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The Impact of Artificial Intelligence Applications on the Development of Users' Metacognitive Skills: A Meta-Analysis of Previous Studies

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Abstract:

This study, entitled "The Impact of Artificial Intelligence Applications on the Development of Users' Metacognitive Skills: A Meta-Analysis of Previous Studies," aimed to estimate the overall effect size of artificial intelligence (AI) applications in developing metacognitive skills. It also sought to examine the degree of homogeneity among the results of previous studies and to diagnose the possibility of publication bias and its impact on the reliability of the findings.

The study adopted a descriptive-analytical approach using the meta-analysis method. The study population consisted of 60 studies identified through multiple scientific databases, while the analytical sample was limited to 10 Arab and international studies selected through simple random sampling according to specific inclusion and exclusion criteria.

To answer the study questions, effect sizes were calculated using Cohen's *d* and corrected using Hedges' *g* to avoid small-sample bias. Data were statistically processed using SPSS and Comprehensive Meta-Analysis software. Homogeneity tests (Q and I^2) were applied, and the appropriate statistical model was selected. In addition, publication bias was diagnosed using funnel plots, Egger's test, and the Trim and Fill method.

The results of the study revealed a statistically significant positive effect of AI applications on the development of students' metacognitive skills, with some variation among studies. However, publication bias correction procedures demonstrated the stability of the overall results, thereby enhancing the reliability of the conclusions reached.

Keywords: Artificial intelligence applications, metacognitive skills, meta-analysis, effect size, study homogeneity, publication bias.

Introduction

In a world that is changing at an unprecedented pace, the individual's personality has become a stage for new challenges we have never witnessed before. In a world where every click on a keyboard and every touch on a phone screen opens new doors that contribute to shaping the future of our children, childhood in the past was simple and tied to tangible reality. Today, however, childhood has become a digital world offering limitless opportunities.

A child can now access information from anywhere. One of the clearest indicators of this transformation is a five-year-old child who masters online shopping, knows how to place orders and arrange home delivery, understands how to buy and sell digital currencies, and can benefit from them in different aspects of life—especially in meeting the requirements of electronic games. Moreover, children now use AI-powered tools such as image editing, voice modulation, and other automated tasks.

This raises a number of questions about whether this development will enable them to become future leaders or turn them into victims in a digitalized world. This concern is precisely what motivated the selection of this topic, by shedding light on the extent to which the use of AI applications in education contributes to the development of metacognitive (meta-knowledge) skills.

Metacognitive skills are considered a cornerstone due to their central role in improving the learning process and enhancing academic and professional performance. They enable individuals to think about their own thinking in a critical and analytical manner, evaluate their strategies, and thereby improve understanding, memory, and academic performance. They also enhance individuals' ability to adapt to changing challenges and solve problems effectively, making them better prepared to face future challenges resulting from digital developments and modern labor market demands.(Okasha& Doha, 2012)

The findings of a study by Bahri Fares (2014) indicated a positive correlation between metacognitive skills in general—and their three dimensions (planning, monitoring, and evaluation)—and problem-solving. This demonstrates that metacognitive skills are essential for effective problem-solving in all areas of life, making them a vital tool for dealing with changing challenges in both personal and professional life.(Bahri& Fares, 2014) Accordingly, developing and enhancing these skills should be an essential component of any educational or training program aimed at preparing individuals for success in a complex and rapidly changing society.

Given the tremendous revolution the world is witnessing due to rapid technological developments—particularly artificial intelligence and its applications across various fields, including education—AI is no longer limited to storing facts but extends to developing users' abilities and skills. It enables effective control over thinking and learning processes by providing vast capabilities that support personalized learning environments tailored to each user's needs and abilities.

Through AI, learning experiences can be customized according to each learner's style and needs, improving comprehension and understanding. It also provides immediate feedback on performance, allowing continuous monitoring of progress and adjustment of learning strategies. Furthermore, AI encourages self-directed learning by offering interactive tools and activities that motivate students to explore and discover knowledge independently, as well as perform repetitive tasks such as grading and assignment submission, thereby saving time.

Additionally, the multiple uses of AI help teachers better understand learners' needs and design more effective learning experiences.(Yuskovych-Zhukovska and all 2022) Recent studies have shown that learning through AI applications is an effective educational approach that improves students' academic achievement. Digital technology also plays a significant role in enabling users to access vast amounts of information anytime and anywhere, fostering creativity and innovation, expanding communication and interaction, and improving learning opportunities for children with disabilities.

In this context, a study by Noboru Matsuda and all. (2022) found that AI-based systems (APLUS, APLUSTUTOR, and COGTUTOR) are effective in improving learners' mastery of solving algebraic equations. Similarly, the study by Porayska-Pomsta (2016) concluded that educational AI helps teachers develop higher-order thinking skills, enabling them to better diagnose educational challenges, generate innovative solutions, and evaluate their consequences through reflective frameworks and educational simulations.(Porayska-Pomsta 2016)

Despite the importance of AI applications and the growing number of studies addressing their role in education, scientific knowledge about their overall role remains limited, according to the researcher's review. Most studies have focused on technical aspects and treated these applications merely as tools for accessing information, largely neglecting their role in developing cognitive abilities and life skills—particularly metacognitive skills such as planning, self-monitoring, and self-evaluation, as identified by Flavell (1979).

Moreover, many studies relied on limited measurement tools such as questionnaires without combining them with observations or in-depth interviews, indicating methodological shortcomings. There is also a noticeable absence of a comprehensive theoretical framework linking AI use to metacognitive skill development, representing a significant theoretical gap.

In addition, previous studies show some inconsistencies regarding the effectiveness of AI applications in enhancing critical thinking and self-directed learning, highlighting the need for deeper analytical research. Most studies have been conducted in specific geographical and cultural contexts—such as Europe, America, and Asia—without considering the specific characteristics of Arab educational environments in general, and Algeria in particular, which represents an important contextual gap.

Furthermore, some studies rely on outdated data that do not reflect recent developments in AI technologies, emphasizing the need for up-to-date research. In light of the rapid advancements in digital technology and AI applications in education, there is a need to achieve a deeper understanding of the role of AI in enhancing metacognitive skills among learners in the digital age and preparing a generation capable of keeping pace with these developments and challenges.

On the other hand, despite the significant potential offered by AI applications, a fundamental issue arises concerning their impact on individuals' self-development: Does increasing reliance on AI enhance individuals' abilities and prepare them to become future leaders, or does it lead to a decline in essential personal skills, reduced self-motivation, and diminished human interaction?

Accordingly, the following main question is posed:

Do AI applications influence the development of users' metacognitive skills according to previous studies, and how consistent and reliable are these findings?

Sub-questions

1. To what extent is there homogeneity among the compiled studies on the impact of AI applications on metacognitive skills?

2. What is the overall effect size of these applications on users' metacognitive skills?
3. Are there indications of publication bias in previous studies that affect the reliability of the results?

Objectives of the Study

The study aims to estimate the impact of AI applications on the development of students' metacognitive skills by analyzing previous studies and evaluating the reliability of their findings through:

1. Measuring the overall effect size of AI applications on students' metacognitive skills.
2. Examining the degree of homogeneity among the different studies to determine the consistency or the variation of the results and the interpretation of the sources of difference.
3. Diagnosing the presence of any publication bias in published studies and its impact on the reliability of analytical results.

Significance of the Study

1. Understanding the role of AI in enhancing metacognitive skills.
2. Preparing a generation capable of keeping pace with developments and challenges.
3. Developing effective educational practices in the age of artificial intelligence.

Conceptual Framework of Metacognitive Skills and Their Importance

Origin of the Concept

The concept of metacognition emerged in the early 1970s through the work of the American psychologist John Flavell, who introduced a new dimension to cognitive psychology. This concept opened broad horizons for experimental studies and theoretical discussions on intelligence, thinking, memory, understanding, and learning.

Interest in metacognition grew significantly in the 1980s and continues to attract researchers' attention to this day due to its strong connection with theories of intelligence, learning, problem-solving strategies, and decision-making.(ElhachemiDelimi 51.2008) Its historical roots can also be traced back to Luria's regulatory mechanisms and Piaget's concept of conscious control (1974).

Flavell (1970) introduced the notion of "production deficiency," referring to cases where individuals possess knowledge of memory strategies but fail to apply them when needed. (Elbarri 47.2005) Initially, this type of thinking was termed "metamemory," but it later expanded to include broader domains and became known as "metacognition."(Aboudjadou and Noufel 343.2007)

Concept of Metacognitive Skills

Resnick (1987) defined metacognitive skills as thinking aloud and engaging in self-talk to monitor and review problem-solving steps. Costa (1991) emphasized that metacognition appears when individuals become aware of their internal dialogue and reconsider their decisions.

Sternberg (1992) described metacognitive skills as higher-order cognitive processes responsible for planning, monitoring, and evaluating performance during problem-solving. Stipek (1998) defined them as awareness of one's abilities, strategies, and resources needed for effective task performance.

Abu Hashem (1999) highlighted that these skills involve awareness of one's learning processes, the ability to set goals, select appropriate strategies, modify or abandon them when necessary, and continuously evaluate oneself.(Abu hashem,1999 ;201)

Marzano et al. (2001) identified two main components of metacognition:

- Self-knowledge (understanding strengths, weaknesses, and thinking patterns)
- Knowledge and control of cognitive processes (Marzano& al,2001)

Livingston (2003) viewed metacognition as complex thinking processes used during cognitive activities, involving continuous planning, monitoring, and evaluation.(Livingston,2003)

Based on the above, metacognitive skills can be defined as higher mental processes that include planning, monitoring, and evaluating performance during problem-solving, enabling individuals to regulate their thinking and improve their effectiveness.

Importance of Metacognitive Skills

Researchers agree that the use of metacognitive skills in learning situations:

- Enhances comprehension and long-term retention
- Improves problem-solving and decision-making
- Encourages active participation in learning
- Increases learner motivation and independence (Ramadane and boubekri P237-P238, 2021)

Conceptual Framework of AI Applications and Their Role in Developing Metacognitive Skills

Artificial Intelligence: Definition and Overview

The term "artificial intelligence" has gained widespread use with technological advancements. Once confined to science fiction, AI is now a tangible reality used in daily life. It can be broadly defined—following Marvin Minsky—as a branch of science concerned with developing machines capable of solving problems.(Elfera P3, 2012)

Types of Artificial Intelligence

- **Reactive Machines:** The simplest type, responding only to current situations without memory (e.g., IBM's Deep Blue). (Stuart and Peter, 2016)
- **Limited Memory AI:** Uses short-term data to make decisions (e.g., self-driving cars). (Wilder, 2025)
- **Self-Aware AI:** A theoretical advanced form where machines possess self-awareness (not yet realized). (Sterne, 2017)

AI Applications in Education

1. **Dragon Speech Recognition:** Enables students with writing difficulties to express ideas through speech.(Terah,2020)
2. **Knewton:** Provides adaptive, personalized learning content. (Fiveable, 2025)
3. **Cognii:** Uses conversational AI to develop critical thinking. (AIS Qust, 2025)
4. **Querium:** Offers personalized STEM instruction and analytics. (Querium, 2024)
5. **Century Tech:** Uses data analytics to create personalized learning plans.(Century Teach, 2025)

Engineering Metacognitive Skills through AI Algorithms

The rapid development of AI technologies has led to fundamental transformations in educational environments. The focus has shifted from knowledge transmission to skill development, including metacognitive skills.

AI applications can be viewed as cognitive mediators that support learners in organizing their mental activities without replacing them. Theirmechanismsinclude :

1. **Immediate Feedback:** Helps learners monitor and evaluate their thinking processes. (Alsaiari, 2025)
2. **Adaptive Learning Models:** Adjust content based on performance, promoting reflective thinking. (Yan, 2023à (Bond, 2024)
3. **Progress Tracking Models:** Provide analytical reports that support self-evaluation and planning. (Cabi and Türkoğlu, 2025)
4. **Personalization Models:** Recommend content based on user behavior and preferences, enhancing awareness and engagement. (Hooshyar and All, 2025)
5. **The Correct Answer Model :**

Is one that matches the concepts of the user's response with concepts that have a standard reference based on a prior knowledge representation of model answers. This allows for the precise identification of the knowledge gap and the classification of the nature of the error, whether it stems from a lack of concepts or a flaw in the logical structure of the answer. This process occurs through the interaction of a set of mechanisms. The first is the standard reference mechanism, which contains the model answer. It is followed by the matching mechanism, which compares the user's response with the standard reference. Next comes the knowledge gap measurement mechanism, followed by the mechanism for generating targeted feedback (Tejaswi et al., 2025).

The researchers argue that when a user defines the concept of cooperative learning within the application as "group work among students," the system compares this answer with the standard answer and then transforms the conceptual gap it identifies into feedback. This mechanism stimulates the process of self-monitoring and the evaluation of understanding, as the user becomes aware of their errors and the reasons behind them. This indicates the actual contribution of artificial intelligence applications in activating metacognitive skills. This is supported by the study conducted by Tejaswi et al. (2025) on an AI-based automated assessment system and personalized feedback in higher education. The study concluded that AI-based grading systems are effective in enhancing metacognitive skills, as applications that convert texts into semantic representations and compare them with model answers provide learners with an opportunity for self-monitoring.

According to the study's findings, the immediate and actionable feedback that users receive from these applications helps them evaluate their processes. In the same context, reference is made to the error diagnosis model, which is based on identifying the type and cause of errors in the user's answer while generating feedback. This model operates through a set of mechanisms. The first is the feature extraction mechanism, which identifies the concepts and ideas in the user's response. This is followed by the cause analysis mechanism, which uses a decision tree that provides an explanation in the form of a visual flowchart resembling a tree to analyze the data. It also employs Bayesian networks, which rely on conditional probabilities, in order to classify errors into categories such as misunderstanding, misapplication, or incomplete analysis.

Based on the type of error, the system generates targeted feedback that clarifies the cause of the error and suggests an appropriate correction. Accordingly, this mechanism allows the user the opportunity to review and correct their concepts, which enhances deep learning, provides opportunities for self-reflection, and strengthens problem-solving abilities (Yi-Fan Zhang et al., 2025).

6. **Intelligent Question Guidance Model:**

His is an instructional model used by artificial intelligence application systems to generate analytical and reflective questions instead of providing direct answers. This model is based on a set of mechanisms. The first is the natural language processing mechanism, through which the system reads the user's responses, understands their content and meaning, and identifies concepts. This is followed by the question generation mechanism based on the user's responses, where the questions are characterized by an analytical, reflective, and evaluative nature that pushes the user toward deep thinking. This is then followed by the dynamic interaction mechanism, where each new question depends on the user's previous response, thereby creating an ongoing dialogue tailored to each user.

Through the interaction of these mechanisms, the user is prepared for reflective thinking and continuous self-evaluation of their answers, which enhances the ability for planning, self-monitoring, evaluation, and conceptual awareness. This explains the system's ability to stimulate and develop metacognitive skills (Degen and Asanov, 2025).

7. **Interactive TasksModel:**

This model relies on educational activities that take place within AI-supported applications, where the user interacts with system elements in real time, such as making decisions or executing a realistic scenario. This is achieved through simulation engines, as this mechanism generates a virtual environment that resembles reality and with which the user interacts. This is followed by the artificial intelligence agents mechanism, which includes intelligent elements within the environment that respond to the choices and decisions made by the user. Next comes the real-time interaction mechanism, where the system responds immediately to every decision made by the user within the virtual environment, allowing the user to see the results of their actions directly while performing them, without waiting for results to appear later in real life.

This enables the user to engage in planning for problem-solving, monitor decisions during their execution, and evaluate the effectiveness of their strategies after observing the results in a realistic context. Through this dynamic interaction, the user enhances their self-awareness of thinking processes and acquires the ability to adjust their metacognitive skills (Abdelghani et al., 2025).

8. **Problem-Based Learning Model:**

This model indicates that the system places the user in front of a problem presented in the form of a scenario similar to what they might encounter in daily life or professional practice, while providing a set of possible solutions and opportunities to make appropriate decisions. This model is based on a set of mechanisms. The first is the real-world problem generation mechanism, where the system generates problems that simulate reality. This is followed by the constraints definition mechanism, where the system allows the user to solve the problem according to rules that must be respected.

After that comes the decision pathway construction mechanism, where each decision made by the user leads to a different path, resulting in new outcomes. This is followed by the scenario-based simulation mechanism, where the system provides virtual environments that simulate reality and change according to the user's decisions. Then comes the adaptive feedback mechanism, where the system responds to the user's decisions by presenting the results of those decisions and their impact on the course of the problem, without simply labeling them as correct or incorrect. This allows the user to reconsider and modify their strategy.

Finally, there is the thinking-path tracking mechanism, where the system records and analyzes the sequence of decisions and cognitive steps followed by the user during problem-solving, rather than merely evaluating the final outcome. This provides the user with an opportunity to understand their problem-solving strategies and cognitive organization. In this context, learning is not limited to reaching a correct solution but rather focuses on organizing the cognitive processes that lead to the solution. This enhances the user's awareness of their thinking, as well as their ability for self-regulation, planning, and reflective evaluation (Rahmadani et al., 2020; Kevin Downing et al., 2009).

9. Self-Correction Model:

This model enables the user to reprocess tasks and solve problems multiple times while providing step-by-step analysis for each action taken. It reveals errors and flawed thinking patterns. These processes are based on a set of mechanisms, the most important of which are iterative feedback loops that analyze the steps followed by the user, provide hints about the incorrect aspects, and allow for repeated attempts. Based on this feedback, repetition transforms error into a learning opportunity rather than a failure.

This is followed by the error-tracking mechanism, which records the type of error—whether conceptual, procedural, or inferential—then monitors the recurrence of errors or improvement in performance across attempts, and adjusts the type of feedback according to the user's error patterns. In this way, thinking processes are corrected. Next comes the stepwise analysis before evaluation mechanism, which involves analyzing each step while highlighting both correct and incorrect steps, followed by the final evaluation after completing the correction process. This directs the user's attention in a practical manner.

For example, we may observe a learner studying Newton's laws of motion on an inclined plane and making an error in calculating the components of forces acting on the object. The system then provides a step-by-step analysis of the error and allows the learner to retry, correcting the calculations. After several attempts, the user reaches the correct solution, gains awareness of how to think and organize the solution, and develops the ability to evaluate problem-solving strategies through the final assessment. In this case, the system allows the user to engage in self-monitoring by continuously reviewing their performance, self-

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regulation by adjusting their strategy based on feedback, and self-evaluation by assessing the quality of their thinking before accepting the result (Lestuny, 2024; Braad et al., 2022).

Thus, from the researcher's perspective, metacognitive skills constitute a fundamental pillar in building effective learning and developing learners' awareness of their cognitive processes, due to their central role in planning, monitoring, and self-evaluation, whether in everyday life or in educational contexts. The theoretical analysis also highlights that artificial intelligence—through its models, algorithms, and adaptive educational applications—plays a significant role in supporting and enhancing these skills by providing flexible learning environments and immediate feedback tailored to individual differences.

Accordingly, it can be said that employing artificial intelligence applications in the educational process represents an important variable for developing metacognitive skills, provided that it is supported by a pedagogical design guided by clear educational objectives. Based on these theoretical foundations, the present study proceeds to present the methodological procedures adopted in order to empirically examine the nature and limits of this effect in the educational context.

Methodological Procedures of the Study

Research Methodology:

The researcher adopted the meta-analysis method due to its suitability for the nature of the study, which involves analyzing the results of previous studies that examined the impact of artificial intelligence applications on the development of metacognitive skills.

Study Population:

The study population consists of research studies that addressed the impact of artificial intelligence applications on the development of metacognitive skills, based on the researcher's scope of access through the following search engines and databases: Google Scholar, ResearchGate, Springer, Shamaa, and ERIC. The total number of studies reached 60 after applying a set of inclusion and exclusion criteria adopted by the researcher, which are as follows:

- The study must be relevant to the topic of artificial intelligence, including intelligent educational applications or smart platforms, and their impact on developing metacognitive skills.
- The dependent variable must be related to metacognitive skills or one of their dimensions.
- The study must be experimental, quasi-experimental, or correlational.
- The availability of statistical values necessary to calculate effect size (such as means, standard deviations, sample size, and values of t, r, β).

Study Sample:

The study sample consisted of 10 foreign and Arab studies selected using simple random sampling. The researcher relied on the method of drawing slips without replacement. Accordingly, after extracting the basic data, the studies were represented in the following table, which included the study number, study title, authors and year of publication, sample size, and calculated effect size (Cohen's d with correction using Hedges' g):

Table (01): Basic Data of the Study Sample

Study No.	Authors / Year / Title	Sample Size	Cohen's d	Hedges' g
01	Amr Mohamed Mohamed Ahmed Darwish& Ahmed Hassan Mohamed El-Leithy (2020): The effect of using AI platforms on developing habits of mind and academic self-concept among low-achieving preparatory students	60 preparatory students	0.87	0.86
02	Inas Mohamed AbdelrahmanSwalmeh (2022): Effectiveness of an AI-based application in developing logical thinking skills and motivation toward learning computer science among 8th-grade students	45 students	0.079	0.078
03	Yingjie Zhang et al. (2025): The relationship between higher-order thinking levels and the development of problem-solving skills among novice teachers using generative AI: A moderated mediation analysis	200 university students	0.34	0.339
04	Waheed Mahmoud et al. (2025): AI-supported metacognitive strategies for improving self-regulated learning among high school students	200 students	0.83	0.83
05	KhoshnulKhotimah et al. (2024): Enhancing metacognitive and creative skills through AI-supported metacognitive learning strategies	42 university students	3.544	3.476
06	Ahsan Filiz&HulyaGoor (2025): Students' perceptions and applications of metacognitive awareness levels in problem-solving using ChatGPT	42 mathematics teachers	0.809	0.794
07	Anjali Srivastava &Shalini Agarwal (2025): A study on the role of AI tools in enhancing or hindering metacognitive skills among youth	200 AI users	0.4	0.4
08	Tayba Rashid (2025): Developing metacognitive skills through AI-enhanced educational platforms: A	250 participants	0.57	0.568

Study No.	Authors / Year / Title	Sample Size	Cohen's d	Hedges' g
	psychological perspective			
09	Yui Chai &BehzadNezakatego (2025): Evaluating AI-supported applications to enhance metacognitive thinking strategies, self-motivation, and social learning among undergraduate English education students	310 university students	1.36	1.36
10	Alia Akram et al. (2025): The effect of AI-based support on problem-solving and the development of metacognitive awareness among learners	300 secondary and university students	1.547	1.543

From Table (01), it is evident that the studies were conducted between 2020 and 2025 and aimed to identify the effect of artificial intelligence (AI) on metacognitive skills. Sample sizes ranged from 42 to 310 participants, with a total of 1,644 individuals from diverse groups, providing suitable diversity for meta-analysis. The effect sizes (Cohen's d) ranged between 0.079 and 6.35, while Hedges' g values ranged between 0.078 and 1.54, indicating the strength of each intervention—especially in studies such as those by Darwish, Khotimah, Chai &Nezakatego, and Alia Akram, where effect sizes ranged between 1.54 and 6.35. Accordingly, it can be concluded that artificial intelligence has a positive effect on the development of metacognitive skills across all the studies considered.

5. Calculation of EffectSizes:

Based on the nature of the available data, the researcher used values such as t, r (correlation coefficient), means, and standard deviations to calculate effect size using Cohen's formula. In cases where the effect size was already provided in the studies, it was reported as is. Subsequently, all values were corrected using Hedges' g to standardize effect sizes and adjust for bias in small samples.

6. Statistical Analysis:

Statistical data were analyzed using SPSS and Comprehensive Meta-Analysis software. Effect sizes for each study (Cohen's d) with Hedges' g correction were used to account for small sample sizes. Measures were standardized to facilitate comparison across studies. A homogeneity test was then conducted to determine variability among studies using the Q-test and I^2 index. Based on the results, the appropriate statistical model (fixed or random effects) was selected to calculate the pooled effect size.

To present the results, a Forest plot was generated to illustrate the effect size of each study and the combined effect size. Publication bias was also assessed using a Funnel plot and Egger's test, along with the Trim and Fill method to estimate the adjusted effect size.
Des réponses plus intelligentes, le chargement de fichiers et d'images, et bien plus encore.

7. Presentation of Results

The results of the hypothesis stating that the use of artificial intelligence applications affects the development of metacognitive skills among learners are presented through a meta-analysis of previous studies. To verify the validity of this hypothesis, the following steps were followed:

1. Results of the First Question

“To what extent is there homogeneity among the combined studies regarding the effect of artificial intelligence applications on metacognitive skills, based on the heterogeneity test?”

To ensure homogeneity between the effect sizes (Hedges’ g) across studies, the researcher relied on the Q (Chi²) test value and the I² value, which indicates the percentage of true variance among studies. These are presented in the following table:

Table (02): Heterogeneity Test Among Studies

Studies	Hedges’ g	df	Q (Chi²)	p-value	τ^2	I^2 (%)
1	0.86					
2	0.078					
3	0.339					
4	0.83					
5	3.476	9	634.73	<0.001	0.44	98.58%
6	0.794					
7	0.4					
8	0.568					
9	1.36					
10	1.543					

From Table (02), it is evident that the corrected effect size (Hedges’ g) for each study ranges between 0.078 and 3.47. The heterogeneity test value Q (Chi²) was estimated at 634.73 with degrees of freedom (df = 9) and a p-value less than 0.001, indicating real differences between the studies. The τ^2 value reached 0.44, which suggests substantial variance among studies. Meanwhile, the I^2 value was estimated at 98.58%, confirming that most of the variability in results is not due to chance but rather due to heterogeneity among the studies.

2. Results of the Second Question

“What is the overall effect size of these applications on users’ metacognitive skills?”

To calculate the overall effect size, the researcher relied on the Random Effects Model, as it is the most appropriate given the heterogeneity among the studies.

Table (03):OverallEffect Size

Overall Effect Size (G_RE)	Standard Error (SE)	SignificanceLevel	Z	StatisticalSignificance
1.01	0.21	0.05	4.78	0.001

From Table (03), it is clear that the overall pooled effect size (G_RE) reached 1.01, with a pooled standard error of 0.21 at a significance level of 0.05. This indicates that the estimate of the overall effect size is highly stable. The Z value reached 4.78 with statistical significance less than 0.001, indicating that the effect size is far from zero and therefore not random. This demonstrates that the effect of artificial intelligence is real and not due to error, despite differences among studies in some results. This reflects the effectiveness of artificial intelligence applications in developing metacognitive thinking skills based on the integration of the analyzed studies.

3. Results of the Third Question

“Are there indicators of publication bias in previous studies that may affect the reliability of the results?”

To answer this question, the researcher relied on diagnosing publication bias to ensure that the results of the meta-analysis are free from such bias. This was done by examining the symmetry of studies using Egger’s test and the Funnel Plot, as presented in Table (04) and the following figure:

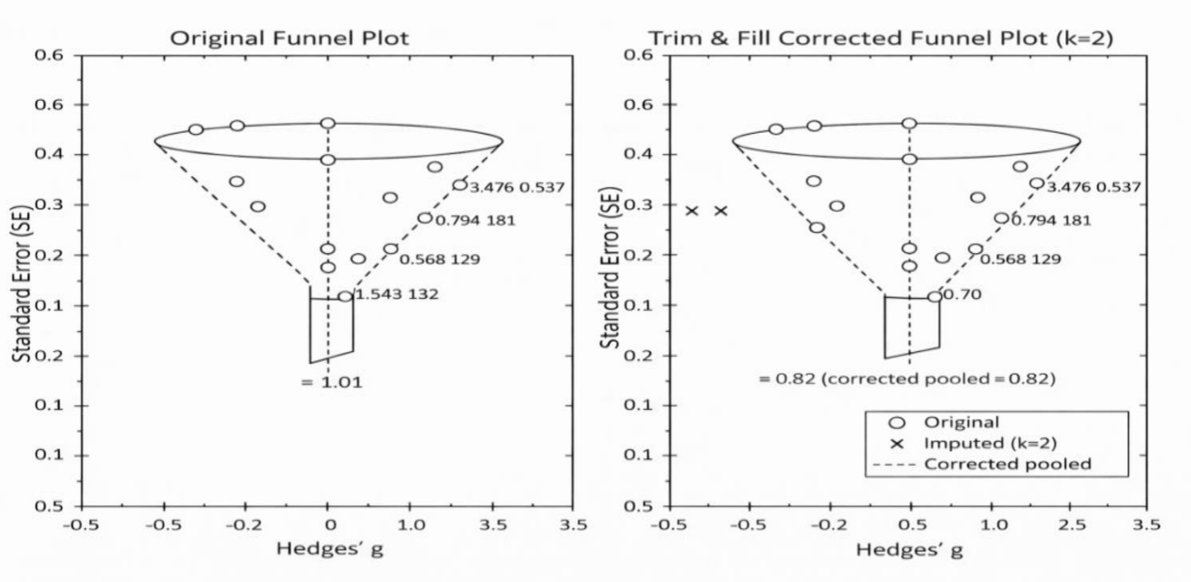
Table (04): Egger’s Test Before and After Correction Using Trim and Fill

Condition	Number of Studies	OverallEffect Size	SE	Egger’s α Coefficient	P-value	StatisticalSignificance
Egger’s Test (Bias)	10	1.01	0.21	9.41	0.029	Significantat 0.05
AfterTrim and Fill	12	0.82	0.16	0.85	0.09	Not significant

Figure (01): Effect Size Values Before and After Correction Using Trim and Fill

From Table (04) and Figure (01), which present the results of Egger’s test before and after correction using the Trim and Fill method, it is clear that the bias coefficient α reached 9.412 with a standard error of 3.441.

The significance value (sig) was 0.029, which is less than 0.05, indicating statistical significance at the 0.05 level. This shows that α is far from zero, meaning that the studies included in the meta-analysis are not symmetrically distributed around the overall effect size.



This indicates the presence of significant publication bias in the meta-analysis.

Therefore, this bias must be taken into account when interpreting the overall effect size. To address this, the Trim and Fill method was applied to correct for publication bias by adding two hypothetical studies (k = 2) to achieve greater symmetry in the funnel plot, increasing the total number of studies to 12.

After correction, Table (04) shows that the bias coefficient α decreased to 0.85 with a standard error of 0.16, while the significance value (sig) became 0.09, which is greater than 0.05 and thus not statistically significant. This indicates that α has become closer to zero. The corrected overall effect size decreased to 0.82. Additionally, the corrected funnel plot (Figure 01) shows improved symmetry around the overall effect size line, indicating a reduction in the impact of publication bias after correction.

This suggests that the positive direction of the effect size remains stable despite the correction, meaning that the positive impact of artificial intelligence applications is not a result of publication bias. Rather, it reflects the actual ability of AI applications to positively influence the development of metacognitive skills.

Accordingly, it can be concluded that integrating artificial intelligence tools and applications into the educational process contributes to enhancing learners' abilities in planning, monitoring, and self-evaluating their cognitive processes. This confirms the positive role of technology in supporting deep learning and developing higher-order thinking skills.

9. Discussion of Results

The results of the current study indicate that artificial intelligence applications have significantly contributed to the development of metacognitive skills among users. This aligns with recent trends in educational literature, which emphasize that these applications are no longer limited to their traditional role as tools for information delivery, but have gone beyond that to perform higher-order cognitive functions by supporting skills such as planning, self-monitoring, evaluation, and the organization of self-regulated learning.

This finding is consistent with several studies that have confirmed that AI-supported learning environments have a significant impact on developing awareness of cognitive processes and self-regulated learning strategies among learners. This alignment is clearly reflected in the findings of the study by NubhaGoyal (2025), which examined artificial intelligence as a cognitive support tool through a systematic review of its impact on metacognitive skills and reflective thinking in critical thinking. The study concluded that these applications play a fundamental role in supporting the teaching and learning process and enhancing self-regulation, while also cautioning that excessive reliance on them may lead to a decline in certain thinking and problem-solving skills (Nubha, 2025).

The results of the current study also agree with the study by Tayiba Rasheed (2025), which found that students who used AI-enhanced educational platforms demonstrated higher levels of metacognitive skills compared to their peers who used traditional learning methods (Rasheed, 2025). In the same context, the findings of the study by YueZhai and BehzadNezakatgoo (2025) indicated that AI-supported educational applications in English language learning contribute to enhancing learner autonomy and developing planning and self-monitoring skills by providing opportunities for academic exploration and offering supportive feedback for evaluating understanding (Zhai&Nezakatgoo, 2025).

Additionally, the study by Faisal Saleh Ali Al-Qarni (2025) showed statistically significant differences in favor of the group that used generative AI applications in developing self-regulated learning skills. This reflects the effectiveness of these applications in supporting self-awareness of learning processes, with recommendations to expand their use in technical curricula and to provide training programs for teachers (Al-Qarni, 2025).

Despite this agreement, some studies have produced findings that differ from those of the current study. These studies suggest that the impact of artificial intelligence applications on metacognitive skills is not automatic or guaranteed, but rather depends on the nature of their use and the design of the learning environment. This is evident in the study by Xusheng Dai et al. (2025), which demonstrated that compulsory and poorly structured use of AI-supported feedback can lead to a decline in autonomy and self-regulation levels among low-achieving students, due to their excessive reliance on the system as a cognitive substitute rather than a supportive tool (Dai et al., 2025).

Similarly, the study by Boxuan Ma et al. (2025), based on the analysis of more than 10,000 conversational records, showed that AI applications may produce negative effects on metacognitive skills if they are not designed and used in a way that ensures the learner's conscious engagement in planning, monitoring, and evaluation processes (Ma et al., 2025).

The significant effect identified in the current study can be interpreted through an integrative theoretical perspective grounded in Flavell's theory of metacognition, which focuses on an individual's awareness of their cognitive processes—namely planning, monitoring, and evaluation—and Vygotsky's social learning theory, which emphasizes that learning occurs through interaction within the zone of proximal development with the assistance of an external agent different from the learner. Within this framework, artificial intelligence applications can be viewed as supportive educational tools that extend beyond the learner's current capabilities without eliminating their active role, by providing cognitive support that enables them to regulate their learning consciously.

Despite the diversity of AI applications and their varying interfaces, they share a set of pedagogical-technological mechanisms that explain their ability to foster metacognitive skills. The most prominent of these mechanisms include immediate feedback, adaptive learning, progress tracking, recommendation-based personalization, error diagnosis, interactive tasks, intelligent question guidance, problem-based learning, and self-correction. Although these mechanisms differ in their technical structures, they collectively direct the learner's attention to their thinking processes and motivate them to engage in prior planning, monitor their performance during learning, and evaluate their strategies after completing tasks.

For example, immediate feedback helps identify knowledge gaps and correct errors at the appropriate time, thereby enhancing self-monitoring and continuous evaluation, as confirmed by Alsaiari et al. (2025). Adaptive learning, which relies on analyzing user performance and tailoring content according to their level, encourages learners to reconsider their strategies and reflect on their errors, as noted in studies by Yan (2023) and Bond (2024). Progress tracking mechanisms, based on learning analytics, enhance awareness of the learning trajectory by presenting accurate data on strengths and weaknesses, thereby supporting informed educational decision-making (Cabı&Türkoğlu, 2025).

At a deeper level, intelligent personalization and recommendation systems enhance learners' awareness of their learning styles and preferences, supporting self-monitoring and the regulation of cognitive effort (Hooshyar et al., 2025). Error diagnosis models and automated assessment systems transform errors into opportunities for reflection and cognitive correction, thereby supporting deep learning (Tejaswi et al., 2025; Yi-Fan Zhang et al., 2025).

Moreover, interactive tasks and simulated environments play an important role in developing planning, decision-making, and self-evaluation skills through dynamic interaction with learning situations (Abdelghani et al., 2025). Similarly, intelligent question guidance models and problem-based learning approaches enhance reflective thinking and awareness of cognitive strategies by encouraging learners to explain their decisions and review their thinking processes rather than merely reaching correct answers (Downing et al., 2009; Rahmadani et al., 2020).

The self-correction model, based on iterative feedback loops and step-by-step analysis, also contributes to enhancing self-monitoring and conscious evaluation of performance, as confirmed by studies such as Braad et al. (2022) and Lestuny (2024).

Accordingly, it can be concluded that the significant effect identified in the current study is attributable to the nature of artificial intelligence applications and their interactive mechanisms when employed within a pedagogically informed design grounded in metacognitive and social learning theories. However, this effect should not be understood as absolute or independent of usage conditions. Some literature indicates that unstructured or excessive automated support may reduce opportunities for self-monitoring among novice learners, which places limits on the generalizability of the findings and highlights the importance of the informed pedagogical use of artificial intelligence applications.

10. Conclusion

Based on the above, it can be concluded that artificial intelligence applications represent effective educational tools for developing metacognitive skills, as confirmed by the results of the current study. This is achieved by enabling users to engage in planning, self-monitoring, and continuous evaluation of their cognitive processes, in alignment with the principles of Flavell's theory of metacognition and Vygotsky's social learning theory within the zone of proximal development.

However, the impact of these applications is not absolute; rather, it depends on the nature of their use and the design of the surrounding learning environment. This calls for careful regulation of how these tools are used to ensure the enhancement of metacognitive thinking without leading to excessive reliance on them.

Accordingly, the study recommends the need to design educational environments that integrate human interaction with intelligent application support, as well as the development of training programs for teachers to familiarize them with how to employ artificial intelligence as a supportive tool rather than a cognitive substitute. It also suggests conducting future studies to evaluate the impact of different types of adaptive and interactive applications on the development of metacognitive skills across various educational levels and academic disciplines, with a focus on achieving a balance between technological support and learner autonomy.

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