as a mechanism regulating learners' engagement with AI-supported environments, whereas critical control of human–AI interaction and direct AI competency development received comparatively less empirical support.

Metacognition Enables Learners to Appropriate AI-Supported Scaffolding

The first analytical theme indicates that metacognition enables learners to engage actively with the affordances provided by AI-supported environments. Across different technologies and learning contexts, goal setting, monitoring, strategy adjustment, and affective–motivational regulation supported learners in directing their engagement with adaptive feedback, intelligent tutoring systems, conversational agents, and personalized AI assistance (Li et al., 2026; Shi et al., 2025; Wan et al., 2026; Wang et al., 2025; Y. Zhao, 2026).

Rather than functioning as educational benefits in themselves, AI-supported scaffolds became pedagogically meaningful when learners monitored their understanding, adjusted strategies, and regulated motivation and engagement. This interpretation was also consistent with evidence from AI-supported programming, project-based learning, and early childhood learning contexts (Serik et al., 2026; Su et al., 2024; Ye et al., 2025). Metacognition therefore functioned as a regulatory bridge between external AI support and learner agency. However, evidence that such externally supported regulation transferred to sustained and autonomous AI use beyond specific learning environments remained limited.

Metacognition Provides Emerging Critical Control over Human–AI Interaction

The second analytical theme extends metacognition from regulating learning with AI toward regulating interaction with AI itself. Several studies showed that monitoring, self-evaluation, reflection, and strategy revision supported more deliberate engagement with AI-generated information and assistance (Makransky et al., 2025; Serik et al., 2026; Wan et al., 2026; Ye et al., 2025; G. Zhao et al., 2025).

These processes suggest that metacognition can provide learners with regulatory resources for questioning understanding, evaluating AI-supported information, revising responses, and adjusting reliance on AI assistance. Metacognition may therefore contribute to epistemic and regulatory control of human–AI interaction, preventing AI-supported learning from becoming passive acceptance of system-generated information. However, this theme had the weakest direct empirical support. Verification of AI outputs, calibration of trust, recognition of hallucinations and bias, evaluation of AI limitations, and ethical judgment were rarely examined directly. Critical control of human–AI interaction should therefore be interpreted as an emerging analytical pattern and a major research gap, rather than an established dominant finding.

Metacognition Supports Regulated Knowledge Construction and AI Competency-Related Development

The third analytical theme indicates that metacognition supports learners in transforming AI-supported experiences into active knowledge construction. Reflection, self-explanation, monitoring, evaluation, knowledge organization, and strategy revision enabled learners to interpret and reorganize information generated through interaction with AI-supported environments (Makransky et al., 2025; Okada et al., 2025; Serik et al., 2026; Wan et al., 2026; Ye et al., 2025).

Through these processes, learners moved beyond receiving AI-generated information toward constructing, evaluating, and revising their own understanding. This pattern was associated with outcomes including conceptual knowledge, computational thinking, AI literacy, AI-related knowledge, and broader AI competency-related development. Metacognition therefore functioned as a knowledge-regulatory mechanism connecting AI-supported experience with meaningful learning and competency development. Nevertheless, only a subset of studies explicitly operationalized AI competency or AI literacy (Okada et al., 2025; Serik et al., 2026; Wan et al., 2026). The evidence was therefore stronger for regulated knowledge construction than for establishing a direct or sustained relationship between metacognition and AI competency development.

Integrative Interpretation

Across the three analytical themes, metacognition emerged as a multi-level regulatory mechanism in AI-supported K–12 learning. First, learners regulated their cognitive, strategic, motivational, and affective engagement with AI-supported learning environments. Second, metacognitive processes showed an emerging role in enabling learners to evaluate and control their interaction with AI-supported information and assistance. Third, reflection and regulatory processes supported the construction and reorganization of knowledge through which AI-supported experiences could contribute to AI competency-related development.

The distribution of metacognitive processes across the analytical themes is presented in Figure 3. Metacognitive monitoring was broadly represented across all three themes, whereas affective–motivational regulation was concentrated primarily in the appropriation of AI-supported scaffolding and learner agency. Critical evaluation was more prominent in the themes concerning control of human–AI interaction and competency-related development, while reflection and knowledge construction were most strongly represented in the third analytical theme.

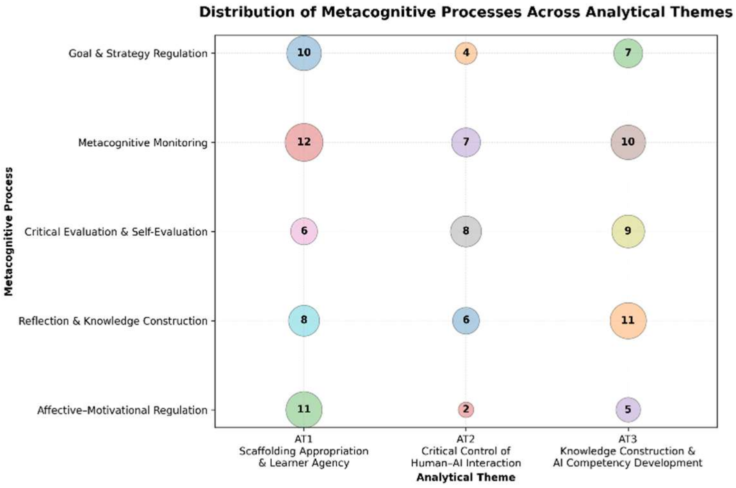

Figure 3 Distribution of Metacognitive Processes Across The Three Analytical Themes

Taken together, the synthesis indicates a conceptual progression from regulating learning in AI-supported environments, to emerging regulation of interaction with AI, and ultimately to regulated knowledge construction and AI competency-related development. This progression should not be interpreted as a causal or universally sequential pathway. Rather, it represents a higher-order explanatory structure derived from recurrent patterns across the evidence base. Thus, in response to the review question, metacognition functions primarily as a regulatory mechanism that enables learners to engage strategically with AI-supported learning, potentially exercise critical control over human–AI interaction, and transform AI-supported experiences into regulated knowledge construction and AI competency-related development.

Evidence Gaps and Underexplored Areas

Despite the growing diversity of AI-supported learning environments, the synthesis revealed several important gaps in the current evidence base. The most prominent gap concerned the limited investigation of AI-specific metacognitive control. Most studies examined how learners regulated their understanding, strategies, motivation, or engagement while learning with AI (Li et al., 2026; Shi et al., 2025; Su et al., 2024; Y. Zhao, 2026), whereas substantially fewer investigated how learners monitored and regulated their reliance on AI itself. Processes such as questioning AI-generated information, deciding when to accept or reject AI assistance, and strategically adjusting interaction with AI were represented only indirectly or in a limited subset of studies (Makransky et al., 2025; Serik et al., 2026; Wan et al., 2026; Ye et al., 2025; G. Zhao et al., 2025). Thus, the literature has developed a stronger understanding of metacognition for learning with AI than of metacognition for regulating AI use.

A related gap concerned the limited empirical attention to verification, trust calibration, and epistemic judgment. Although critical thinking, self-evaluation, reflection, and error interpretation appeared across several studies, few directly examined whether K–12 learners could verify the accuracy of AI-generated outputs, recognize hallucinations or unreliable information, calibrate trust in AI recommendations, identify algorithmic bias, or evaluate the limitations of AI systems. Ethical judgment was similarly underrepresented as an observable metacognitive process. These findings indicate that critical and responsible AI use is conceptually relevant to metacognition but remains insufficiently operationalized and measured within K–12 empirical research.

The synthesis also identified limited evidence concerning the transfer and sustained development of metacognitive regulation and AI competency. Most intervention studies examined learners within specific instructional environments and assessed outcomes during or shortly after participation. Although longitudinal designs were represented in the evidence base (Okada et al., 2025; Shi et al., 2025), few studies investigated whether metacognitive strategies developed in AI-supported learning transferred across technologies, subjects, learning tasks, or everyday uses of AI. Similarly, evidence remained limited regarding whether learners gradually progressed from externally scaffolded regulation toward independent and sustained control of their learning and AI use. The developmental relationship between metacognition, learner agency, and AI competency therefore remains underexamined.

A further limitation concerned the conceptual and methodological heterogeneity of AI competency and metacognition. Only a small subset of studies explicitly operationalized AI competency, AI literacy, or AI-related knowledge as primary outcomes (Okada et al., 2025; Serik et al., 2026; Wan et al., 2026), whereas most examined broader outcomes such as computational thinking, conceptual knowledge, programming performance, self-efficacy, engagement, or academic achievement. Metacognition was similarly represented through heterogeneous constructs, including self-regulated learning, self-regulation, monitoring, self-evaluation, reflection, self-explanation, critical thinking, and affective regulation. This heterogeneity limited direct comparison across studies and made it difficult to determine which metacognitive processes are most strongly associated with specific dimensions of AI competency.

Finally, the evidence base showed important contextual imbalances. The reviewed studies were concentrated predominantly in China and other Asian educational contexts, while evidence from other geographical regions remained comparatively limited. Socially shared and collaborative forms of metacognitive regulation were also underrepresented relative to individual regulation, despite the presence of AI-supported project-based and collaborative learning environments. Furthermore, the evidence base included relatively few studies examining younger learners, long-term developmental trajectories, and differences in metacognitive regulation associated with learner characteristics or educational contexts. These patterns indicate the need for broader cross-cultural, developmental, and socially situated investigations of metacognition in AI-supported K–12 learning.

Taken together, the identified gaps demonstrate that current research provides substantially stronger evidence for the role of metacognition in regulating learning within AI-supported environments than for its role in regulating AI use itself or supporting sustained AI competency development. Future research therefore needs to move beyond measuring general self-regulation and learning outcomes toward directly examining AI-specific metacognitive processes, including verification, trust calibration, critical reliance, ethical judgment, and strategic control of human–AI interaction. Longitudinal and cross-context research is also needed to determine whether externally scaffolded metacognitive activity develops into transferable learner agency and enduring AI competency.

Discussion

This review examined the role of metacognition in developing AI competency within AI-supported K–12 learning. The findings indicate that metacognition plays a broader role than supporting students' learning processes alone. Across the evidence base, metacognitive processes enabled learners to regulate their engagement with AI-supported environments, contributed to emerging forms of critical control over human–AI interaction, and supported reflective knowledge construction associated with AI competency-related development. However, these roles were not equally supported empirically. Evidence was strongest for metacognition as a mechanism for regulating learning within AI-supported environments, whereas direct evidence concerning AI-specific regulatory control and sustained AI competency development remained limited.Table 1 The Title of The Table

Metacognition as a Regulatory Mechanism in AI-Supported Learning

The findings suggest that the educational value of AI-supported learning environments depends not only on technological affordances but also on learners' capacity to regulate their engagement with these affordances (Setiawan & Al Faruq, 2025; B. Yang & Sun, 2026). Adaptive feedback, personalized learning pathways, conversational assistance, and intelligent scaffolding created opportunities for learning, but productive engagement involved learners monitoring their understanding, regulating strategies, evaluating progress, and sustaining motivation and engagement. Metacognition therefore emerged as a regulatory bridge between external AI support and learner agency, enabling students to engage with AI-supported environments more deliberately rather than merely following system-generated recommendations.

This interpretation also highlights the changing relationship between external regulation and learner agency. AI systems increasingly participate in functions traditionally associated with learner regulation (Babayev, 2025; Englmeier, 2025; Lima et al., 2025; J. Xu et al., 2026)geycy, including feedback provision, progress monitoring, strategy recommendation, and personalized guidance. Consequently, the educational challenge is not simply whether AI can improve learning outcomes, but whether learners progressively develop the capacity to interpret, evaluate, and strategically use such support (L. Yang, 2026). AI scaffolding should therefore support the gradual transfer of regulatory responsibility from AI systems to learners rather than promote sustained dependence on external assistance.

The synthesis further indicates that metacognitive regulation supports active knowledge construction. Monitoring, reflection, self-explanation, evaluation, knowledge organization, and strategy revision enabled learners to interpret and reconstruct AI-supported information rather than consume it passively. Metacognition thus provides a mechanism through which external AI-supported experiences can be transformed into learner-directed cognitive activity, meaningful knowledge construction, and potentially more autonomous learning practices.

From Learning Regulation to Critical Regulation of AI Use

A central contribution of this review is the distinction between metacognition for regulating learning with AI and metacognition for regulating AI use itself. Most reviewed studies focused on students' regulation of understanding, strategies, motivation, and engagement while learning in AI-supported environments. However, the synthesis also revealed an emerging extension of metacognitive regulation toward learners' capacity to evaluate and control their interaction with AI-generated information and assistance.

This distinction is increasingly important because AI systems participate directly in information generation, explanation, recommendation, and decision support (Babayev, 2025; Bachtiar & Sylvia, 2026; Englmeier, 2025; Lima et al., 2025). Learners therefore need to regulate not only their own cognitive processes but also their epistemic relationship with AI (Mai et al., 2025; Tomisu et al., 2025). Monitoring involves recognizing uncertainty in both one's own understanding and AI-generated responses; evaluation involves judging the credibility, relevance, and limitations of AI assistance; and strategic control involves deciding when AI-generated information should be accepted, verified, revised, challenged, or rejected. Metacognition may therefore provide the regulatory capacity required to manage cognitive reliance and epistemic dependence during human AI interaction (Mai et al., 2025; Pal et al., 2026; Tomisu et al., 2025).

Based on this synthesis, we propose AI-specific metacognitive regulation as an evidence-informed concept describing learners' awareness, monitoring, evaluation, and strategic control of their cognitive and epistemic interaction with AI systems. This regulatory process may involve monitoring understanding and reliance, evaluating the credibility and limitations of AI assistance, calibrating trust according to evidence quality and task demands, and strategically controlling the use of AI-generated information. Importantly, this concept should be interpreted as a theoretical proposition rather than an empirically validated construct because direct evidence concerning verification behavior, trust calibration, hallucination detection, bias recognition, ethical judgment, and reliance decisions remains limited.

The transition from regulating learning with AI toward regulating AI use itself represents an important direction for AI education research. Future studies should directly investigate learners' verification behaviors, trust judgments, reliance decisions, and strategic adjustments during authentic AI interactions. Such research could clarify whether AI-specific metacognitive regulation represents a distinct developmental capacity and how it contributes to critical, autonomous, and responsible AI use.

Implications for AI Competency Development and K–12 Education

The synthesis suggests that AI competency development should not be conceptualized solely in terms of what learners know about AI or what they can technically accomplish with AI tools (Long & Magerko, 2020; J. Yang et al., 2025) . AI competency also depends on learners' capacity to regulate how AI-related knowledge, skills, and judgments are developed and enacted. Students may possess technical knowledge while remaining unable to recognize gaps in understanding, evaluate unreliable AI assistance, revise ineffective strategies, or determine when AI use is appropriate. Metacognition therefore functions as a cross-cutting regulatory mechanism connecting AI knowledge and skills with strategic, critical, and responsible AI use.

From this perspective, metacognition performs three interconnected functions in AI competency development: a learning-regulatory function, through which learners plan, monitor, and adapt their engagement within AI-supported environments; an interaction-regulatory function, through which learners evaluate and strategically control AI-generated information and assistance; and a knowledge-regulatory function, through which learners reflect on, reorganize, and integrate AI-supported experiences into meaningful knowledge and practices. Together, these functions support the concept of metacognitively regulated AI competency development, describing how learners may progressively develop AI-related knowledge, skills, judgment, and responsible practices by regulating both their own learning and their interaction with AI.

This interpretation has implications for future research. Studies should develop and validate measures of AI-specific metacognitive regulation, examine whether regulatory processes predict the development and transfer of AI competency, and investigate how externally supported regulation becomes internalized across age groups, technologies, subjects, and cultural contexts. Longitudinal and experimental research is particularly needed to test the proposed relationships among AI scaffolding, learner regulation, critical control of AI interaction, and sustained AI competency development.

For K–12 education, metacognitive regulation should be integrated explicitly into AI-supported learning activities (Kong & Yang, 2024; X. Xu et al., 2025). Students should be given opportunities to plan AI use, monitor understanding and reliance, verify uncertain outputs, evaluate AI-generated information, revise strategies, justify reliance decisions, and reflect on how AI influences their reasoning (Anders & Dux Speltz, 2025; Melanou & Beege, 2026; X. Xu et al., 2025). Instructional practices such as metacognitive prompts, self-explanation, verification routines, reflective AI-use logs, and progressively fading scaffolds may support the development of learner agency and more autonomous AI use.

Assessment should similarly extend beyond technical AI knowledge and final learning outcomes toward the processes through which students regulate AI use (Anders & Dux Speltz, 2025; Knoth et al., 2024; Masla et al., 2025; Melanou & Beege, 2026). Evaluating how learners identify uncertainty, verify outputs, calibrate reliance, revise strategies, explain decisions, and reflect on AI-supported actions may provide stronger evidence of critical and responsible AI competency development. Overall, the findings position metacognition as a regulatory architecture for AI competency development. AI-supported learning environments provide opportunities and external scaffolds, but metacognitive regulation enables learners to strategically engage with these supports, exercise emerging critical control over human–AI interaction, and transform AI-supported experiences into meaningful knowledge and practices. The educational goal of K–12 AI education should therefore extend beyond teaching students how to use AI toward developing learners who can determine when AI should be used, how its outputs should be evaluated, when assistance should be questioned or rejected, and how responsibility for reasoning and decision-making should remain with the learner.

CONCLUSION

This systematic review synthesized evidence from 13 empirical studies to examine the role of metacognition in developing AI competency within AI-supported K–12 learning. The findings demonstrate that metacognition functions not merely as a cognitive support for learning but as a multi-level regulatory mechanism that shapes how learners engage with AI-supported environments, regulate their interaction with AI, and transform AI-supported experiences into meaningful knowledge construction.

The synthesis identified three interconnected roles of metacognition. First, metacognition enables learners to appropriate AI-supported scaffolding through monitoring, goal and strategy regulation, reflection, and affective–motivational regulation, thereby strengthening learner agency rather than passive dependence on AI assistance. Second, metacognitive processes extend beyond regulating learning activities toward the emerging regulation of human–AI interaction, supporting learners in evaluating AI-generated information, calibrating reliance on AI, and exercising increasingly deliberate judgment during AI-supported learning. Third, metacognition supports regulated knowledge construction through reflection, self-explanation, evaluation, and strategic revision, providing a foundation for AI competency-related development beyond the acquisition of technical knowledge and skills.

Building on these findings, this review contributes two complementary conceptual propositions. The first is AI-specific metacognitive regulation, referring to learners' awareness, monitoring, evaluation, and strategic control of their cognitive and epistemic interaction with AI systems. The second is metacognitively regulated AI competency development, which conceptualizes AI competency as a developmental process supported by metacognitive regulation rather than as a collection of isolated technical skills or AI knowledge. Together, these propositions extend current perspectives on AI competency by positioning metacognition as a cross-cutting regulatory mechanism connecting AI-supported learning experiences with critical, autonomous, and responsible AI use.

Despite these contributions, the evidence base remains limited in several important respects. Direct empirical evidence concerning AI-specific metacognitive regulation remains scarce, and relatively few studies explicitly measured AI competency or examined its longitudinal development. Future research should therefore investigate how learners verify AI-generated information, calibrate trust, regulate cognitive reliance, and transfer metacognitive strategies across AI systems and learning contexts. Such research will be essential for validating the conceptual relationships proposed in this review and for advancing theoretical models of AI competency development.

Overall, this review suggests that the future of K–12 AI education should move beyond teaching students how to use AI toward developing learners who understand when, why, and how AI should be used critically, strategically, and responsibly. From this perspective, metacognition should not be regarded as an additional component of AI competency but as the regulatory foundation that enables learners to transform AI from a source of information into a partner for meaningful learning, informed judgment, and responsible human–AI collaboration. down the findings or conclusions in a concise, concise, and clear manner. Conclusions are not recommended to be written into several parts or points.

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