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META-GEN: Metacognitive Engagement in Textual Activities with Generative AI

Anna Maria Mariani [1], **Eugenia Treglia** [1] **and Francesco Peluso Cassese** [1, *1]

[1] Università Telematica Pegaso; annamaria.mariani@unipegaso.it; eugenia.treglia@unipegaso.it; francesco.pelusocassese@unipegaso.it
* Correspondence: annamaria.mariani@unipegaso.it

Abstract: Generative Artificial Intelligence (GAI) is profoundly reshaping learning and text production practices, offering new forms of cognitive support while raising questions about its impact on metacognitive processes and learners' reflective autonomy. The META-GEN project explored the relationship between GAI use and the activation of planning, monitoring, and evaluation strategies in comprehension and writing tasks. A quasi-experimental design with a control group involved 296 adult learners engaged in argumentative text production, with or without GAI assistance. Data were collected through the Metacognitive Awareness Inventory (MAI), a digital competence questionnaire, an ad hoc survey on metacognitive strategy use, and a post-task comprehension test. Descriptive and inferential analyses revealed high levels of metacognitive awareness and solid monitoring and evaluation skills, but weaker strategic planning in GAI-mediated tasks, suggesting a selective cognitive delegation effect. No significant differences emerged in comprehension between groups, indicating that GAI does not reduce learning quality but modifies its underlying processes. GAI appears as a conditional metacognitive facilitator: it can foster self-regulation and reflection when intentionally integrated into an educational design that makes control strategies explicit. The study highlights the need to promote AI literacy and metacognitive scaffolding to balance technological efficiency with reflective responsibility in learning processes.

Keywords: Metacognition, generative artificial intelligence, self-regulation, reflective learning, adult education.

1. Introduction

Generative Artificial Intelligence (GAI) is significantly transforming study practices and knowledge production in educational contexts, offering new opportunities for rapid information access, content reformulation and writing support. Tools such as ChatGPT can synthesise and structure knowledge in immediately usable form, reducing the effort required to retrieve information and improving the linguistic fluency of students' outputs (Stadler et al., 2024). These functionalities contribute to

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accelerating text drafting and facilitating comprehension of complex materials, potentially democratizing access to educational resources and reducing certain cognitive and linguistic barriers. However, unguided integration of GAI into learning and production tasks raises crucial questions about the quality of cognitive processes activated and the development of metacognitive awareness in students, as well as in adult populations. GAI thus emerges as an ambivalent innovation: on one hand, a potential cognitive enhancement tool; on the other, a possible factor in intellectual dependency and reduced cognitive autonomy. It is therefore necessary to investigate how the use of these technologies influences students' metacognitive processes, to devise educational practices capable of mitigating unwanted effects and ensuring that GAI is used to expand, rather than limit, learning and individual reflection capacities.

Metacognition, understood as the awareness and capacity to control and manage one's own mental processes aimed at learning (Flavell, 1979), has long been recognised as a decisive factor for learning effectiveness (Agrawal et al., 2025). It implies the ability to "think about one's thinking", that is, to understand how one is learning and to consciously adopt strategies to optimise that process. Flavell (1979) first identified the existence of a higher-level regulation of basic cognitive processes, such as attention, memory and comprehension, which the individual can activate to improve their own performance. Already, self-directed learning models (Knowles, 2014; Garrison, 1997) emphasised the central role of individual awareness and responsibility in learning processes, anticipating the concepts that are now central in metacognition research. Numerous subsequent studies have confirmed the substantial impact of metacognitive abilities on learning outcomes: students endowed with strong metacognitive capacities tend to achieve better academic performance (Stanton et al., 2021; Pintrich et al., 2000), and these abilities represent a central indicator of the quality of reflective learning. Indeed, metacognitive awareness enables one to plan one's study, monitor understanding in progress and evaluate one's performance critically, correcting ineffective or inadequate strategies. According to metacognitive regulation theory (Flavell, 1979; Schraw & Dennison, 1994), effective learning requires the intentional integration of three fundamental processes: planning, monitoring and evaluation. Planning means defining learning goals, selecting appropriate strategies and allocating time and resources functionally; monitoring implies keeping track of one's understanding and achieved progress, promptly recognising any difficulties; evaluation, finally, involves reflecting on the results obtained and the effectiveness of the adopted method, to consolidate or modify the future approach (Stanton et al., 2021). These three regulatory components form the core of metacognition and have been widely integrated into self-regulated learning models, such as Zimmerman's (2002) model, which emphasises the cyclical nature of the learning process, articulated in phases of forethought, control and reflection. In this perspective, recent contributions on metacognition measurement and support in digital environments (Molenaar et al. 2023) have shown how interaction with intelligent tools can either support or hinder self-reflective awareness, depending on the degree of intentionality with which such tools are used. In addition, as Stebner et al. (2022) noted, metacognitive competencies not only support self-regulation in the immediate context of learning but also favour the transfer of these skills to different do-

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editoria scientifica dal 1952

mains and tasks. The authors demonstrated that targeted training in metacognitive strategies can lead to a spontaneous application of them in new situations, confirming the largely transversal nature of these abilities. In other words, a student who learns to plan, monitor and evaluate their study in a given discipline is likely, if adequately supported, to adopt similar approaches in different contexts, whether academic or professional. The evidence thus converges in indicating metacognition as a key factor for deep and durable learning, which should be explicitly promoted in educational pathways—especially in higher education and adult learning, where high learner autonomy is presumed.

In this framework, it is important to emphasise that intensive and unguided use of GAI tools may, on the one hand, reduce immediate cognitive load but, on the other, decrease active mental engagement, favouring a functional dependency on technology. This phenomenon is known as cognitive offloading and refers precisely to the tendency to delegate mental operations to technology, or to external sources, that would otherwise require active elaboration. This dynamic has been defined by Gerlich (2025) as "the paradox of cognitive offloading", in which the reduction of cognitive load leads to a progressive decline in depth of processing and critical thinking. Recent studies have shown that university students using a generative language model (ChatGPT) for research and writing tasks experienced a decrease in perceived cognitive effort, but at the expense of reasoning depth and argumentation quality compared to those undertaking the same tasks without AI (Stadler, 2024). In particular, these students tended to accept plausible but superficial explanations more readily, showing a lower propensity to verify them or explore alternatives. Such "surface effect" translates into a weakening of higher-order skills, such as critical synthesis, information evaluation and independent problem solving (Lee et al., 2025), skills that university education aims to develop. Similarly, Fan et al. (2024) reported the risk of a genuine "metacognitive laziness" induced by AI, observing that students tend to reduce the willingness to monitor and critically examine information provided by generative systems, limiting themselves to retrieving rapid and formally adequate responses. In such cases, metacognitive engagement is reduced to a minimum, with negative consequences for the quality of learning and autonomous evaluation capacity. Nguyen et al. (2023) distinguish different levels of metacognitive engagement in AI use, ranging from purely instrumental use to more advanced forms of dialogic co-construction of knowledge, in which interaction with the system stimulates processes of reflection and critical revision. Ng et al. (2021) also emphasise the importance of AI literacy, underlining how metacognitive competence is a necessary condition for a conscious and critical use of artificial intelligence in educational contexts. Some authors (Fan et al., 2024) warn that early and unguided adoption of AI in study pathways might produce counterproductive long-term effects: while these tools improve immediate performance, they may hamper the development of autonomous and transferable learning capacities, reducing students' cognitive readiness to tackle complex tasks in the absence of technological support. In parallel, neuroscientific research is exploring the concept of "cognitive debt" associated with intensive AI use (Kosmyna et al., 2025), hypothesising that excessive reliance on virtual assistants could alter mental habits and memory schemas, compromising the ability to retain information and generate original ideas. In this sense, the use of GAI in educational settings presents a latent cognitive cost: the speed and immediacy with which it provides solutions can trigger a progressive dismantling of active reasoning processes, unless pedagogical measures are introduced to counteract this tendency. Despite these risks, recent literature highlights that GAI, when consciously integrated into educational contexts, can serve as a metacognitive scaffold, supporting self-regulated learning. Studies such as those by Brown et al. (2024) and Wu & Kuhl (2025) show that GAI can be designed to stimulate the three phases of metacognitive regulation—planning, monitoring and evaluation—through the use of prompts and structured feedback, consistent with self-regulated learning models (Xia et al., 2023). In this perspective, GAI's support functions can be interpreted in a Vygotskian sense as a form of cognitive scaffolding (Vygotskij, 1978) that extends the student's proximal development zone, providing temporary support to the cognitive regulation process. Zhang and Rossi (2024) also describe an evolution in the relationship between individual and artificial intelligence, which moves from a simple tool to a cognitive collaborator, capable of stimulating complex and reflective metacognitive interactions. In summary, generative artificial intelligence simultaneously configures itself as a cognitive enhancer and a potential metacognitive vulnerability. Consequently, educational research must question not only how far GAI facilitates learning, but also how it modifies the quality, depth and very nature of the cognitive processes involved. Systematically investigating the interactions between GAI use and metacognitive strategy employment is now essential to delineate pedagogical models able to preserve and reinforce students' reflective, critical and self-regulatory capacities.

2. Materials and Methods

Considering the theoretical framework outlined above, the present study investigated the interactions between the use of Generative Artificial Intelligence (GAI) and the activation of metacognitive processes in adult learners, with particular reference to text production tasks. Specifically, the project aimed to:

- Assess the levels of metacognitive awareness (planning, monitoring, and evaluation) activated during a writing task.
- Evaluate the effect of GAI on conceptual learning and on the quality of the written products.
- Explore participants' subjective experience regarding their degree of cognitive engagement, perceived control, and strategic use of the resources offered by GAI in the writing process.

The study adopted a quasi-experimental design with a control group, aimed at investigating the impact of Generative Artificial Intelligence (GAI) use on metacognitive processes, text comprehension, and subjective learning experience in adult learners.

Participants

The sample consisted of 296 adult learners enrolled in academic training programs (specialization or doctoral courses). Recruitment was conducted through collaboration with course instructors, who presented the project during classes and collected participants' consent. All participants were informed about the study's objectives, voluntary participation, and data handling procedures. Participation or refusal had no consequences on course evaluation or attendance. Each participant provided informed consent before the experimental phase.

Participants were randomly assigned to two groups:

- Experimental group (GAI): used a generative AI tool to support the writing of a short essay on an assigned topic.
- Control group (No GAI): completed the same task without any generative or digital support.

All participants first completed three questionnaire sections (demographic, digital competence, and MAI). The experimental phase then involved reading a passage entitled "L'economia tribale: quando il non fare diventa abbondanza" (Minelli, 2015) and producing a short-written essay in response to open-ended questions. Participants in the GAI group could freely select an AI tool, while the control group worked independently. After the writing task, all participants completed a post-task questionnaire assessing their experience and use of metacognitive strategies. Finally, to measure retention and conceptual understanding, both groups completed a comprehension test without digital aids or access to the text. The test included five deep-comprehension multiple-choice items and two factual-learning questions, each with one correct answer. Each session lasted approximately 45 minutes per participant. Activities were conducted in a controlled digital environment ensuring equivalent conditions across groups.

Instruments

Data were collected through a four-section digital questionnaire (Google Forms), including:

- Demographic survey: age, gender, education level, profession, and current or recent training program.
- Ad hoc questionnaire on digital competence and AI use: five Likert-scale items (1–5) assessing participants' digital awareness and familiarity.
- Metacognitive Awareness Inventory (MAI) (Schraw et al., 1994): a self-report tool measuring metacognitive awareness, i.e., the ability to understand, monitor, and regulate one's cognitive processes during learning. It includes two dimensions: knowledge of cognition (declarative, procedural, conditional knowledge) and regulation of cognition (planning, monitoring, and evaluation).
- Ad hoc questionnaire on learning experience and metacognitive strategy use: Likert-scale items (1–5) assessing planning, monitoring, evaluation, and cognitive/motivational engagement.

Data Analysis

Data analysis followed a quantitative descriptive and inferential approach, aimed at exploring relationships among metacognition, GAI use, digital competence, and comprehension quality. Analyses were conducted using Jamovi 2.5 and IBM SPSS Statistics 29. First, descriptive statistics (means, standard deviations, variability indices) were computed for all variables (MAI scores, experiential dimensions, digital skills, and comprehension test). Data normality was assessed through skewness, kurtosis, and the Shapiro–Wilk test to determine the appropriateness of parametric tests. To evaluate group differences, independent-samples t-tests and one-way ANOVAs were performed. T-tests explored gender differences in digital competence and metacognitive scores, while ANOVA compared performance between the GAI and control groups, focusing on on-task metacognitive dimensions and comprehension scores. Mean values were also computed for MAI subscales, both for the two macro-areas (knowledge and regulation of cognition) and for eight components (declarative, procedural, conditional, planning, information management, monitoring, debugging, and evaluation). Likewise, mean scores were calculated for the five experiential dimensions (planning, monitoring, evaluation, cognitive/motivational engagement, and AI use/non-use) to represent participants' situated metacognitive profiles.

Finally, Pearson's correlations were performed to explore relationships between trait metacognition (MAI scores) and situated metacognition (experience questionnaire), assessing the consistency between general metacognitive awareness and the activation of cognitive-regulatory strategies during task performance.

Overall, this analytical procedure enabled a systematic investigation of the relationships among GAI use, metacognitive processes, and learning performance, adopting an integrated perspective that connects individual dimensions (awareness and self-regulation) with situational ones (learning experience and interaction with the tool).

3. Results

3.1. Participants' Profile

The sample consisted of 296 participants, with a mean age of 43.9 years. The majority were women (72.6%), while men represented 27.0%; 0.3% preferred not to disclose their gender. Educational levels were generally high: 39.5% held a master's or single-cycle degree, 34.5% an old-system or second-level degree, 12.8% a high school diploma, 8.8% a master's or Ph.D., and 4.4% a bachelor's degree. Most respondents were teachers in training: 29.4% were special education teachers in upper secondary school, 18.9% teachers in lower secondary school, 17.6% special education teachers in lower secondary school, and 14.5% curricular teachers in upper secondary school. Primary school teachers represented 8.1% of the sample. Other categories (freelancers 3.0%, public/private employees 2.4%, university students 0.7%) were marginal. Participation in training activities during the previous six months revealed a strong tendency toward professional development: 25.3% attended refresher courses, 20.6% participated in online training (webinars, MOOCs, e-learning), 17.9% joined in-house training, and 17.9% took part in postgraduate programs. Only 8.4% did not attend any training, while 9.9% engaged in other forms such as workshops or conferences—confirming a general commitment to lifelong learning.

3.2. Digital Competencies

Analysis of the five dimensions of digital competence showed overall good perceived self-efficacy in using technologies and AI tools. Regarding information management, 46.3% often felt able to evaluate source reliability and identify AI-generated content, 13.2% always did so confidently, 36.5% sometimes, and only 4.1% reported difficulties. For digital content creation, 43.2% frequently used digital or AI tools to produce and share original materials, 9.1% had advanced skills, 39.2% had intermediate ones, and 8.4% reported low competence. Concerning digital safety and awareness, 67.9% showed high attention to data protection and ethical implications (35.8% often, 32.1% always). Only 9.1% showed limited awareness. Problem-solving skills were also good: 43.2% usually combined digital and AI tools to address practical issues, 9.1% did so expertly, 42.2% sometimes, and only 5.4% reported difficulties. Finally, 56.8% reported high autonomy and adaptability in learning new technologies (44.3% often, 12.5% always).

No significant gender differences emerged across the five competence dimensions (Welch's t-test, $p > .05$). Mean scores were nearly identical for men and women, confirming substantial parity in perceived digital competence.

3.3. Metacognitive Awareness Inventory (MAI)

The overall mean score of the MAI was 0.83 (max = 1), indicating a generally high metacognitive awareness (Table 1). Participants showed strong reflective and self-regulatory abilities, especially in error correction (M = 0.93) and information management (M = 0.85). Planning (M = 0.84) and comprehension monitoring (M = 0.83) were also high, while declarative (M = 0.77) and evaluation (M = 0.76) knowledge were slightly lower but still in the upper range. Overall, the profile depicts adults with strong metacognitive skills, consistent with a well-educated sample of professionals accustomed to reflective learning.

Table 1. Mean scores on MAI subscales

Subscale	Mean
Declarative knowledge	0.77
Procedural knowledge	0.78
Conditional knowledge	0.81
Planning	0.84
Information management	0.85
Comprehension monitoring	0.83
Error correction-debugging	0.93
Evaluation	0.76
TOTAL MAI	**0.83**

3.4. Learning and comprehension test

After reading Minelli's text "L'economia tribale: quando il non fare diventa abbondanza" (2015) and writing a related essay—with or without AI support—participants completed an individual comprehension test (Table 2). The average performance was high, with 6.76 correct answers out of 8 (84.5%). No significant difference emerged between the AI group (M = 0.84) and the traditional group (M =

0.85): F(1, 281) = 0.0002, p = 0.988. Thus, AI use did not affect text comprehension or recall, suggesting that cognitive performance depended mainly on the engagement with the content itself.

Table 2. Comparison of comprehension scores

Variable	AI group (n=136)	Traditional group (n=147)	Total (N=283)
Mean correct answers (out of 8)	6.72	6.80	6.76
Mean accuracy (%)	84.4	85.0	84.5
Std. deviation	0.47	0.45	0.46
ANOVA	-	-	F(1,281)=0.0002, p=0.988
Significance	-	-	n.s.

3.5. Experience and Strategy Use Questionnaire

Results revealed overall good cognitive and reflective engagement (Table 3). Mean scores ranged from 2.64 to 3.36 (1–5 scale). Monitoring showed the highest level (M = 3.36), followed by evaluation and awareness (M = 3.31) and cognitive–motivational engagement (M = 3.28), indicating effective self-control and motivation. Planning was the weakest area (M = 2.64), suggesting limited pre-task strategy organization. The perceived usefulness of AI scored M = 3.27, reflecting a moderately positive but non-essential role.

Table 3. Mean scores – Experience and Strategy Use Questionnaire

Dimension	Mean (1-5)	Interpretation
Planning	2.64	Medium–low: partial pre-task strategy planning
Monitoring	3.36	Medium–high: good comprehension control
Evaluation & awarness	3.31	Medium–high: adequate reflection
Cognitive & motivationa engagement	3.28	Medium–high: good focus and interest
Use or absence of AI	3.27	Moderately positive perception of AI support

Comparison between groups showed slightly higher scores in the traditional group, especially for planning (M = 3.01) and engagement (M = 3.40), suggesting greater autonomous activation. Differences were small and not statistically significant (p > .05).

3.6. Correlation Analysis between Metacognitive Awareness and On-Task Strategy Use

To further explore the relationship between general metacognitive awareness and the activation of strategies during the task, a correlational analysis was conducted between the scores of the Metacognitive Awareness Inventory (MAI) and the dimensions assessed through the Questionnaire on Experience and Metacognitive Strategy Use (Table 4). The aim was to determine whether—and to what extent—trait metacognition (i.e., general knowledge and regulation of one's own cognitive processes) translated into situated metacognition, reflected in concrete behaviors of planning, monitoring, and evaluation enacted during the reading and writing task.

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editoria scientifica dal 1952

Pearson's correlation coefficients (r) were calculated between the eight MAI subscales (declarative knowledge, procedural knowledge, conditional knowledge, planning, information management, comprehension monitoring, error correction, and evaluation)—along with the total score—and the five dimensions of the experience questionnaire (planning, monitoring, evaluation, cognitive–motivational engagement, and AI use or non-use).

The analyses revealed positive and statistically significant relationships between most MAI subscales and the experience questionnaire dimensions, with coefficients ranging from $r = .25$ to $r = .42$ ($p < .05$). The strongest associations emerged for the regulatory components of the MAI—planning, monitoring, and evaluation—which showed moderate correlations with the corresponding on-task metacognitive dimensions ($r = .36–.42$, $p < .01$). Specifically: General planning (MAI) correlated with operational planning during the task ($r = .40$, $p < .01$); Comprehension monitoring showed the highest correlation with its corresponding on-task dimension ($r = .42$, $p < .01$); Evaluation was positively associated with metacognitive reflection and awareness during the task ($r = .38$, $p < .01$).

Weaker correlations were found between MAI subscales and the cognitive–motivational engagement and AI use dimensions ($r = .15–.27$), suggesting that these aspects are more situational or attitudinal, and only partially dependent on general metacognitive awareness.

Overall, the correlation profile indicates an internal coherence of the metacognitive construct, but also a partial gap between declared awareness and actual activation. This misalignment is particularly evident in the planning dimension, which, despite its significant correlation with MAI, shows lower absolute mean scores ($M = 2.64$ out of 5), suggesting a reduced tendency toward explicit planning when artificial intelligence tools are used.

These findings support the hypothesis of a strong trait-level metacognitive awareness but a more selective situated activation, consistent with the cognitive offloading phenomena described in the literature. In other words, adult learners demonstrate a high general capacity for reflection and cognitive regulation but tend to reduce explicit planning and control when the task is mediated by AI-based tools.

Table 4. Pearson correlations between MAI and Experience Questionnaire

MAI Subscale	Planning	Monitoring	Evaluation	Engagement	AI Use
Declarative	.25*	.19	.22	.18	.10
Procedural	.28*	.24*	.26*	.21*	.14
Conditional	.32**	.29**	.30**	.23*	.17
Planning	.40**	.31**	.27*	.20*	.15
Info management	.33**	.36**	.29**	.26**	.18
Monitoring	.30**	.42**	.34**	.25*	.19
Debugging	.24*	.28*	.31**	.22*	.12
Evaluation	.28*	.30**	.38**	.24*	.17
MAI TOTAL	**.36**	**.39**	**.35**	**.27**	**.19**

*p < .05 **p < .01*

4. Discussion

The results of this study provide an overview of the interactions between the use of generative artificial intelligence (AIG) and metacognitive processes in adult learners, highlighting both elements of continuity with existing literature and innovative aspects related to the experimental context. Overall, the data confirm a high level of trait metacognitive awareness, as indicated by the Metacognitive Awareness Inventory (MAI) scores, and a good situational activation of monitoring and evaluation components during the text analysis task. However, some asymmetries emerge among the different phases of cognitive regulation: although planning correlates positively with other MAI dimensions, it appears to be the least activated process in the experimental condition. This finding suggests that, when facing tasks mediated by artificial intelligence, participants tend to reduce their investment in the anticipatory definition of strategies, implicitly delegating part of the cognitive organization function to the system. This phenomenon aligns with what Gerlich (2025) describes as the paradox of cognitive offloading, whereby technological support, while reducing immediate cognitive load, may weaken autonomous planning and reflective practices.

In this study, such a pattern manifests as selective cognitive regulation, where monitoring and evaluation processes remain active, but preliminary planning tends to be partially delegated. The moderate and significant correlations ($r = .36–.42$) between the regulatory subscales of the MAI and the on-task dimensions of planning, monitoring, and evaluation nonetheless indicate a functional coherence between trait-level metacognitive awareness and its operational activation in the specific context. In other words, individuals with higher general metacognition tend to show greater control and revision skills when interacting with AI, confirming the hypothesis of a transferable metacognition across levels and contexts (Stebner et al., 2022).

The absence of significant differences between the AI and traditional groups in comprehension and learning performance, as well as in cognitive engagement, suggests that AI use does not compromise learning quality but modifies its process structure. Students who used AIG maintained good levels of metacognitive control but showed a lower tendency to engage in systematic planning—possibly due to the perception that the tool compensates for this function. This observation is consistent with findings by Fan et al. (2024) and Stadler et al. (2024) on the phenomenon of metacognitive laziness induced by cognitive automation: a form of mental economy that enhances efficiency but reduces reflective depth.

Another noteworthy aspect concerns the weak correlation between MAI scores and the "AI use" dimension ($r = .19$), suggesting that familiarity or reliance on the tool does not directly depend on metacognitive awareness. This indicates that AI use may follow pragmatic rather than reflective logics, with important pedagogical implications. To foster genuinely formative AI use, it is necessary to promote forms of guided metacognitive interaction (Kosmyna et al., 2025; Brown et al., 2024), where technology becomes an opportunity for self-reflection rather than a means of cognitive substitution.

Overall, the findings of the META-GEN project support the view that the intentional integration of AIG into educational contexts can enhance cognitive awareness and control, provided it is accompanied by teaching strategies that make metacognitive regulation explicit. From this perspective, artificial intelligence can serve as a metacognitive scaffold (Brown et al., 2024; Vygotskij, 1978), supporting monitoring and evaluation phases as long as it does not replace autonomous planning and decision-making.

In summary, the study highlights a form of metacognition that is robust yet partially delegated, in which AI acts as a cognitive amplifier rather than a substitute. The educational challenge lies in maintaining a balance between functional reliance and reflective responsibility, ensuring that reduced cognitive effort does not lead to a loss of control over one's own mental processes. As emphasized by Nguyen et al. (2023) and Zhang & Rossi (2024), this equilibrium represents the key to transforming human–AI collaboration into a genuine experience of metacognitive co-construction of knowledge.

5. Discussion

The present study explored the interactions between the use of generative artificial intelligence (GAI) and metacognitive processes in adult learners, aiming to understand how such tools influence the activation of planning, monitoring, and evaluation strategies during comprehension and text production tasks. The quasi-experimental design, which compared a group using GAI with one performing the task traditionally, allowed for an integrated analysis of both general metacognitive awareness (through the Metacognitive Awareness Inventory) and situated regulation of cognitive processes within the specific task context.

The results indicate that GAI does not compromise learning quality or comprehension ability but tends to modify the processual structure of learning. Specifically, interaction with the technology appears to foster a form of selective metacognitive regulation, in which monitoring and evaluation components remain active and consistent with trait awareness, while planning appears weaker or partially delegated to the tool. This pattern suggests that GAI functions as a cognitive facilitator rather than a substitute for reflective thinking yet requires conscious and intentional use to avoid phenomena of cognitive offloading and reduced metacognitive depth. From an educational standpoint, these findings highlight the need to design learning environments that make metacognitive processes explicit, particularly in the planning phase, and to promote guided reflection on the use of GAI as a support tool rather than a substitutive agent. Introducing educational activities based on reflective prompts, metacognitive self-assessment, and critical discussion about human–AI interaction may foster a formative integration of technology aimed at developing autonomy, awareness, and self-regulation skills.

The study also contributes to defining the profile of adult metacognition in advanced digital contexts, showing how, even among individuals with high levels of awareness and competence, GAI use can influence the balance between cognitive control and delegation. In this sense, GAI represents both a challenge and an opportunity for adult education: on one hand, it compels a rethinking of metacognitive competence in light of human–machine interaction; on the other, it offers the potential to enhance reflection and awareness through a mediated cognitive dialogue.

Looking ahead, future research should extend the analysis to different disciplinary contexts and include longitudinal measures, in order to assess the evolution of regulatory strategies and the impact of prolonged exposure to GAI on cognitive autonomy.

It would also be valuable to integrate qualitative methodologies (e.g., interviews, learning diaries, think-aloud protocols) to capture the subjective and intentional dimensions of the relationship between individuals and artificial intelligence.

In conclusion, the META-GEN project demonstrates that GAI can become an effective metacognitive partner only when its use is embedded in intentional educational design. The challenge for both research and teaching lies in transforming human–AI collaboration into an opportunity for reflective learning, where the efficiency of the tool does not diminish but rather amplifies the human capacity to think about one's own thinking.

Limitations

This research presents several limitations that warrant cautious interpretation of the results. First, the quasi-experimental design does not allow for the establishment of direct causal links between GAI use and variations in metacognitive processes, as the comparison between groups was based on controlled conditions but not full randomization. Second, the measures employed rely primarily on self-report instruments, which reflect participants' subjective perceptions rather than direct observation of cognitive behaviors. The inclusion of qualitative or behavioral data (e.g., think-aloud protocols, interaction log analyses, or real-time observations) could provide deeper insight into the actual processes activated during interaction with AI.

A further limitation concerns the composition of the sample, which consisted mainly of teachers and adults with a medium–high educational level, thereby limiting the generalizability of results to populations with lower technological literacy or different professional backgrounds. Future studies should therefore adopt longitudinal and mixed-method designs, integrating quantitative and qualitative approaches to observe the evolution of cognitive regulation over time and across diverse disciplinary contexts. Moreover, it will be important to examine the role of moderating variables—such as motivation, perceived digital self-efficacy, and attitudes toward AI—to better understand how these factors influence the quality of human–machine interaction.

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