BRAIN. Broad Research in Artificial Intelligence and Neuroscience
e-ISSN: 2067-3957 | p-ISSN: 2068-0473
Covered in: Web of Science (ESCI); EBSCO; JERIH PLUS (hkdir.no); IndexCopernicus; Google Scholar; SHERPA/RoMEO; ArticleReach Direct; WorldCat; CrossRef; Peeref; Bridge of Knowledge (mostwiedzy.pl); abcdindex.com; Editage; Ingenta Connect Publication; OALib; scite.ai; Scholar9; Scientific and Technical Information Portal; FID Move; ADVANCED SCIENCES INDEX (European Science Evaluation Center, neredataltics.org); ivySCI; exaly.com; Journal Selector Tool (letpub.com); Citefactor.org; fatcat!; ZDB catalogue; Catalogue SUDOC (abes.fr); OpenAlex; Wikidata; The ISSN Portal; Socolar; KVK-Volltitel (kit.edu)
2025, Volume 16, Special Issue 1 (April 2025), pages: 250-263.
Special Issue 1: *Neuroscience, Artificial Intelligence, and Innovation in Education*
Submitted: January 17th, 2025 | *Accepted for publication:* March 5th, 2025

Rethinking AI in Education: Highlighting the Metacognitive Challenge

Ilya Levin
School of Computer Science, Holon Institute of Technology, Holon 5810201, Israel.
levini@hit.ac.il
https://orcid.org/0000-0002-0298-4547

Michal Marom
School of Education, Tel Aviv University, Israel.
marommi19@gmail.com
https://orcid.org/0009-0003-1648-0897

Andrei Kojukhov
School of Computer Science, Holon Institute of Technology, Holon 5810201, Israel.
andreiko@hit.ac.il
https://orcid.org/0009-0001-0864-9950

Abstract: *Generative Artificial Intelligence (GenAI) is revolutionising education, but in doing so, it is often seen simply as a tool for automation and efficiency. This paper challenges this narrow perspective, arguing that GenAI's transformative potential lies in fostering Meta-AI skills—specialised metacognitive competencies for engaging AI as a cognitive partner. Our objective is to explore how GenAI reshapes learning environments and necessitates a pedagogical shift, hypothesising that traditional education paradigms are insufficient without Meta-AI skills to navigate GenAI's dynamic outputs. Drawing on constructionist theory, we conceptually analyse seven phenomena: learners' perceptions, reasoning transitions, scientific research paradigms, information processing shifts, tacit knowledge articulation, multimodal interactions, and early AI education.. The methodology involves synthesising theoretical and empirical literature to frame Meta-AI skills as essential for modern learning. Key results reveal that GenAI transforms education into interactive, exploratory spaces, shifting from symbolic to indexical processing and generalisation-based to situated reasoning. Multimodal GenAI enhances metacognitive awareness, while tacit knowledge exploration deepens self-reflection—outcomes requiring Meta-AI skills beyond conventional metacognition. Practically, educators can integrate these skills into curricula through scaffolded prompt engineering (e.g., refining AI queries), multimodal projects (e.g., creating cross-media narratives), and critical evaluation of AI outputs, empowering students to leverage GenAI effectively. We conclude that GenAI's integration demands a reevaluation of pedagogy, with Meta-AI skills bridging theoretical shifts and practical applications.*

Keywords: *generative AI; education; metacognitive skills; Meta-AI skills; constructionism; pedagogy.*

How to cite: Levin, I., Marom, M., & Kojukhov, A., (2025). Rethinking AI in education: Highlighting the metacognitive challenge. *BRAIN. Broad Research in Artificial Intelligence and Neuroscience, 16*(Sup1), 250-263. https://doi.org/10.70594/brain/16.S1/21

1. Introduction

The rapid advancement of generative artificial intelligence (GenAI) has brought about sweeping transformations across diverse areas of human endeavor, including education. In many conventional discussions, GenAI is conceptualised mainly as a technology designed to enhance day-to-day tasks and overall quality of life, particularly by automating processes and streamlining interactions. Indeed, it does fulfill these expectations, demonstrably improving efficiency and personalising the learning experience (Holmes, Bialik, & Fadel, 2023). Nevertheless, we argue that this view—while acknowledging GenAI's tangible benefits—remains incomplete and, in certain respects, significantly misguided.

Our research is guided by the conviction that the full potential of GenAI in education cannot be realised unless it is coupled with the systematic development of metacognitive skills among both learners and educators. Metacognition understood as the ability to plan, monitor, and critically reflect on one's own cognitive processes (Flavell, 1976), becomes increasingly vital in the GenAI era: it not only facilitates more effective use of technology but also provokes a central reconsideration of how learning unfolds, how educational interactions are structured, and how information is perceived (Winne & Hadwin, 1998). However, the unique attributes of GenAI—its dynamic, multimodal outputs and role as a cognitive partner—demand a specialized subset of metacognitive competencies—we term *Meta-AI skills*. Unlike traditional metacognitive skills focused on self-regulation in predictable contexts (e.g., monitoring comprehension during reading), Meta-AI skills encompass the ability to critically examine human-AI interactions, interpret variable and context-sensitive outputs, and strategically leverage GenAI's generative potential (Sidorkin, 2025). Recognising the pivotal role of these skills in unlocking GenAI's transformative capacity was the starting point of our investigation and remains the essence of our argument. We thus view GenAI not merely as a complementary tool but as a catalyst for profound changes in thinking, teaching, and self-organisation—shifts that demand a thorough reevaluation of conventional pedagogical paradigms.

The concept of meta-AI skills builds on a growing body of research exploring metacognition in AI-enhanced learning environments. Scholars have long recognised metacognitive skills as critical for self-regulated learning (Winne & Hadwin, 1998), but recent studies highlight their evolution in the context of AI integration. For instance, Luckin (2018) argues that AI systems amplify metacognitive processes by providing adaptive scaffolds that challenge learners to reflect on their strategies. Empirical evidence supports this: Khotimah and Rusijono (2024) found that AI-driven meta-learning strategies enhance both metacognitive and creative thinking skills in secondary students, while Yang and Xia (2023) demonstrated that AI-supported systems improve metacognitive regulation through personalised feedback, enabling learners to refine self-assessment. Similarly, Ojeda-Ramirez, Rismanchian, and Doroudi (2023) showed that active engagement with AI tools fosters self-awareness, enhancing students' ability to evaluate their learning processes.

Further research underscores the need for meta-AI skills as distinct from traditional metacognition. Chardonnens (2025) illustrates how Generation Z students benefit from AI-enhanced metacognitive scaffolding, leading to autonomous and intentional learning behaviours—outcomes tied to navigating AI's non-deterministic nature. Sidra and Mason (2024) emphasise that AI literacy must incorporate metacognitive awareness to prepare learners for AI-augmented environments, highlighting skills like assessing AI-generated content validity. These studies collectively suggest that while traditional metacognition supports individual cognitive management, meta-AI skills enable a collaborative cognitive partnership with AI, addressing its variability and interactivity (Holmes, Bialik, & Fadel, 2023).

One critical challenge emerging from GenAI integration is the inadequacy of traditional assessment models. As AI-generated outputs become increasingly personalised and adaptive, standardised metrics and fixed grading systems lose effectiveness (Bennett, 2011). For example, a GenAI-produced essay might vary significantly with each iteration, complicating traditional evaluation. This dynamic, non-deterministic nature necessitates a shift toward assessing metacognitive engagement, such as how students critique AI feedback or refine their strategies, over rote memorisation (Pellegrino & Hilton, 2012). Our research posits that meta-AI skills empower learners to discern the validity of AI-supported evaluations and adapt their self-assessment, aligning with calls for new assessment paradigms in AI-driven education (Luckin, 2018).

From a theoretical perspective, GenAI alters the epistemological landscape of learning, requiring students to engage with knowledge as emergent and co-constructed rather than static (Sidorkin, 2025). This aligns with broader discussions on AI as an epistemic partner, emphasising cognitive flexibility and adaptive reasoning over traditional knowledge delivery (Floridi, 2015). Our research builds on these foundations by systematically addressing meta-AI principles across seven phenomena: reshaping learners' perceptions, cognitive reasoning, research methodologies, information processing, tacit knowledge articulation, multimodal interactions, and early AI education. These phenomena, detailed in the following chapters, illustrate how Meta-AI skills foster critical thinking, enhance personalised learning, and equip students for real-world AI applications.

It is important to emphasise that the need for Meta-AI skills arises directly from new phenomena initiated by GenAI's technological advancements. The interplay of these phenomena and the metacognitive competencies required to navigate them form the core of our article. The structure of the paper is as follows: Chapter 1 explores how GenAI reshapes students' perceptions of the educational environment into a "cognitive playground," necessitating Meta-AI skills, analysed through Papert's (1980) constructionist "Bricolage." Chapter 2 contrasts traditional AI's deductive reasoning with GenAI's data-driven synthesis, calling for new pedagogical approaches. Chapter 3 examines GenAI's transformation of scientific research paradigms, requiring adaptability via Meta-AI skills. Chapter 4 addresses the shift from symbolic to indexical information processing, demanding nuanced interpretive skills. Chapter 5 highlights GenAI's interaction with tacit knowledge, enhancing self-awareness through Meta-AI literacy. Chapter 6 analyses how multimodal GenAI fosters metacognitive awareness across diverse representations. Chapter 7 investigates early AI education's role in nurturing metacognitive foundations. Chapter 8 outlines practical implications for educators, detailing strategies to integrate Meta-AI skills across educational levels. Next, in the rest of the paper, we will demonstrate how these phenomena cultivate critical thinking, personalised learning, and real-world readiness.

2. Thinking Like a Bricoleur: Epistemological Shift in the GenAI Age

The human relationship with digital technology has always been marked by ambiguity—an ambiguity that became particularly evident with the rise of personal computing (PC). In her book *The Second Self – Computers and the Human*, Sherry Turkle (1984/2005), observed that "children in a computer culture are touched by the technology in ways that set them apart from the generations that have come before" (p.155). She further noted that while adults tend to cling to the familiar, some moments and objects disrupt conventional ways of thinking, forcing us to reconsider what we take for granted. The PC was one such disruption. The PC, which became widely available in the late 1970s, was initially seen as another technological tool designed to improve efficiency and convenience, much like the telephone, washing machine, or car. However, unlike previous technologies that primarily required physical effort, PCs demanded cognitive engagement. Operating them required writing code, making computational thinking an essential skill. This marked the beginning of a deep ambiguity in our relationship with digital technology—was it merely a tool, or was it something more, an extension of human cognition?

This ambiguity has reached a new peak with the advent of GenAI, which does not simply assist human activities but plays an active role in shaping knowledge and altering our perception of the world.

Seymour Papert was among the first to recognize that the PC was not just a computing device but an entirely new cognitive phenomenon. He saw digital technologies as catalysts for profound changes in human thought, enabling individuals to construct knowledge in new ways (Levin, Semenov, & Gorsky, 2025). Unlike non-digital technologies, where interaction followed a standardised process, computers allowed for individualised engagement, where users could shape their interactions, and styles, and even construct personal "microworlds" (Papert, 1980). This reflective interaction allowed people to externalise their thinking and explore their own identity, as Turkle described: "The actual experience of using the machine offered a way to think about who one is and who one would like to be" (Turkle, 2005). However, at that time, this deep cognitive engagement was limited by the necessity of coding, which imposed structured, rule-based interaction that paradoxically resonated with the "instructionist" model of education that Papert himself opposed.

With GenAI's natural language interface, the reflective and interactive potential of computers is no longer confined to those who can program—it is now available to all. Papert envisioned computers as "a machine that brings back a natural character to learning" (Papert, 1980), and with GenAI, this vision is fully realised. Learning through exploration and personalised knowledge construction no longer requires mastery of formal programming languages—it can now be achieved through one of the most natural human abilities: verbal communication. Moreover, GenAI interactions are dialogue-based, where the AI's responses are shaped by the user's individual thoughts, interests, and articulation.

This brings us back to the broader epistemological transformation introduced by GenAI. Digital technology is no longer just a tool; it is an epistemic entity that actively participates in knowledge construction. The shift from knowledge scarcity to knowledge abundance (Floridi, 2015), and the rise of interactive, user-generated content in the Web 2.0 era, have already reshaped how we perceive expertise and authority. GenAI takes this transformation a step further, making the act of learning itself an iterative, interactive, and emergent process. Understanding this requires Meta-AI skills, which enable learners to engage with AI-generated content critically, navigate iterative knowledge construction, and recognise the epistemological implications of AI-mediated learning.

A helpful metaphor for this shift is the concept of Bricolage, introduced by Claude Lévi-Strauss (1968) and later applied by Turkle and Papert (1992) in their study of programming styles. Traditional epistemology, embodied in university-level programming education, was based on structured, rule-driven mastery, following a top-down, divide-and-conquer approach. In contrast, Bricolage was characterised by playful, exploratory engagement, where elements were moved around like words in a sentence, notes in a musical composition, or collage fragments. With the digital era dissolving rigid boundaries between knowledge producers and consumers, Bricolage has become a dominant epistemological mode, reflecting a shift from linear, predefined knowledge acquisition to interactive, emergent learning.

In the GenAI era, Bricolage evolves into artistic thinking. Lévi-Strauss (1968) positioned the artist as a bridge between the adaptive, resourceful Bricoleur and the structured, goal-oriented engineer. This hybrid approach defines knowledge construction in the age of GenAI—combining open-ended exploration with precision and intentionality. Interacting with GenAI reflects this dynamic: learners engage in iterative cycles of shaping AI outputs, refining responses, adjusting prompts, and remixing ideas, much like an artist working on a canvas.

Thus, integrating GenAI into education requires rethinking its role—not just as a functional assistant for creating lesson plans or quizzes but as a transformative epistemic entity that reshapes how knowledge is constructed. Meta-AI literacy is crucial for making this transition, equipping learners to critically and creatively engage with AI as a partner in knowledge construction.

3. From Traditional AI to Generative AI: A Paradigm Shift

The emergence of GenAI in education has highlighted a significant cognitive barrier: the deeply rooted perception of artificial intelligence shaped by decades of experience with traditional digital systems. This established understanding of AI, grounded in deterministic and rule-based systems, creates substantial challenges for effectively implementing emerging GenAI in educational settings. The difference between these two types of AI systems necessitates not only technical adaptation but also a comprehensive transformation in how educators and students perceive and engage with artificial intelligence.

The traditional perception of AI as a symbolic system is characterised by a deterministic approach to information processing. Its algorithms follow clearly formulated rules and logical inferences, ensuring transparency and predictability of results. For example, early AI tutoring systems like the Geometry Tutor (Anderson et al., 1995) provided step-by-step guidance based on predefined rules, offering consistent feedback such as "Move the line segment here" when a student erred. This approach has shaped the expectations of educational process participants, who view AI systems as predictable tools that operate with explicit rules, provide unambiguous answers, and function within well-defined evaluation criteria. As a result, educators and students have internalised a rigid understanding of AI that assumes stability, determinism, and rule-based reasoning.

GenAI, however, represents a different paradigm. Built on neural networks and trained on vast datasets, GenAI systems generate new content, adapt contextually, and engage in open-ended dialogue. For instance, a teacher might ask a tool like ChatGPT to create a lesson plan on climate change, receiving a unique response that includes a narrative, suggested activities, and even a generated image of a melting glacier—outputs that vary with each request and depend on the context of the prompt. These attributes clash with traditional mental models of AI, requiring new technical strategies for implementation and a profound cognitive shift in how artificial intelligence is understood within the educational process.

This extraordinary situation creates a perceptual disconnect that manifests in several key ways. Educators accustomed to deterministic systems struggle to evaluate student work involving GenAI because its outputs are variable and context-dependent rather than fixed and traceable. For example, a student using GenAI to write an essay might produce a different version each time, challenging a teacher used to grading standardised responses. Students, meanwhile, often approach GenAI with inappropriate expectations—either seeking definitive answers, as they would from traditional AI, or underestimating its potential for creative dialogue. Both groups frequently misinterpret GenAI's capabilities and limitations, leading to either overreliance (e.g., accepting an AI-generated historical analysis without fact-checking) or hesitancy in integrating it effectively into learning.

Overcoming these challenges requires developing Meta-AI skills, which enable educators and learners to navigate this cognitive shift. These skills help users recognise and critically engage with the principal differences between traditional and generative AI, fostering an understanding of AI as a dynamic, interactive, and context-sensitive entity rather than a deterministic tool. For example, a student with Meta-AI skills might refine a GenAI prompt (e.g., "Explain photosynthesis with a metaphor") to improve the output's relevance, demonstrating adaptability and critical evaluation. By cultivating these skills, learners move beyond a rigid, rule-based view of AI, gaining the ability to interpret and evaluate AI-generated content with an awareness of its variability and situational nature. They learn to engage in productive, iterative dialogues with AI rather than expecting static answers, developing cognitive flexibility to adapt to AI's evolving responses and leverage its generative potential instead of seeking deterministic outcomes.

For educators, meta-AI literacy is essential in redefining assessment methods, such as using rubrics that reward creativity over conformity, guiding students in meaningful AI interactions, and rethinking pedagogical approaches that accommodate GenAI's creative and adaptive nature. Students, in turn, must learn to navigate AI's outputs critically, distinguishing between its generative strengths (e.g., brainstorming ideas for a science project) and its limitations (e.g., potential factual inaccuracies) while harnessing its potential as a partner in exploration rather than merely a source of predefined knowledge.

4. The Impact of GenAI on Scientific Research Paradigms

Another defining characteristic of GenAI, distinguishing it from traditional AI, is its generativity, an aspect embedded in its very name. While conventional AI systems follow pre-set rules to analyse data, GenAI can produce entirely new content that didn't exist before. This creative capability transforms scientific research by opening new possibilities for discovery and innovation. GenAI is changing how we approach scientific inquiry itself. Rather than just following established research methods, scientists can now explore knowledge in more contextual and flexible ways. This shift challenges traditional research approaches and introduces new methodologies. Adapting to these changes requires more than technical training; researchers and students need to develop "Meta-AI skills" to effectively navigate this transformation in creating and acquiring scientific knowledge.

Historically, scientific research has been anchored in pursuing universal principles through systematic generalisation and abstraction. Researchers sought to reduce the complexity of fundamental laws, constructing hierarchical knowledge structures that could be transmitted through education. For example, Newton's laws of motion were derived from generalised observations, forming a cornerstone of classical physics taught in schools. However, GenAI challenges this paradigm by demonstrating that knowledge can be generated dynamically, rather than extracted and classified. Consider NVIDIA's StyleGAN (Karras et a., 2019) as an illustrative example of this transformation. Traditional computer vision systems generate facial images based on mathematical averages and symmetrical ideals, reinforcing the principle of generalisation. In contrast, StyleGAN produces highly detailed, individualised faces that embrace natural asymmetries and variations (Figure 1). This capability underscores a crucial insight: valuable knowledge need not be reduced to universal patterns but can emerge through embracing complexity and specificity. This shift mirrors the broader epistemological transformation enabled by GenAI, one in which specificity and emergence take precedence over reductionism.

Figure 1. Images produced using NVIDIA's StyleGAN generative neural network

The faces in Figure 1 don't belong to real people—they were created by NVIDIA's generative neural network. These images are significant to our discussion of meta-AI skills because they appear completely authentic, challenging our assumptions about artificial content. We typically expect anything "artificial" to look generic or average. Since StyleGAN uses vast datasets, we might expect the results to look artificial, yet they appear remarkably real. This directly demonstrates why meta-AI skills are necessary: without them, we lack the cognitive tools to distinguish between human-created and AI-generated content or to understand the implications of this blurred boundary in educational contexts.

This transformation manifests across multiple dimensions. First, it challenges the traditional dominance of explanatory models over predictive capabilities. Classical scientific approaches prioritise understanding causal mechanisms, whereas GenAI systems can generate accurate predictions and useful outputs without explicitly revealing their internal processes. For instance, a GenAI model might predict protein folding patterns for drug design with high accuracy, even if the underlying reasoning remains opaque, offering practical value before full explanation. Meta-AI skills enable researchers to critically engage with this shift, ensuring they do not dismiss new forms of knowledge simply because they do not fit traditional explanatory frameworks.

Second, GenAI reconceptualises the relationship between knowledge and creation. Traditional research viewed knowledge as an external truth waiting to be discovered. In contrast, GenAI demonstrates how knowledge can be actively generated through interactions between AI systems and human users. For example, a biologist might collaborate with GenAI to simulate evolutionary scenarios, co-creating hypotheses that emerge from iterative dialogue rather than pre-existing data alone. This perspective introduces a more participatory and dynamic understanding of knowledge formation, where researchers are no longer just passive observers but co-creators of insights. Meta-AI skills help researchers navigate this new role, equipping them with the ability to engage in iterative, interactive knowledge production rather than relying solely on deductive reasoning.

The implications extend beyond scientific methodology and into education itself. This shift suggests a move away from standardised curricula toward personalised, context-aware learning approaches. Knowledge is increasingly understood not as a static body of information to be transmitted but as an emergent property arising from specific interactions and contexts. For instance, a student using GenAI to explore climate models might develop a unique understanding based on their prompts, differing from a classmate's—requiring meta-AI skills to adapt and validate this personalised knowledge. Without meta-AI literacy, students and educators may struggle to adapt to this shift, clinging to outdated models of knowledge transmission rather than embracing knowledge co-construction with AI.

Moreover, GenAI challenges the deterministic worldview prevalent in traditional scientific research. While classical approaches sought definitive answers, GenAI embraces probability, multiplicity, and contextual fluidity. This aligns with complexity theory (Cilliers, 2002), suggesting that knowledge might be better conceived as a space of possibilities rather than a collection of fixed truths. For example, a GenAI tool might generate multiple plausible solutions to an engineering problem, each valid in different contexts, rather than a single "correct" answer. Understanding this shift requires students and researchers to develop meta-AI competencies that foster epistemological flexibility, allowing them to work within uncertain, dynamic knowledge environments rather than expecting static, universally applicable results.

The methodological impact of this transformation is profound. Rather than strictly adhering to hypothesis-testing models, research incorporating GenAI can explore vast, previously unimagined possibilities, generating novel solutions and insights that might never emerge through conventional deductive approaches. For instance, chemists might use GenAI to design new materials by exploring thousands of molecular combinations, a task infeasible with traditional methods. This suggests a new model of scientific discovery, in which creativity and generation become as crucial as analysis and deduction. Meta-AI skills empower researchers to engage with this model, enabling them to balance exploratory generation with rigorous validation rather than rejecting GenAI's outputs as insufficiently structured.

At the heart of this transformation lies an emphasis on individual experience and context in knowledge creation. GenAI demonstrates how knowledge emerges through active engagement and creation, rather than through the passive reception of established truths. However, this shift requires new cognitive literacy, and meta-AI skills, which enable researchers and students to embrace a nuanced view of GenAI's outputs, treating them as starting points for exploration rather than absolute truths or dismissing them as unreliable. For example, a student might use a GenAI-generated dataset to hypothesise a new ecological trend, and then validate it with field observations, blending AI insights with traditional methods. Developing these competencies ensures learners can engage critically and productively with AI-generated knowledge, using it to enhance rather than replace traditional scientific methodologies.

5. From Symbol to Index: The Emerging Perception of Digital Technology

Integrating GenAI into educational practice necessitates a significant reconceptualisation of how we understand and perceive digital technologies. Charles Sanders Peirce's semiotic theory, particularly his concept of indexicality, provides a crucial theoretical framework for understanding these technological transformations and their contemporary relevance (Weatherby & Justie, 2022).

Traditional computer systems employed in education have been based on symbolic information processing, which involves manipulating symbols according to predetermined rules. Such systems are predictable and unambiguous in their responses, making them comprehensible to both educators and learners. However, GenAI systems operate in a markedly different manner, exemplifying what Peircean terminology defines as indexical information processing.

Indexicality in Peirce's understanding is inextricably linked with situationality, expressed in the triad of "here-now-with me." This characteristic explains one of the key features of GenAI systems, their capacity to generate different responses to identical inputs depending on the interaction context. Each system response is unique and conditioned by the specific moment of dialogue as if the system were reconceptualising the situation repeatedly.

This characteristic of GenAI radically transforms human perception of technology in the educational context. Unlike traditional educational tools, which are perceived as predictable and controllable, GenAI systems emerge as more "alive" and unpredictable interlocutors. This creates a new educational reality where interaction with technology assumes characteristics of genuine dialogue while simultaneously generating uncertainty and potentially causing discomfort for users accustomed to deterministic systems.

In this unprecedented situation, where digital technologies no longer function as mere tools but as interactive, adaptive agents, the development of meta-AI skills becomes essential. Learners must acquire the ability to interpret the variability of AI-generated responses, understand the situational nature of AI interactions, and critically assess how context influences outputs. Meta-AI skills enable students not only to navigate this new technological landscape but also to leverage the inherent flexibility of GenAI to create adaptive, personalized learning experiences. Instead of perceiving unpredictability as a drawback, learners equipped with meta-AI competencies can recognise it as a powerful feature, one that allows for deeper engagement, creativity, and co-construction of knowledge in the learning process.

Understanding the indexical nature of GenAI is thus not merely a technical necessity but a cognitive and epistemological imperative. It requires a shift in mindset, from viewing digital technologies as deterministic systems to engaging with them as dynamic, context-sensitive entities. By fostering meta-AI literacy, educators can help learners embrace this shift, transforming uncertainty into a resource for exploration and innovation in the educational process.

6. Unveiling Tacit Knowledge with LLMs

Introducing personal computers into people's homes marked a turning point in how individuals could create, store, classify, and process information. While initially instrumental in nature, these innovations significantly expanded human capabilities. As digital technologies evolved, they ceased to function merely as tools; instead, they began actively shaping and transforming human perception and experience (Levin, Semenov, & Gorsky, 2025). Early interactions with computers required users to define strict operational rules, making the computer's functionality an externalized reflection of human cognition (Turkle, 2005). This interaction was inherently structured, computational thinking necessitated formalised communication through programming languages and algorithmic flows. Users had to frame their thoughts within explicit syntactic and logical structures to interact with digital systems effectively.

LLMs introduce an essential shift in this relationship by enabling interaction through natural language. While some may view this as a mere UX (user experience) improvement, simplifying the interface, it represents a much more profound transformation. Communication through natural language moves beyond explicit formal structures into the realm of the implicit. Unlike traditional human-computer interaction, which relied on rigid syntax, LLM-based interactions allow for contextual, fluid, and personalised communication. Each exchange is shaped by the user's unique linguistic style, individual phrasing, and even errors, leading to AI-generated responses that are equally unique and non-reproducible. This makes interactions with GenAI deeply situated, personalised, and sensitive to individual nuances, resembling an authentic dialogue rather than a deterministic system response.

The most striking outcome of this situated dialogue is the uncovering of tacit knowledge—the implicit understanding we possess but struggle to articulate explicitly. Michael Polanyi (2009) states, "we know more than we can tell." Tacit knowledge consists of deeply ingrained cognitive patterns, experiences, and insights that are difficult to formalise. By generating responses uniquely tailored to the user's thoughts and context, LLMs act as a mirror to this unarticulated knowledge, making it more tangible than ever. This reflective dialogue allows users to engage with their own implicit understanding in ways previously inaccessible through traditional human-computer interaction.

Empirical studies underscore how GenAI facilitates this tacit knowledge acquisition, enhancing the development of meta-AI skills. For instance, research on conversational agents in organisational settings demonstrates their potential to elicit tacit expertise. A study by Zhang et al. (2024) explored tacit knowledge acquisition among academic researchers in Chinese universities, finding that LLM interactions, such as iterative questioning and contextual dialogue, enabled participants to externalise implicit insights about research processes, with social interaction via AI significantly enhancing awareness (aligned with Chapter 2's GenAI shift). Similarly, a cross-country analysis of IT professionals in Poland and the US (Kucharska & Erickson, 2023) showed that LLM-driven "learning by interaction" prompted tacit knowledge sharing, boosting innovation by making unconscious expertise actionable—echoing Chapter 3's emphasis on situated reasoning. In educational contexts, Yang and Xia (2023) found that AI-driven feedback systems in high school settings helped students articulate tacit problem-solving strategies, improving metacognitive regulation (Chapter 6), while the reflective nature of these interactions surfaced in implicit learning patterns (Chapter 7's multimodality). Arslan et al. (2024) indicate that incorporating LLMs for students' learning assessments allows a highly adaptive approach where students can express their knowledge in ways that correspond to their personal context, background, language, and even preferred modality. This means students' sub-surfaced, tacit knowledge has a better chance of being reflected in their assessment, rather than being lost in the standardised 'one-size-fits-all' approach.

These findings highlight GenAI's role beyond mere dialogue facilitation. In a multinational corporation study, AI conversational agents were shown to capture tacit knowledge from employees across cultures, transforming it into explicit organisational assets through iterative exchanges (Tyukin et al., 2018), a process tied to Chapter 4's indexical processing, as responses adapted to situational cues. Moreover, the reflective capacity of LLMs fosters Meta-AI skills by prompting users to critically analyse AI outputs against their own implicit understanding, as seen in studies where design students used GenAI to refine tacit design heuristics (Ojeda-Ramirez, Rismanchian, & Doroudi, 2023), resonating with Chapter 1's cognitive playground. Collectively, these studies suggest that GenAI not only mirrors tacit knowledge but also amplifies its acquisition through dynamic, personalised interaction, necessitating Meta-AI skills like adaptability and self-reflection.

In this unique situation, where AI systems do not merely execute predefined commands but engage in reflective, dynamic dialogues, developing meta-AI skills becomes essential. Learners must cultivate an awareness of how their tacit knowledge is surfaced and restructured through interaction with GenAI. They must learn to critically analyse AI-generated content, recognise its resonance with their own implicit understanding, and leverage this reflective process for deeper cognitive engagement. Meta-AI skills enable students to navigate this new learning paradigm, transforming AI from a passive tool into an active cognitive partner that helps articulate and expand their implicit knowledge. This transformation echoes Turkle's (2005) early observations about human-computer interaction, where computers served as a medium for externalising thought processes. However, GenAI takes this to an entirely new level, the interaction is no longer one-sided but a dynamic, two-way reflective experience. By integrating meta-AI skills, learners can move beyond the passive reception of AI-generated content and actively engage in a self-reflective dialogue, gaining an exceptional level of insight into their own cognition and knowledge construction.

7. Multimodal Generative AI as a Catalyst for Metacognitive Awareness

The power of generative AI emerges from its fluid integration of multiple modalities, text, speech, images, audio, and beyond. This multimodality invites both teachers and students into a more contemplative relationship with their thinking processes. When engaging with multimodal AI, users naturally begin to observe how meaning shifts and transforms as it flows through different channels of expression. This interaction creates a unique metacognitive space where students and teachers become more attuned to the subtle interplay between different forms of representation. They begin to notice, for instance, how an idea expressed in text might take on new dimensions when transformed into an image, or how verbal explanation might illuminate aspects that remain hidden in visual form. This heightened awareness isn't taught through formal instruction but emerges naturally through exploration and reflection.

As users navigate between different modes of expression, they develop an intuitive understanding of how these various channels complement and sometimes challenge each other. They might discover that certain concepts resonate more deeply when expressed visually, while others gain clarity through verbal articulation. This organic development of metacognitive awareness becomes particularly vital as AI platforms seamlessly integrate into daily learning experiences. The richness of this multimodal landscape often reveals unexpected connections and insights. Teachers and students might find themselves naturally questioning why certain modes of expression feel more authentic or effective in particular contexts. This spontaneous reflection on their thinking processes, the essence of metacognition, emerges not from following prescribed guidelines but from genuine engagement with the multidimensional nature of knowledge representation.

GenAI's capacity to facilitate multimodal learning extends this process further, transforming educational environments into dynamic spaces where knowledge is explored across text, images, audio, and video through mechanisms like dynamic content generation and cross-modal translation (Mayer, 2009). For example, a student might use GenAI to generate a textual description of photosynthesis, a diagram of the process, and an audio narration, each reinforcing understanding while prompting reflection on how these representations differ, an interaction fostering meta-AI skills like cognitive flexibility and self-awareness (Chapter 5). Empirical studies support this: Yang and Xia (2023) found that AI-driven multimodal feedback in high school settings enhanced students' metacognitive regulation by revealing tacit strategies across formats, while Touretzky and Gardner-McCune (2022) note that early exposure to multimodal AI nurtures epistemological thinking (Chapter 7). This aligns with 21st-century competencies, critical thinking emerges as students assess coherence across modalities, problem-solving develops through reconciling discrepancies, and creativity flourishes in remixing outputs, echoing the Bricolage approach (Chapter 2). Educators can leverage this by assigning projects like multimodal narratives, though challenges like cognitive overload require scaffolding to ensure accessibility (Holmes, Bialik, & Fadel, 2023).

As AI continues to evolve, this natural development of metacognitive awareness opens new possibilities for creative expression and understanding. The interplay between different modalities creates a vibrant space for discovery, where both teachers and students can explore new ways of communicating, teaching, and learning, guided by their own reflective insights rather than predetermined frameworks.

8. The AI4K12 Initiative as a Theoretical Model for Meta-AI Skills Development

In their seminal chapter, "Artificial Intelligence Thinking in K–12", Touretzky and Gardner-McCune (2022) provide a theoretical model that resonates with our paper's central argument: the necessity of developing Meta-AI skills to effectively integrate generative artificial intelligence (GenAI) into education. Their work explores the integration of AI concepts into K–12 education, highlighting AI's pervasive influence and the societal transformations it drives, which necessitate a foundational understanding among young learners. Central to their discourse is the AI4K12 Initiative, which outlines a framework of five pivotal concepts, the "Five Big Ideas in AI" (Figure 2), delineating what K–12 students should comprehend about AI; these include how computers interpret sensory data to perceive the world through perception, how AI systems model information and make decisions via representation and reasoning, the mechanisms through which machines improve performance based on data in learning, the ways AI enables seamless communication between humans and machines through natural interaction, and a reflection on the ethical, cultural, and societal implications of AI integration as societal impact. This model not only demystifies AI technology but also frames it as a catalyst for shifting learners from static, ontological perspectives toward dynamic, epistemological thinking, a shift that mirrors our emphasis on meta-AI skills as specialized metacognitive competencies.

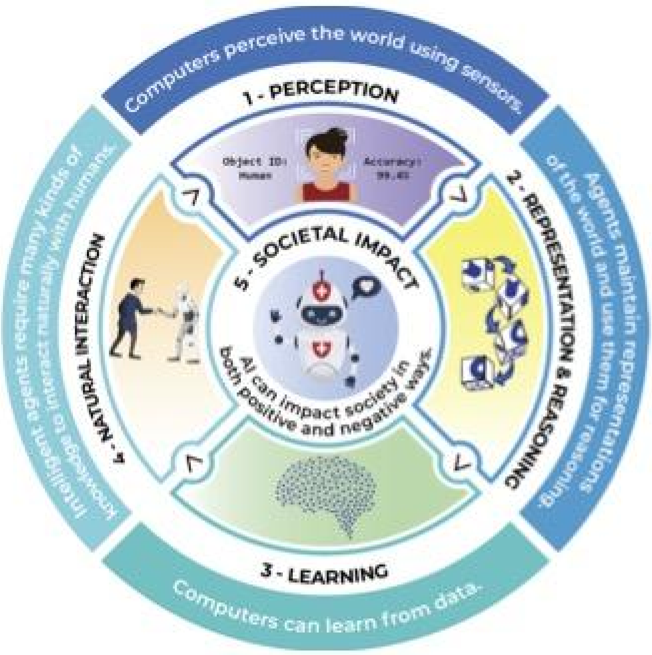

Figure 2. The Five Big Ideas in AI graphic from AI4K12.org

The AI4K12 Initiative supports our exploration of meta-AI skills as a compelling theoretical model, illustrating how early engagement with AI concepts fosters cognitive development vital for navigating GenAI's complexities. This alignment is evident across the initiative's framework: the "Perception" big idea connects to GenAI's multimodal capabilities, discussed in Chapter 6 of this paper, where learners interpret diverse outputs like text and images, requiring metacognitive awareness beyond traditional tools; "Representation & Reasoning" reflects the transition from symbolic to indexical processing, explored in Chapter 5, demanding adaptability to GenAI's context-sensitive responses; "Learning" ties to its data-driven synthesis, examined in Chapter 3, necessitating skills to refine dynamic outputs; "Natural Interaction" parallels GenAI's dialogue-based engagement, highlighted in Chapter 1, encouraging co-construction in a cognitive playground, and its capacity to surface tacit knowledge through reflective exchange, detailed in Chapter 5; finally, "Societal Impact" relates to reasoning through specific cases, outlined in Chapter 3, as students consider AI's broader implications, enhancing epistemological flexibility. Touretzky and Gardner-McCune's model thus provides empirical and theoretical support for our claim that Meta-AI skills, encompassing awareness, regulation, and strategic deployment, are critical for transforming GenAI from a passive tool into an active cognitive partner, offering a K–12 lens that complements our broader framework and underscores the urgency of metacognitive development in an AI-driven educational landscape.

9. Implications for Educators

The integration of generative artificial intelligence (GenAI) into education beckons a reimagination of teaching practices, where the cultivation of Meta-AI skills, specialised metacognitive competencies for partnering with GenAI, emerges as an urgent imperative to unlock its transformative promise. Drawing on the theoretical insights woven through this study, educators can weave these skills into the fabric of learning by guiding students to refine prompts, such as nudging "Explain gravity" toward "Explain gravity with a real-world example" to probe GenAI's fluid, context-sensitive responses, a practice that sharpens adaptability amid shifting information landscapes. This approach blossoms into multimodal explorations, where a middle school history class might conjure stories of ancient civilizations through GenAI-crafted text, images, and sound, inviting reflection on how these forms interplay to deepen understanding, an endeavor that sparks creativity and unveils tacit insights. In high school biology, students could simulate genetic mutations with GenAI, wrestling with variable outcomes to craft hypotheses, honing their capacity to reason through ambiguity, while a university computer science course might task learners with designing a user interface, critically sifting GenAI's suggestions to refine their craft, fostering a dialogue that bridges intuition and precision. Even at the elementary school, a weather unit could see young learners comparing GenAI-generated maps and narrations to real data, questioning their validity with a metacognitive curiosity that echoes the AI4K12 Initiative's vision (Touretzky & Gardner-McCune, 2022). Through such engagements, whether evaluating essays for reliability, co-creating experiments in collaborative exchanges, or journaling on AI's feedback, educators nurture a spectrum of Meta-AI skills, from self-awareness to epistemological flexibility, aligning with 21st-century demands like critical thinking and problem-solving. Yet, this shift calls for replacing conventional assessments with approaches that prize process and creativity, such as reflecting on GenAI interactions, a move that hinges on robust professional development to empower teachers, address challenges like cognitive overload, and chart a path for future research into scalable impact (Holmes, Bialik, & Fadel, 2023).

10. Conclusion

This study has examined the integration of generative AI (GenAI) in education, focusing on the metacognitive dimensions that underpin its effective implementation. Our analysis has revealed several emergent phenomena in human-AI educational interactions, including epistemological shifts in learner-AI relationships, enhanced access to tacit knowledge, and a transformation in traditional approaches to scientific generalisation. These findings underscore that successful AI integration in education extends beyond instrumental implementation, requiring reforming how we perceive, pursue, and engage with knowledge. It does not depend only on technical training but also on a fundamental reimagining of how we co-create knowledge alongside AI. Without this epistemological shift, attempts to incorporate GenAI into educational contexts risk reinforcing outdated instructional paradigms rather than unlocking the full potential of AI-driven learning.

Bridging this cognitive gap relies on developing specific metacognitive skills, which we term meta-AI skills. These skills enable researchers and learners to adapt to dynamic, AI-mediated knowledge environments, navigate uncertainty, and co-construct knowledge meaningfully. By fostering Meta-AI literacy, educators can transform uncertainty into a resource for innovation and deeper learning, ensuring that the potential of GenAI for scientific inquiry and human understanding is fully realised. Meta-AI skills align with and enhance 21st-century competencies essential for navigating an increasingly complex, technology-driven world.

First, meta-AI skills cultivate critical thinking by empowering learners to evaluate the validity, variability, and contextuality of AI-generated outputs. This involves questioning assumptions, assessing the reliability of dynamic content, and synthesizing insights across multimodal representations, indispensable skills in a knowledge-abundant era where information is both abundant and often ambiguous. Second, these skills reinforce problem-solving by enabling learners to engage in iterative, adaptive interactions with GenAI, leveraging its generative capabilities to explore non-standard solutions and address real-world challenges. For example, the Bricolage way of thinking portrays exploratory knowledge construction, fostering resourcefulness and creativity—key attributes of effective problem-solvers in the 21st century.

Moreover, the development of Meta-AI skills equips students with the cognitive flexibility to collaborate with AI as a partner, rather than merely a tool, mirroring the collaborative and innovative demands of modern workplaces. This alignment with critical thinking and problem-solving positions meta-AI literacy as a cornerstone of 21st-century education, preparing learners to address global challenges such as ethical AI deployment, through informed, reflective engagement with technology.

This work opens several avenues for future research, particularly in understanding the emerging phenomena associated with human-AI interaction in learning environments. As AI continues to reshape educational paradigms, further research into these areas will be crucial for developing resilient and adaptive educational systems. While this study provides a foundation for understanding the metacognitive dimensions of AI in education, additional research is needed to create specific pedagogical frameworks and implementation strategies that can support the systematic development of meta-AI skills across different educational contexts, ensuring they effectively nurture these essential 21st-century competencies.

References

Anderson, J. R., Corbett, A. T., Koedinger, K. R., & Pelletier, R. (1995). Cognitive tutors: Lessons learned. *Journal of the Learning Sciences, 4*(2), 167-207. https://doi.org/10.1207/s15327809jls0402_2

Arslan, B., Lehman, B., Tenison, C., Sparks, J. R., López, A. A., Gu, L., & Zapata-Rivera, D. (2024). Opportunities and challenges of using generative AI to personalize educational assessment. *Frontiers in Artificial Intelligence, 7*, Article 1460651. https://doi.org/10.3389/frai.2024.1460651

Bennett, R. E. (2011). Formative assessment: A critical review. *Assessment in Education: Principles, Policy & Practice, 18*(1), 5–25. https://doi.org/10.1080/0969594X.2010.513678

Chardonnens, S. (2025). Adapting educational practices for Generation Z: Integrating metacognitive strategies and artificial intelligence. *Frontiers in Education, 10*, Article 1504726. https://doi.org/10.3389/feduc.2025.1504726

Cilliers, P. (2002). Why we cannot know complex things completely. *Emergence*, 4(1–2), 77–84. https://doi.org/10.1080/15213250.2002.9687736

Doroudi S. (2023). On the Paradigms of Learning Analytics: Machine Learning Meets Epistemology December 2023 Computers and Education Artificial Intelligence 6(1):100192 https://doi.org/10.1016/j.caeai.2023.100192

Flavell, J. H. (1976). Metacognitive aspects of problem solving. In L. B. Resnick (Ed.), *The nature of intelligence* (pp. 231–236). Routledge.

Floridi, L. (Ed.). (2015). *The onlife manifesto: Being human in a hyperconnected era*. Springer. https://doi.org/10.1007/978-3-319-04093-6

Holmes, W., Bialik, M., & Fadel, C. (2023). Artificial intelligence in education. In *Data ethics: Building trust: How digital technologies can serve humanity* (pp. 621–653). Globethics Publications. https://doi.org/10.58863/20.500.12424/4276068

Karras, T., Laine, S., & Aila, T. (2019). A style-based generator architecture for generative adversarial networks. *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, 4401–4410. https://doi.org/10.1109/CVPR.2019.00453

Khotimah, K., & Rusijono, A. M. (2024). Enhancing metacognitive and creativity skills through AI-driven meta-learning strategies. *International Journal of Interactive Mobile Technologies, 18*(5), 1–15. https://doi.org/10.3991/ijim.v18i05.47705

Kong & H. Abelson (Eds.). (2022). *Computational thinking education in K–12: Artificial intelligence literacy and physical computing* (pp. 153–180). The MIT Press. https://doi.org/10.7551/mitpress/13375.001.0001

Kucharska, W., & Erickson, G. S. (2023). Tacit knowledge acquisition & sharing, and its influence on innovations: A Polish/US cross-country study. *International Journal of Information Management, 71*, 102647. https://doi.org/10.1016/j.ijinfomgt.2023.102647

Lévi-Strauss, C. (1966). *The savage mind*. University of Chicago Press.

Levin, I., Semenov, A. L., & Gorsky, M. (2025). Smart learning in the 21st century: Advancing constructionism across three digital epochs. *Education Sciences, 15*(1), Article 45. https://doi.org/10.3390/educsci15010045

Luckin, R. (2018). *Machine learning and human intelligence: The future of education for the 21st century*. UCL IOE Press.

Mayer, R. E. (2009). *Multimedia learning* (2nd ed.). Cambridge University Press. https://doi.org/10.1017/CBO9780511811678

Ojeda-Ramirez, S., Rismanchian, S., & Doroudi, S. (2023). Learning about AI to learn about learning: Artificial intelligence as a tool for metacognitive reflection. *OSF Preprints*. https://doi.org/10.35542/osf.io/64ekv

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. Basic Books.

Pellegrino, J. W., & Hilton, M. L. (Eds.). (2012). *Education for life and work: Developing transferable knowledge and skills in the 21st century.* National Academies Press. https://doi.org/10.17226/13398

Polanyi, M. (2009). The tacit dimension. In L. Prusak (Ed.), *Knowledge in organizations* (pp. 135–146). Routledge

Sidorkin, A. M. (2025). *AI integration blueprint: Transforming higher education for the age of intelligence*. AI-EDU Arxiv. https://doi.org/10.36851/ai-edu.vi.5126

Sidra, S., & Mason, C. (2024). Reconceptualizing AI literacy: The importance of metacognitive thinking in an artificial intelligence (AI)-enabled workforce. In *2024 IEEE Conference on Artificial Intelligence (CAI)* (pp. 1181–1186). IEEE. https://doi.org/10.1109/CAI59869.2024.00211

Touretzky, D. S., & Gardner-McCune, C. (2022). Artificial intelligence thinking in K–12. In S.-C.

Turkle, S. (2005). *The second self: Computers and the human spirit* (20th anniversary ed.). MIT Press.

Turkle, S., & Papert, S. (1992). Epistemological pluralism and the revaluation of the concrete. *Journal of Mathematical Behavior, 11*(1), 3–33.

Tyukin, I. Y., Gorban, A. N., Sofeikov, K., & Romanenko, I. (2018). Knowledge transfer between artificial intelligence systems. *Frontiers in Neurorobotics, 12*, 49. https://doi.org/10.3389/fnbot.2018.00049

Weatherby, L., & Justie, B. (2022). Indexical AI. *Critical Inquiry*, 48(2), 381–415. https://doi.org/10.1086/717312

Winne, P. H., & Hadwin, A. F. (1998). Studying as self-regulated learning. In D. J. Hacker, J. Dunlosky, & A. C. Graesser (Eds.), *Metacognition in educational theory and practice* (pp. 277–304). Lawrence Erlbaum Associates Publishers.

Yang, Y., & Xia, N. (2023). Enhancing students' metacognition via AI-driven educational support systems. *International Journal of Emerging Technologies in Learning, 18*(24), 133–148. https://doi.org/10.3991/ijet.v18i24.45647

Zhang, J., Li, J., Alam, S., Boamah, F. A., & Wen, D. (2024). Factors of tacit knowledge acquisition and its mechanism of action on academic research performance: An empirical research from Chinese universities. *Kybernetes*. Advance online publication. https://doi.org/10.1108/K-09-2023-1650