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Toward a Socio-Cognitive Framework for AI Literacy in K–8: Integrating Cognitive Science and Learning Sciences Perspectives

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Abstract: Artificial Intelligence (AI) is reshaping the civic, social, and educational landscapes that children inhabit. While calls for K–8 AI literacy are expanding globally, the field lacks coherent theoretical grounding for how children learn to understand and reason about AI systems. This paper proposes a socio-cognitive framework that integrates cognitive science and Learning Sciences perspectives to conceptualize AI literacy as a process that is both individually constructed and socially situated. The framework highlights how cognitive mechanisms (such as analogy, metacognition, and reasoning about uncertainty) emerge through collaborative, participatory learning contexts. By positioning cognition within designed social ecologies, this framework provides a foundation for designing equitable, developmentally appropriate AI literacy experiences. We argue that understanding how children make sense of AI requires integrating cognitive and sociocultural theories to advance design, research, and practice in AI education.

Introduction

Artificial Intelligence (AI) is rapidly transforming what it means to learn, work, and participate in society (Miao et al., 2021; Holmes et al., 2022). As AI systems increasingly shape daily life—from recommendation engines to automated decision-making—understanding how such systems work and how they affect individuals and communities has become a critical dimension of 21st-century literacy. Within K–8 education, this has given rise to the growing field of AI literacy, which aims to help students understand, reason about, and ethically engage with AI (Touretzky et al., 2019; Lee et al., 2021).

Despite the momentum around AI literacy, current educational efforts remain largely fragmented across technical, ethical, and social domains. While existing frameworks such as AI4K12 (Touretzky et al., 2019), UNESCO's AI and Education guidelines (Miao et al., 2021), and Digital Promise's AI Literacy Competencies (Digital Promise, 2024) define essential content and skills, much less is known about how children actually learn about AI. What forms of reasoning enable young learners to conceptualize abstract ideas like learning algorithms or bias? How do social interactions, tools, and designed environments shape these developing understandings?

Addressing these questions requires bridging two influential traditions: cognitive science and the Learning Sciences. Cognitive science offers powerful theories for understanding how learners make sense of novel, complex systems, highlighting mechanisms such as analogical reasoning, metacognition, and reasoning about uncertainty (Gentner, 1983; Chi & Ohlsson, 2005; D'Mello & Graesser, 2015). The Learning Sciences, in turn, emphasize that cognition is distributed across people, tools, and practices, and that learning is inherently social, participatory, and designable (Greeno, 1998; Sawyer, 2014; Nasir et al., 2023). Yet these perspectives are rarely integrated in current AI literacy research. Although existing AI literacy frameworks articulate competencies and ethical commitments, they rarely explain how learners develop conceptual understanding of AI systems. This paper addresses that gap by proposing a socio-cognitive framework that specifies the cognitive mechanisms through which AI understanding develops within participatory learning environments.

This paper advances a socio-cognitive framework for AI literacy that integrates cognitive and Learning Sciences perspectives to explain how children reason about and participate with AI. The framework positions reasoning processes, such as analogy, metacognition, and reasoning about uncertainty, within socially and culturally mediated learning environments. In this view, learning about AI involves both constructing conceptual coherence and negotiating meaning with others.

Our contributions are threefold:

1. We synthesize cognitive and learning sciences perspectives to conceptualize how children engage in AI literacy learning.
2. We propose a socio-cognitive framework that situates reasoning processes within social, ethical, and design contexts.
3. We outline implications for designing and studying AI literacy experiences that support understanding, participation, and agency in AI-mediated worlds.

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Theoretical background

This paper advances a conceptual synthesis grounded in structured theoretical integration rather than empirical data collection. We conducted an iterative review of scholarship across (1) AI literacy frameworks (e.g., Touretzky et al., 2019; Lee & Ali, 2020; Grover et al., 2022), (2) cognitive science research on reasoning about complex systems (e.g., Gentner, 1983; Chi & Ohlsson, 2005), and (3) Learning Sciences perspectives on situated and participatory learning (Greeno, 1998; Nasir et al., 2023). Through comparative analysis, we identified a gap: existing AI literacy frameworks specify competencies and ethical commitments but rarely articulate mechanisms of conceptual development. The socio-cognitive framework emerged from mapping cognitive mechanisms onto participatory AI literacy practices, iteratively refining alignments to ensure theoretical coherence and design utility.

Integrating cognitive science and learning sciences for AI literacy

While the Learning Sciences have long emphasized learning as situated and socially mediated, we argue that understanding AI literacy also requires attending to how learners reason about complex, non-intuitive systems. Our use of cognitive principles does not isolate mental mechanisms from context but treats them as emergent features of participation. Cognition, in this view, is enacted through talk, tool use, and reflection rather than internalized separately from them (Greeno, 1998; Enyedy, 2005).

The Learning Sciences and Cognitive Science share a central concern: understanding how people learn complex concepts in authentic contexts. Yet they have traditionally approached this challenge from different vantage points. Cognitive science focuses on the internal mechanisms of learning—such as analogy, metacognition, and conceptual change—while the Learning Sciences highlight how learning is socially situated, culturally mediated, and supported by design (Greeno, 1998; Lave & Wenger, 1991; Sawyer, 2014).

In the context of AI literacy, these perspectives are complementary and necessary. Understanding AI requires children to reason about abstraction, uncertainty, and probabilistic relationships—concepts that depend on robust cognitive mechanisms. At the same time, learning about AI occurs through participation in designed social contexts, including collaborative inquiry, storytelling, or project-based design, where meaning is co-constructed and culturally embedded (Nasir et al., 2023; Grover et al., 2022).

This integrative perspective aligns with growing calls within the Learning Sciences for multi-theoretical pluralism, recognizing that understanding learning about AI requires both the explanatory power of cognitive mechanisms and the ecological validity of situated, participatory learning (Gašević et al., 2023; D'Mello & Graesser, 2015).

Frameworks defining AI literacy in K–8 education

AI literacy is increasingly formalized through international frameworks that guide curriculum design and policy. The AI4K12 Initiative, developed by ACM, AAAI, and ISTE, defines Five Big Ideas in AI Education: Perception, Representation & Reasoning, Learning, Natural Interaction, and Societal Impact (Touretzky et al., 2019). These serve as developmentally appropriate entry points for understanding core AI principles.

Complementing this, Digital Promise's AI Literacy Framework (2024) defines AI literacy as the knowledge and skills that allow humans to understand, evaluate, and use AI systems safely and ethically. It emphasizes human judgment and justice-centered design. The AI Literacy Framework (AILit) (European Commission & OECD, 2025) further integrates global perspectives, combining insights from UNESCO (Miao et al., 2021) and DigComp 2.2 (Carretero et al., 2022) to articulate competencies across knowledge, skills, and attitudes.

Across these frameworks, a consensus emerges: AI literacy is multi-dimensional, blending cognitive understanding, ethical reasoning, and socio-technical participation. It requires learners not only to grasp algorithmic processes but also to reflect on the implications of those processes for equity and agency. This view moves AI literacy beyond the technical domain of computer science, positioning it as a critical 21st-century literacy aligned with the Learning Sciences' commitment to contextualized, justice-oriented education (Lee & Ali, 2020; Williams & Breazeal, 2022).

While socio-technical and justice-oriented models have significantly advanced the field by foregrounding ethics, civic participation, and power (Lee & Ali, 2020; Grover et al., 2022; Williams et al., 2022), they tend to emphasize competencies, dispositions, and design principles rather than mechanisms of learning. For example, frameworks often articulate that students should understand bias or engage in critical evaluation, but provide less theoretical guidance on how children develop the conceptual resources needed to reason about probabilistic systems, abstraction, or algorithmic agency. As a result, instructional designs risk either oversimplifying technical concepts or treating ethical critique as detached from conceptual understanding. The

socio-cognitive framework proposed here addresses this gap by specifying how cognitive processes, including analogy, metacognition, and causal reasoning, interact with social participation to produce AI understanding.

Recent scholarship further explores AI at the intersection of pedagogy and dialogic learning (e.g., Ilic, Casebourne, & Wegerif, 2024), emphasizing AI as a mediating partner in collaborative inquiry. These perspectives deepen our understanding of AI as a cultural and dialogic tool. Our framework complements this work by foregrounding the cognitive mechanisms that learners mobilize within such dialogic contexts, offering a cross-level account that connects reasoning processes to participatory pedagogy.

AI literacy and its relationship to computer science education

AI education is often introduced under the broader umbrella of Computer Science (CS) or Computational Thinking (CT). However, this conflation can obscure the distinct reasoning and learning demands of AI. Traditional CS emphasizes procedural problem-solving (such as mastery of syntax, control flow, and debugging) whereas AI literacy requires learners to engage in probabilistic reasoning, data interpretation, and ethical reflection (Ng & Nicholas, 2021; Lee et al., 2021).

For example, when students train a classification model, they must reason about uncertainty, overfitting, and bias—concepts that differ fundamentally from the deterministic logic of programming. These forms of reasoning rely on analogical mapping (Gentner, 1983), conceptual change (Chi & Ohlsson, 2005), and metacognitive reflection (Schraw, 1998), calling for design supports that make such cognitive processes visible and scaffolded.

Pedagogically, AI learning experiences often diverge from programming-based approaches. Rather than focusing on code execution, K–8 AI literacy often involves:

- Visual tools for model training (e.g., Teachable Machine, Machine Learning for Kids),
- Unplugged simulations exploring bias and fairness, and
- Narrative-driven projects connecting AI to civic life (Lee & Ali, 2021).

These design approaches align with the Learning Sciences' emphasis on participatory design and cross-disciplinary integration. For instance, integrating AI literacy into social studies or language arts enables students to engage both computationally and ethically with how data-driven systems shape civic life. By positioning AI literacy as related to but distinct from CS education, this paper underscores the need for theories of learning that address both the cognitive demands of reasoning about intelligent systems and the sociocultural contexts in which that reasoning develops.

The case for an integrative perspective

Cognitive and sociocultural theories each explain different aspects of how children learn about AI. Cognitive science helps explain how learners reason about abstract system behaviors, while the Learning Sciences clarify where and why that reasoning becomes meaningful through participation, tools, and discourse. A socio-cognitive approach therefore provides a more complete account: it recognizes that learners construct understanding through interaction between mental processes and designed environments.

For instance, when a group of students collaboratively debates whether a model's prediction is fair, they engage in joint sensemaking that integrates cognitive reasoning (interpreting the model's logic) with social negotiation (evaluating fairness in a shared context). This dual lens enables educators to design AI literacy experiences that are simultaneously cognitively generative and socially transformative (Enyedy, 2005; Nasir et al., 2023).

Our contribution builds on these approaches by clarifying the cognitive mechanisms that underlie meaning-making—how learners draw analogies, manage uncertainty, and reflect on algorithmic behavior. Integrating these processes with sociocultural perspectives offers a mechanistic account of reasoning that strengthens both theoretical coherence and design utility. Rather than replacing socio-technical or justice-oriented models, this framework deepens them by specifying how conceptual understanding and ethical reflection co-develop through activity.

Framework: A socio-cognitive model for AI literacy

Overview

Extending this argument, the socio-cognitive framework conceptualizes AI literacy learning as a dynamic process that integrates cognitive reasoning with social participation. Whereas existing socio-technical and ethical models

emphasize what learners should know about AI and why these understandings matter, this framework focuses on how reasoning develops through activity. It treats core cognitive processes as emergent within social interaction and tool-mediated practice, not apart from them. In this view, learning about AI involves both constructing conceptual coherence and negotiating meaning with others. The framework (Figure 1) models this interplay through three nested layers (cognitive processes, AI literacy practices, and learning ecologies) each influencing and being shaped by the others through cycles of participation, reflection, and design. Each layer represents a dimension of learning that interacts dynamically with the others:

- Outer layer: Learning Sciences ecology. Encompasses the social, cultural, and participatory contexts in which learning occurs—classrooms, community projects, and digital environments designed to promote collaboration and equity (Lave & Wenger, 1991; Nasir et al., 2023).
- Middle layer: AI literacy practices. Represents learners' engagement with the technical, ethical, and civic dimensions of AI, including understanding how models learn, reasoning about bias, and reflecting on societal impact (Touretzky et al., 2019; Lee et al., 2021; Digital Promise, 2024).
- Inner layer: Cognitive processes. Includes mechanisms such as analogical reasoning (a form of relational reasoning that supports mapping between known and novel systems; Gentner, 1983), metacognitive regulation (Schraw, 1998), and causal reasoning (Chi & Ohlsson, 2005) that enable learners to make sense of AI as an adaptive, probabilistic system.

Rather than depicting these as separate domains, the framework emphasizes reciprocal influence. Cognitive processes develop through social participation and tool-mediated activity, while participatory contexts are shaped by learners' developing cognitive repertoires.

Learning as socio-cognitive coordination

At its core, the framework treats AI literacy as a coordination problem—learners must integrate intuitive understandings of intelligence with novel, abstract representations of algorithms and data. For example, when students train a simple machine learning model, they may draw analogies to human learning ("the computer is practicing") while also reasoning about statistical patterns ("it's counting examples"). These analogies are not simply cognitive shortcuts but socially negotiated explanations constructed through dialogue and collaboration (Enyedy, 2005). Through this coordination, learners develop increasingly sophisticated mental models of AI that are both cognitively coherent and socially meaningful. Teachers and peers scaffold this process by introducing tools, representations, and ethical discussions that connect computational mechanisms to real-world implications (Grover et al., 2022; Williams et al., 2023).

A common example of socio-cognitive coordination occurs when learners anthropomorphize AI, treating it as a "trusted friend" or moral agent (Druga, 2018; Williams et al., 2023). Such analogies can both aid and hinder understanding: they help students reason about learning and communication but may obscure the role of data or bias in shaping AI behavior. Within the socio-cognitive framework, these moments are interpreted not as errors but as productive entry points for reflection and conceptual refinement. Teachers can leverage them to prompt critical discussion about what distinguishes social intelligence from algorithmic pattern recognition, fostering deeper metacognitive and ethical reasoning.

Design implications

The framework provides a foundation for designing AI literacy learning environments that are:

- Cognitively grounded: Support reasoning about abstraction, uncertainty, and model behavior through analogies, visualizations, and reflective prompts.
- Socially situated: Embed learning in collaborative, participatory contexts that foreground ethics, fairness, and civic implications.
- Developmentally appropriate: Align tasks with children's cognitive readiness and experiences with AI in everyday life.

Effective AI literacy design depends on aligning supports across all three layers of the framework (Figure 1).

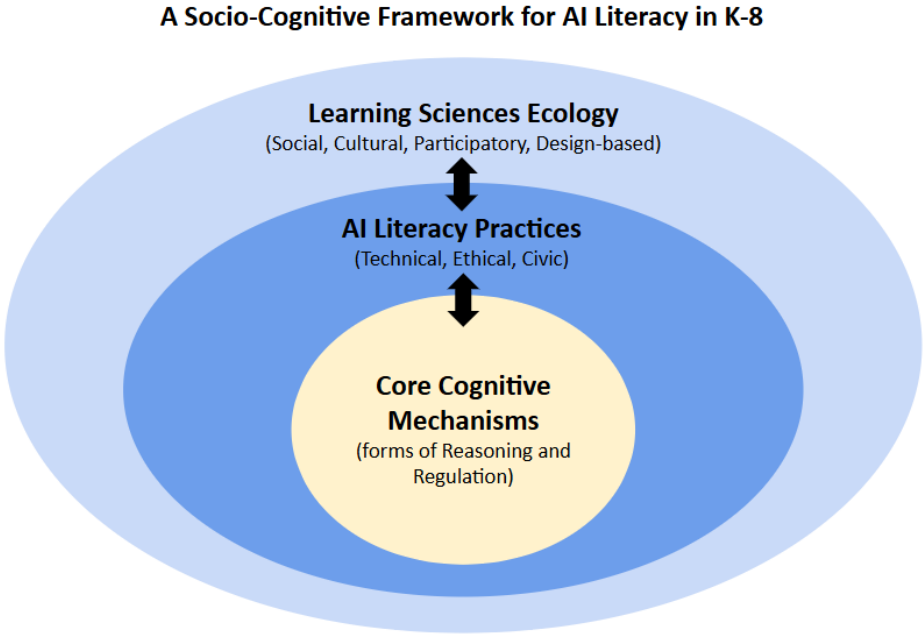
Contributions and significance

This paper contributes to the Learning Sciences in three interrelated ways.

1. *First, a conceptual synthesis.* We integrate cognitive and sociocultural perspectives to explain how K–8 learners come to understand, reason about, and participate with AI systems. Rather than treating cognition and context as competing explanations, we propose that children's reasoning about AI emerges through the coordination of mental processes and socially mediated practices. This synthesis extends ongoing work on the convergence of cognitive and situative perspectives (Greeno, 1998; Enyedy, 2005; Sawyer, 2014).
2. *Second, a socio-cognitive framework for design and analysis.* The framework (Figure 1) positions core cognitive mechanisms as interpretive anchors within broader social and cultural ecologies. It offers a structure for analyzing how learners engage in AI literacy practices, supporting design-based research that links cognitive reasoning with collaboration, dialogue, and participation.
3. *Third, a foundation for equitable AI learning.* By embedding cognition within designed, participatory contexts, the framework supports learning environments that connect technical understanding with ethical and civic engagement. It responds to calls for AI education that addresses both conceptual mastery and social responsibility (Lee & Ali, 2021; Nasir et al., 2023).

Together, these contributions position the paper as a mechanistic extension of existing AI literacy frameworks (articulating how understanding develops, not only what it entails), thereby advancing theoretical precision within the field.

Figure 1
A socio-cognitive framework for AI literacy in K–8 education.



*Note.*The framework models learning as a layered system where core cognitive processes (including forms of reasoning such as analogy and causal inference) are nested within AI literacy practices (technical, ethical, civic) and broader learning ecologies (social, cultural, participatory). Arrows indicate reciprocal influence across layers.

Implications for design and research

Designing learning environments

The framework suggests that AI literacy experiences should intentionally connect cognitive supports with participatory practices, ensuring that abstract reasoning about AI is grounded in meaningful social activity. For example, instruction might pair visualizations that make model reasoning transparent with classroom discussions about fairness and bias. Such activities help students reason about uncertainty and reflect on their own thinking (Schraw, 1998) while encouraging collective inquiry and critique (Nasir et al., 2023).

The framework also helps educators make design choices responsive to students' reasoning. For example, analogical reasoning may be strengthened through teacher prompts that connect AI systems to familiar human experiences ("How is this like when you learn something new?"). Metacognitive reflection can be encouraged through classroom discussions that ask students to explain why a model made a certain decision or how they might improve it. When students encounter uncertainty (such as when a model misclassifies an image) teachers can guide them to articulate hypotheses about data or bias. These instructional strategies position cognitive processes as visible and discussable, turning reasoning moments into shared opportunities for sensemaking.

AI learning environments should also make model interpretability and human judgment central design goals. In early prototypes, this might include scaffolded visualizations that reveal how data shape predictions or adaptive prompts that encourage learners to compare human and machine reasoning processes (Lee & Ali, 2021; Williams & Breazeal, 2022). Embedding these design features within collaborative structures, such as paired discussions or classroom debates, supports both conceptual and ethical dimensions of AI literacy.

Furthermore, design-based research (DBR) approaches are well positioned to iteratively test how cognitive scaffolds function in authentic settings. DBR aligns with the Learning Sciences commitment to design for understanding, not control, and to refine both theory and practice through cycles of co-design, implementation, and analysis (Design-Based Research Collective, 2003). Applying this approach to AI literacy allows researchers to trace how children's reasoning evolves through different representational tools, social configurations, and epistemic framings.

Illustrative example

As students examine misclassifications, one student remarks, "It thinks all the darker bees are the same kind." Another responds, "Maybe it didn't get enough pictures of those." The teacher probes: "How is that similar to how people learn?" A student replies, "If I only study one example, I'll probably get confused."

The teacher then introduces a visualization of the training data distribution and asks, "What might happen if most of our pictures come from one region?" Students begin discussing whether the model might misrepresent pollinators from underrepresented ecosystems. One student notes, "Then it wouldn't be fair to those species."

In this sequence, multiple layers of the framework interact. At the cognitive level, students use analogical reasoning to map human learning onto statistical pattern recognition and engage in causal reasoning about data distribution. At the AI literacy practice level, they analyze model training and bias. At the ecological level, classroom norms of dialogue and shared critique make uncertainty and fairness discussable. The teacher's prompts make metacognition visible ("Why do you think it predicted that?"), linking conceptual refinement with ethical reflection.

Teacher professional learning

To operationalize the socio-cognitive framework across disciplines, professional learning should focus on helping teachers recognize shared epistemic practices that support AI reasoning, such as explanation, evidence evaluation, modeling, and critique. Across subject areas, educators can make reasoning visible through structured discussion routines, prompt students to compare human and AI-generated explanations, and create opportunities to examine how data shape conclusions. These practices align with familiar inquiry-based pedagogies while foregrounding cognitive mechanisms such as analogy, metacognition, and causal reasoning.

At the same time, enactment will vary by discipline. In science, teachers might emphasize causal modeling and data representation when students analyze AI-driven ecological or climate predictions. In mathematics, instruction may foreground probabilistic reasoning and interpreting model accuracy or error rates. In social studies, educators can center historical and civic analysis of algorithmic governance, surveillance, and power. In ELA, students might critique AI-generated narratives, examining voice, bias, and representation while reflecting on how data influence textual production. These subject-specific instantiations illustrate how the framework supports both conceptual development and ethical inquiry without requiring teachers to abandon existing curricular structures.

Professional learning communities can use classroom artifacts, such as student explanations of model behavior or dialogue transcripts, to practice pedagogical noticing of socio-cognitive reasoning (van Es & Sherin, 2008). Such work helps teachers align cognitive scaffolds with ethical and civic engagement rather than treating them as separate instructional goals.

Future research directions

The framework invites design-based and mixed-methods research examining how cognitive reasoning unfolds within social activity. Studies might trace how students' analogies evolve through collaboration, or how discussions of algorithmic bias influence conceptual change. Combining multimodal data sources (such as transcripts, clickstream data, and reflective journals) can reveal the interplay between individual and collective reasoning processes (D'Mello & Graesser, 2015).

The framework provides a lens for studying how instructional moves support reasoning-in-action. For instance, researchers might examine how specific prompts or representational tools elicit analogy, metacognition, or ethical reflection during collaborative AI activities. Design-based research could iteratively test and refine these supports, helping teachers recognize when learners are overextending social analogies (e.g., treating AI as a "trusted friend" or authority figure) and guide them toward more accurate conceptual models. Such work connects cognitive and social dimensions of reasoning, illuminating how classroom discourse shapes understanding of intelligent systems.

Methodologically, the framework encourages multi-level analysis: tracing micro-level cognitive mechanisms (e.g., analogical mapping or metacognitive monitoring) alongside macro-level social dynamics (e.g., group discourse, classroom norms). Integrating discourse analysis, computational modeling, and learning analytics can yield richer insights into how AI reasoning develops across contexts. The socio-cognitive framework can function as an analytic heuristic for design-based research (DBR), supporting iterative cycles of design, implementation, and analysis (Design-Based Research Collective, 2003). Within such cycles, the framework can guide researchers in tracing how specific scaffolds (such as reflective prompts or representational tools) support cognitive and social coordination during AI learning activities.

Finally, this perspective underscores the importance of equity-centered research. AI literacy learning should build both conceptual understanding and critical awareness of power, representation, and justice in data-driven systems. Future work can explore how learners from diverse cultural and linguistic backgrounds make sense of AI, and how design can amplify their voices and epistemologies within technology-mediated learning environments.

Conclusion

Developing AI literacy in K–8 settings requires more than teaching technical content; it requires understanding how learners think, feel, and act within AI-mediated worlds. This paper has argued that children's reasoning about AI is inherently socio-cognitive, emerging through the dynamic interplay between mental processes and socially situated participation.

By articulating a multi-layered framework grounded in both cognitive science and Learning Sciences traditions, we offer a conceptual foundation for designing and studying AI literacy as a complex, culturally embedded learning phenomenon. The framework encourages researchers and educators to look beyond isolated skills or abstract cognition toward holistic understandings of how children make sense of, critique, and co-construct the intelligent systems shaping their futures. While cognitive mechanisms such as analogy and metacognition may appear universal, their enactment is always culturally mediated. Learners' reasoning reflects the epistemic resources and values of their communities. Designing equitable AI literacy therefore requires recognizing cognitive diversity—the varied ways children across contexts explain, evaluate, and act upon intelligent systems (Nasir et al., 2023).

This socio-cognitive stance also carries an ethical imperative: fostering AI literacy means supporting children's ability to reason with and reason about technology as active participants in a data-driven society. By integrating cognitive, social, and ethical dimensions, this work aims to guide the next generation of designs, teacher practices, and research that help young learners engage critically and creatively with AI. Within this framework, equity is not treated as an add-on ethical topic but as structurally embedded in learning processes. When students reason about data distribution, representation, and uncertainty, they are simultaneously reasoning about whose experiences are encoded and whose are marginalized. Cognitive acts such as questioning model outputs or revising analogies become opportunities to interrogate power embedded in data systems. By situating reasoning within culturally responsive learning ecologies (Nasir et al., 2023), the framework links conceptual development with critical awareness of justice in data-driven systems. In this sense, equity emerges not only from curriculum content but from how reasoning is scaffolded and socially organized.

By integrating cognitive and sociocultural lenses, this work contributes to a growing movement within the Learning Sciences to reconcile mechanism- and participation-oriented accounts of learning. Such synthesis is increasingly vital for domains like AI literacy, where understanding both how and why learners construct meaning is essential for equitable educational design.

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