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Mapping AI Literacy Development Through Minecraft: An Epistemic Network Analysis Study

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Abstract

As Artificial Intelligence (AI) rapidly reshapes societal, economic, and technological systems, developing AI literacy among secondary school learners has become an essential educational priority. Yet, little is known about how students construct AI-related understanding within immersive, game-based environments that mirror authentic computational systems. This study addresses this gap by investigating how students engage with AI concepts while completing constructionist tasks in Minecraft and by modelling the structure of their conceptual connections using Epistemic Network Analysis (ENA). Six secondary school students were selected purposively, participating in a series of AI-focused challenges involving automation, data tracking, and ethical reflection, with discourse and digital artefacts captured and coded across three themes: (i) AI Concepts, (ii) Collaboration, and (iii) Problem-Solving. Classification into "advanced" and "novice" groups was determined by a pre-study computational thinking diagnostic and teacher-recorded performance in prior technology elective modules, thereby enhancing methodological transparency and ensuring that group comparisons were grounded in observable prior competence indicators. ENA visualizations suggested that, within this small sample, advanced learners generated dense, triangular epistemic networks indicating tightly integrated conceptual engagement, whereas novice learners demonstrated more fragmented networks that became increasingly cohesive over time. Post-task analyses further demonstrated a strengthened co-occurrence between algorithmic thinking and ethical considerations across all participants. The study's small sample size and reliance on a single digital platform limit the generalizability of the results, and qualitative coding decisions may introduce interpretive bias. Future work should expand the participant pool, explore additional game-based or simulation environments, and examine the longitudinal trajectories of AI literacy development to understand better how conceptual, collaborative, and ethical dimensions evolve through sustained engagement.

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Introduction

Artificial Intelligence (AI) literacy has become a foundational competency for secondary school learners as societies navigate rapid automation, pervasive data-driven economies, and the ethical complexities of algorithmic decision-making (Kong et al., 2024; Zhou et al., 2025). Preparing students for AI-mediated futures requires pedagogical strategies that move beyond rote technical instruction toward fostering conceptual reasoning, ethical awareness, and applied problem-solving (Ng et al., 2024). Game-based learning environments, such as Minecraft Education, offer unique affordances for this purpose, as their constructionist design supports active engagement with computational thinking and system-based reasoning through authentic, manipulable digital experiences (Alawajee & Delafield-Butt, 2021; Slattery et al., 2025). Features such as Redstone logic, agent-based automation, and customizable in-game mechanics provide fertile ground for contextualizing abstract AI concepts, enabling learners to translate theoretical ideas into tangible actions within a virtual sandbox (Smit & Smuts, 2023). Despite growing interest in AI education, empirical research examining how immersive environments cultivate AI literacy remains scarce, and few studies employ advanced analytic techniques to uncover the epistemic structures underlying students' learning processes (Casal-Otero et al., 2023; Wu & Zhang, 2025). Epistemic Network Analysis (ENA), a quantitative ethnography method that models dynamic connections among concepts in discourse and collaborative problem-solving, offers a powerful lens for investigating these structures (Elmoazen et al., 2022; Viberg et al., 2024). Addressing this gap, the present study explores how secondary students engage with AI concepts during Minecraft-based activities and examines the epistemic patterns that characterise their conceptual connections as revealed through ENA (Touretzky et al., 2019; Long & Magerko, 2020). Therefore, this study was guided by two research questions: (i) How do students engage with AI concepts through Minecraft-based learning tasks? and (ii) What epistemic patterns emerge in their discourse and actions?

Literature Review

AI Literacy in Secondary Education

Artificial Intelligence (AI) literacy has emerged as a vital competency for students, focusing not only on the technical knowledge of AI technologies but also encompassing critical ethical reasoning, data awareness, and socio-cultural implications. Chee et al. (2024) emphasise the importance of developing a fundamental understanding of AI, which balances both technical skills and ethical reasoning. Recent educational research highlights the necessity of integrating these aspects into AI curricula, aligning with findings from Du et al. (2024) and Zhang et al. (2022), who advocate for a comprehensive approach to AI education incorporating ethics alongside foundational knowledge.

Ongoing global initiatives are striving to incorporate AI into secondary school curricula. However, significant challenges remain. Otero et al. (2023) reveal discrepancies in defining specific competencies and effective assessment tools for AI literacy in diverse disciplinary contexts. While existing interventions primarily stress technical proficiencies, they often overlook essential facets of critical engagement and ethical considerations, as highlighted by Zhang et al. (2022) and Morales-Navarro et al. (2024). These studies argue for the necessity of training students in both operational aspects of AI and understanding its societal implications.

Furthermore, the literature identifies a critical gap in pedagogical strategies that incorporate a deep conceptual understanding of AI ethics. A focus on ethical reasoning and its implications is paramount for preparing students to interact with AI technologies responsibly. Integrated curricula that effectively blend technical and ethical instruction have demonstrated the potential to enrich students' mastery of AI concepts, as supported by Yim and Su (2024), who argue for a holistic approach to AI education. In conclusion, equipping learners with AI literacy requires a balanced approach that transcends technical skills by embedding ethical reasoning and critical engagement within educational frameworks. This approach is crucial for facilitating students' understanding of AI and preparing them to navigate and influence the socio-cultural landscapes shaped by such technologies.

Game-Based Learning and Minecraft in Education

Game-based learning (GBL) has emerged as a promising approach to engage learners in complex problem-solving and computational thinking. Studies indicate that GBL, particularly through platforms like Minecraft, fosters student engagement and enhances cognitive skills essential for today’s learning environments (Cipollone et al., 2014; Sackl et al., 2021). Minecraft provides an open-ended, constructionist environment conducive to experiential learning, creativity, and collaboration, effectively aligning with contemporary educational paradigms (Cipollone et al., 2014; Sripan & Manyam, 2025). The ability to create and manipulate virtual environments allows learners to immerse themselves in physics, mathematics, and computational thinking through hands-on experiences (Valovičová et al., 2020; Sripan & Manyam, 2025).

Empirical studies have demonstrated the effectiveness of Minecraft in enhancing STEM interest, spatial reasoning, and scientific creativity. For example, Cipollone et al. (2014) highlight that tasks designed within Minecraft can simulate real-world systems, thus providing a practical framework for learning. Additional research supports this by showing that game-based tasks in Minecraft promote critical problem-solving skills while enabling learners to navigate complex conceptual landscapes (Sackl et al., 2021). The features of Minecraft, such as Redstone logic and agent-based automation, enable students to model algorithmic processes and explore system-based reasoning effectively. These capabilities make Minecraft particularly valuable for contextualizing concepts related to programming and logic skills in an interactive setting (Vostinar & Dobrota, 2022; Fedorenko et al., 2021).

However, systematic reviews highlight that while Minecraft-based interventions show positive cognitive and motivational outcomes, the evidence on conceptual transfer and long-term impact remains limited (Cipollone et al., 2014; Sackl et al., 2021). Therefore, educational frameworks and curricula should be developed to ensure that the teaching methodologies applied through Minecraft explicitly target the transferable skills associated with GBL and computational thinking. This reflects findings in existing literature emphasizing the necessity for a structured approach to integrating game-based learning within formal educational contexts (Wijaya et al., 2024; Udvaros et al., 2023). In summary, while the integration of GBL indicates a fruitful path toward fostering key competencies in learners, further research is vital to substantiate claims regarding the long-term benefits and transferability of skills gained through such interventions. The call for enhanced pedagogical structures and rigorous assessment methodologies remains essential for maximizing the educational potential of game-based learning environments (Bado, 2022; Udeozor et al., 2024).

Epistemic Network Analysis in Education

Understanding how learners construct and connect ideas necessitates analytic methods that effectively capture the complexity of discourse and collaborative problem-solving. Epistemic Network Analysis (ENA) addresses this need by modeling co-occurrences of coded elements, such as concepts, actions, and reasoning, within interaction windows, producing both visual and statistical representations of epistemic structures (Reid et al., 2025). This methodology has shown promise in various educational contexts, including science education, collaborative programming, and peer feedback, revealing ENA's capacity to uncover patterns of conceptual integration and social-cognitive dynamics (Flynn et al., 2023; Wu et al., 2019). Applications of ENA highlight its effectiveness in analyzing student interactions and learning processes, as detailed by Vandenberg et al. (2021) and Flynn et al. (2023), where ENA is employed to elucidate the mechanisms through which learners develop a deeper understanding of complex subjects. For example, Wu et al. (2019) found that ENA can illustrate how students' discourse reflects their collaborative problem-solving skills in programming environments, enabling educators to track cognitive processes and interactions over time.

Despite the growing applications of ENA, systematic reviews indicate that many studies rely on small samples and manual coding procedures, which could hinder scalability and generalizability. However, Galarza Tohen (2025) employed ENA to analyze conversations of two teams of three students each, which was a total of six participants, demonstrating ENA's suitability for small sample sizes. Supporting the small sample sizes, Elmoazen et al. (2022) found that most ENA studies use small samples with manually coded interactions, validating its application in small-scale research in their review study. For the aspect of manual coding procedures, Elmoazen et al. (2022) and Daniele et al. (2025) emphasised the need for methodological innovations that can enhance the reliability and efficiency of ENA, such as automated coding techniques that reduce the subjectivity often associated with manual analysis. The pursuit of higher inter-rater reliability in coding data is particularly critical, as noted by Kurasaki (2000), who argues that systematic steps, such as establishing intercoder agreement, are necessary to validate conclusions drawn from qualitative analyses. In summary, ENA offers a framework for analyzing educational discourse.

Theoretical Framework

This study is grounded in an integrated theoretical framework (see Figure 1) that draws from constructionism (Papert, 1980; Kafai & Resnick, 1996), sociocultural learning (Vygotsky, 1978), and epistemic cognition (Chinn et al., 2014) to explain how learners develop AI literacy within immersive, game-based environments. Constructionism positions learning as a process that occurs through the active creation of meaningful artefacts, making it particularly relevant to Minecraft's design, where students build automated structures, test logical systems, and iteratively refine solutions. These constructionist activities do not occur in isolation; rather, they are embedded in sociocultural learning processes, as students collaborate, negotiate meaning, and co-construct solutions through dialogue and shared problem-solving (Alawajee & Delafield-Butt, 2021). The social interactions that emerge during Minecraft tasks provide rich opportunities for learners to articulate reasoning, challenge assumptions, and collectively develop more sophisticated understandings of AI concepts (Slattery et al., 2025).

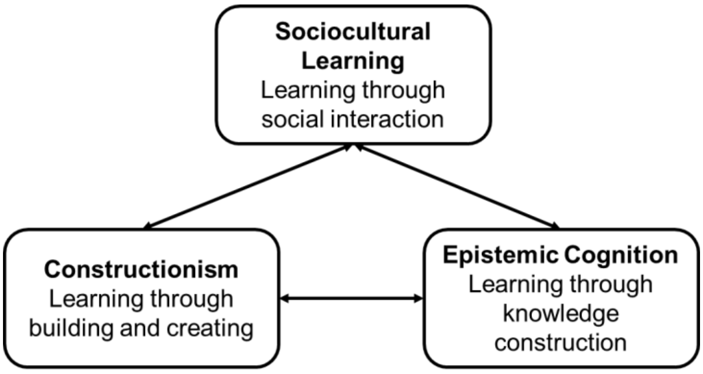

Figure 1. The Theoretical Framework of this Study

Complementing these perspectives, epistemic cognition focuses on how learners evaluate, justify, and connect knowledge as they engage with complex problems. It highlights the cognitive processes through which students make sense of AI-related ideas, such as algorithms, data, and automation, while constructing meaningful conceptual frameworks. In this study, epistemic cognition is operationalised through ENA, which models how students' ideas interconnect during collaborative discourse and action. These three theories form a mutually reinforcing foundation, where constructionism provides the hands-on context for exploration, sociocultural learning explains the collaborative dynamics through which understanding develops, and epistemic cognition captures the underlying knowledge-building processes (Chinn et al., 2014; Greene et al., 2016). In summary, this theoretical integration enables a holistic examination of how students construct and connect AI concepts while engaging in authentic Minecraft-based tasks.

Conceptual Framework

The conceptual framework (see Figure 2) guiding this study integrates three foundational pillars, which are AI literacy dimensions, Minecraft affordances, and Epistemic Network Analysis (ENA), to explain how students develop AI-related understanding within immersive game-based tasks. First, AI literacy is conceptualised across three key dimensions that are knowledge of foundational AI concepts, ethical awareness of the societal implications of AI systems, and application of algorithmic and data-driven reasoning in problem-solving contexts (Biagini, 2025; Chiu et al., 2025; Tadimalla & Maher, 2025). These dimensions represent the target competencies that contemporary AI education aims to cultivate among learners. Second, Minecraft functions as an enabling learning environment, offering unique constructionist affordances that allow learners to build, test, and iterate digital structures, where Redstone logic, which mirrors computational circuits and algorithmic flows, and agent-based automation simulate autonomous behaviours akin to simplified AI agents (Bado, 2022).

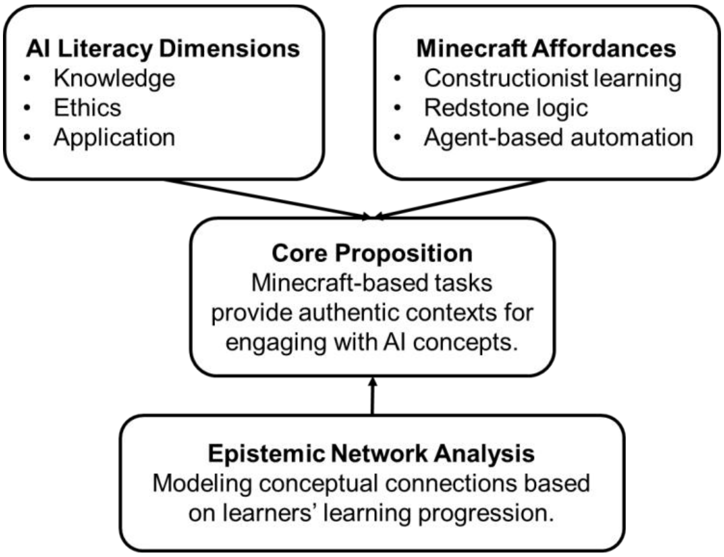

Figure 2. The Conceptual Framework of this Study

These affordances create authentic and manipulable contexts through which students can meaningfully engage with AI concepts. Third, ENA provides the analytic lens for modelling how learners connect these concepts during collaborative discourse and in-game actions. ENA captures the structure and strength of co-occurring ideas, thereby revealing the epistemic patterns that emerge as students reason through AI-themed challenges. At the intersection of these pillars lies the study's core proposition, that is, Minecraft-based tasks offer rich, situated opportunities for AI literacy development, and ENA enables the visualization and quantification of the conceptual connections, providing deeper insight into their epistemic growth and learning processes.

Methodology

Research Design

This study employed a mixed-methods research design that integrates qualitative discourse analysis with quantitative modelling through Epistemic Network Analysis. This design enables a comprehensive examination of both the content of students' engagement with artificial intelligence (AI) concepts and the structure of their conceptual connections as they collaborate on Minecraft-based learning tasks (see Figure 3). The qualitative component captures the richness of students' interactions, allowing for detailed insights into the ways they articulate their understanding of AI. Meanwhile, the quantitative ENA component systematically models the co-occurrences of coded elements, such as concepts, actions, and reasoning, producing visual and statistical representations of epistemic structures. ENA was chosen because it effectively visualises the interconnections between various elements of students' discourse, thereby illuminating the cognitive and social dynamics involved in collaborative learning. Recent studies have demonstrated that ENA can be successfully applied in various educational contexts, revealing patterns of conceptual integration and the evolution of learning through interaction (Otero et al., 2023). For example, although Du et al. (2024) focus primarily on AI literacy in teacher education, their framework indirectly supports our understanding of how analytical methods, including ENA, can inform the investigation of student learning in AI contexts by highlighting the complexities of these educational environments.

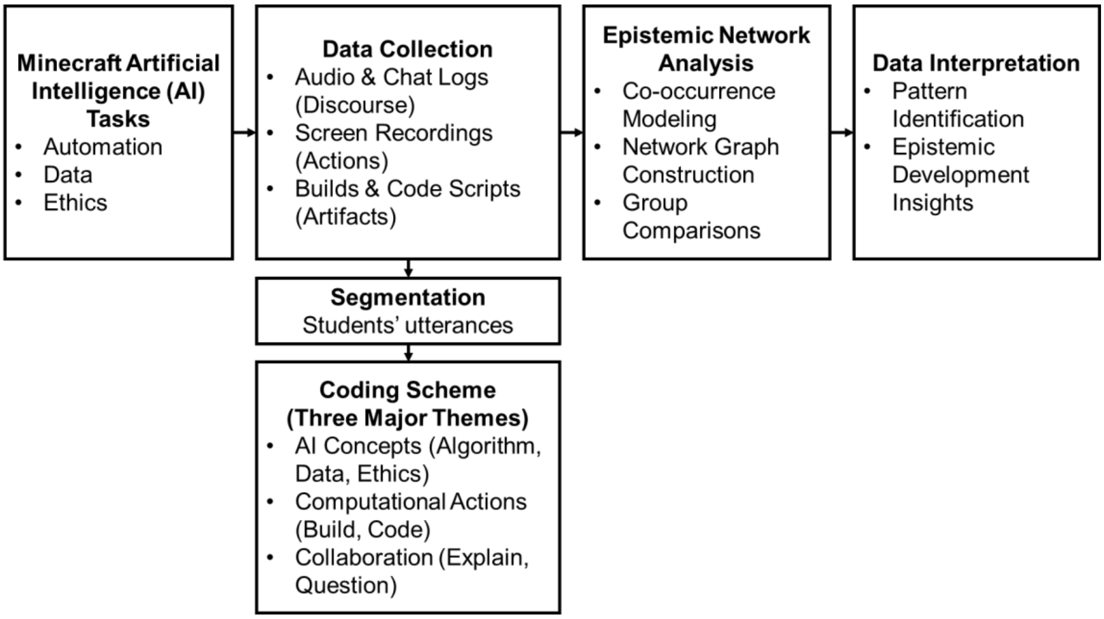

Figure 3. The Methodology Flow of this Study

Study Participants

The study involved six secondary school students, aged 13 to 16, who were enrolled in a technology elective course at a Malaysian secondary school. A purposive sampling technique was employed; students were classified as 'Advanced' (IDs 1–3) based on scoring above 80% in a Redstone logic diagnostic and 'Novice' (IDs 4–6) based on scores below 50% and no prior experience with Minecraft's Code Builder. This sampling criterion allowed the study to focus on authentic novice engagement with AI literacy within an immersive digital environment. To facilitate meaningful collaboration and discourse, students were organised into two teams of three, with grouping informed by classroom dynamics and instructor recommendations. Each team worked cooperatively to complete the Minecraft Education Edition tasks, enabling the study to capture rich interactional data reflective of small-group problem-solving and conceptual reasoning.

Learning Tasks

All learning activities were conducted within Minecraft Education Edition, a platform selected for its constructionist affordances and capacity to simulate computational and automated systems through tools such as Code Builder, Redstone circuitry, and command blocks. These features enabled learners to engage with AI-related ideas through authentic, hands-on digital creation. The study implemented three tasks that aligned with key dimensions of AI literacy, which are knowledge, ethics, and application, and were structured to scaffold increasingly sophisticated forms of conceptual reasoning. Table 1 shows the summary of Minecraft tasks and their alignment to AI literacy dimensions.

Table 1. Summary of Minecraft tasks and their alignment to AI literacy dimensions

Task	**Description of Activity**	**Aligned AI Literacy Dimensions**	**Learning Outcomes**
Automated Farm Challenge	Students design and build an automated crop-harvesting system using Redstone logic, sensors, and basic command-block scripts. AI Application (designing rule-based systems): • Translate algorithmic thinking into functional Redstone mechanisms • Debug and optimise system efficiency	AI Knowledge (algorithmic logic, automation)	Understand how automated systems operate
Data Collection Simulation	Students create mechanisms to track production rates, resource flow, or system performance using counters, Redstone circuits, or code. AI Application (simple data interpretation): • Build systems that collect and represent data • Interpret in-game data to improve automation	AI Knowledge (data concepts, measurement)	Recognise the role of data in decision-making
Ethical Scenario Reflection	After completing automation tasks, students discuss the ethical implications of automation in Minecraft and real-world contexts. AI Knowledge (social impact of AI): • Connect in-game experiences to real AI ethics • Develop awareness of responsible AI practices	AI Ethics (fairness, labour impact, bias)	Reflect critically on the consequences of automation

Note: Ethical prompts were delivered via in-game non-Player Characters (NPCs) to maintain environmental immersion (Task 3: Ethical Scenario Reflection).

First, in the Automated Farm Challenge, students designed and built an automated crop-harvesting system using Redstone logic and simple command-block scripts, providing an immersive entry point into algorithmic thinking, automation, and system optimization. Second, the Data Collection Simulation required students to construct mechanisms capable of tracking resource flow, production rates, or system performance, thereby fostering awareness of data generation, interpretation, and the role of data in automated decision-making. Finally, the Ethical Scenario Reflection prompted students to participate in guided discussions that connected their in-game automation experiences to broader ethical questions surrounding labour, fairness, and the societal impacts of AI technologies. In summary, these tasks created an integrated learning environment that encouraged iterative building, collaborative problem-solving, and reflective dialogue, enabling students to engage deeply with AI concepts while constructing meaningful digital artifacts.

Data Collection Method

Data was gathered through a multi-source collection strategy designed to capture the complexity of students' discourse, actions, and artefacts as they engaged with AI-focused tasks in Minecraft Education Edition. To document collaborative reasoning and verbal meaning-making processes, audio recordings of team discussions and in-game chat logs were collected throughout the activity sessions. These discourse traces provided insight into how students articulated AI concepts, negotiated design decisions, and resolved challenges. Coding procedures were designed to systematically link in-game behaviors to conceptual categories within the ENA framework. For example, the placement of a "Comparator" block was coded as "AI Knowledge (Data)" when used to read container states, even in the absence of verbal discourse, thereby ensuring that multimodal evidence contributed to the analytic model. Complementing these verbal data, screen recordings captured students' real-time computational actions, including building automation systems, manipulating Redstone circuits, debugging command-block scripts, and iteratively refining their designs, thereby offering behavioural evidence of AI concept application.

Additionally, digital artefacts such as final Minecraft builds, circuitry layouts, automation mechanisms, and code scripts were preserved to represent the tangible outcomes of students' problem-solving processes. All data sources were time-stamped and systematically segmented into analytic windows, for example, one to two minutes of interaction or sequences of three to five utterances, in accordance with established Epistemic Network Analysis (ENA) conventions. This segmentation enabled the integration of discourse and action data into a coherent structure suitable for modelling conceptual co-occurrences and tracking epistemic development across the learning activities.

To extract the data, the coding scheme for this study was developed to capture the conceptual, behavioural, and collaborative dimensions of students' engagement with AI literacy during Minecraft-based tasks. Drawing on established ENA frameworks and prior research in AI and computational learning, the scheme comprised three major themes: (i) AI Literacy Concepts, (ii) Computational Actions (Problem Solving), and (iii) Collaborative Processes. The first theme, AI literacy, included codes representing algorithmic thinking, data awareness, AI application, and ethics and impact, allowing the analysis to identify where students invoked core conceptual elements of AI. The second theme, Computational actions, captured the procedural dimensions of students' work, including design and planning, coding and programming, and debugging, each representing distinct stages of constructing and refining automated systems. The third theme, collaborative process, included explaining, questioning, and decision-making, reflecting the social interactions through which students co-constructed understanding.

Two trained coders independently applied the coding scheme to all discourse and action segments after an iterative calibration process using sample data. Both coders were selected based on their prior experience in qualitative coding, particularly in analysing discourse or interaction data within educational or technology-enhanced learning contexts. Before formal coding conducted, the coders participated a structured training and calibration process, which included: (i) reviewing the coding manual and operational definitions for all AI literacy, computational action, and collaboration codes; (ii) jointly coding a subset of sample transcripts and screen-recorded interactions to refine shared interpretations; and (iii) participating in iterative feedback sessions to reconcile ambiguities and strengthen conceptual alignment. To ensure consistency, the inter-rater reliability was assessed using Cohen's Kappa, with discrepancies resolved through negotiated consensus. The final Cohen's Kappa coefficient was calculated at 0.84, indicating high inter-rater reliability, which supports the methodological rigor and trustworthiness of the coding framework. This integration of multimodal data strengthens the analytical validity of ENA modelling by capturing both cognitive reasoning and embodied computational actions within the learning environment.

Data Analysis Method

Data analysis of this study followed a multi-stage process grounded in the principles of ENA to model how students connected AI literacy concepts during Minecraft-based learning tasks. First, a coding scheme was developed to capture the core dimensions of students' engagement, including AI-related concepts (algorithmic thinking, data awareness, and ethical considerations), computational problem-solving actions, and collaborative discourse moves based on the operational definitions as follows:

a) AI concepts refer to students' explicit or implicit engagement with foundational elements of artificial intelligence, including algorithmic logic, data awareness, and ethical considerations. Operationally, this theme is identified through verbal statements, in-game actions, or design decisions that demonstrate understanding of how automated systems operate, how data are generated or used, or how technological choices carry societal implications. Behaviours classified under this theme include discussing algorithm steps, referring to input–output rules, interpreting resource or performance data, and reflecting on the ethical impact of automation. Instances are coded when students articulate or apply AI-related reasoning during the Minecraft tasks.

b) Collaboration includes the social and communicative processes through which students jointly construct understanding and coordinate actions while working in teams. It is operationalised through observable behaviours such as explaining ideas to peers, asking clarifying questions, justifying decisions, negotiating roles, and reaching group consensus. Collaborative instances also include co-regulation of task progress, shared monitoring of system performance, and collective troubleshooting discussions. This theme is coded whenever students engage in discourse or actions that reflect cooperative meaning-making and joint problem management during the activity.
c) Problem-Solving refers to the cognitive and procedural actions students undertake to design, test, and refine solutions within Minecraft tasks. Operationally, this includes planning system structures, constructing Redstone circuits or command-block sequences, debugging malfunctioning mechanisms, and iteratively modifying designs to improve efficiency or functionality. Problem-solving behaviours may appear through both discourses, for example, proposing strategies and diagnosing failures. Action traces, for example, reconfiguring circuits and altering automation logic. Utterances are coded when students demonstrate strategic thinking, troubleshooting, or iterative refinement aimed at resolving task challenges.

This coding scheme was iteratively refined through coder calibration sessions to ensure conceptual clarity and reliability. Once the discourse and action data were fully coded, ENA was applied to quantify and visualise the structure of co-occurring concepts within defined interaction windows. The ENA Webtool generated epistemic networks that represented the density and configuration of connections between ideas, enabling the analysis to move beyond frequency counts toward modelling students' underlying patterns of reasoning. Comparative ENA models were then constructed to examine differences across learners. Statistical tests on ENA centroids, complemented by qualitative interpretation of the network structures, provided insight into how students' conceptual integration evolved and how deeply they engaged with AI concepts through the collaborative, constructionist learning environment.

Findings

Epistemic Network Analysis of the Advanced Group

The ENA visualizations for the three advanced students (ID1, ID2, and ID3) show consistently triangular and highly integrated network structures linking AI Concepts, Collaboration, and Problem-Solving (see Figure 4). In ID1, the network displays strong and balanced co-occurrences, supported by utterances such as "Let's begin by mapping out the algorithm: detect growth, activate piston, collect wheat and store output," which frequently co-activated AI Concepts and Problem-Solving, as well as "I'll track the yield every 10 seconds to measure whether our logic improves," reflecting the simultaneous focus on conceptual reasoning and computational diagnostics. The edge between AI Concepts and Collaboration is also reinforced through statements like "We need to coordinate the timing loop, so everyone knows which module they are testing."

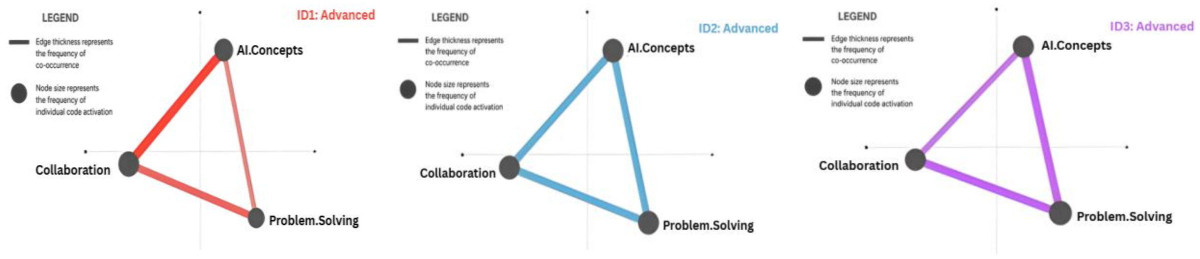

Figure 4. The ENA visualizations of the Advanced Group

ID2 demonstrates a similar triangular configuration, with especially prominent co-occurrence between AI Concepts and Collaboration. This is reflected in the ID2's utterances, such as "Our automation should only activate when resources are fully grown like a rule-based AI," which triggered peer explanation and discussion, and "Let's integrate a comparator so the machine reads crop states before triggering output," which paired conceptual understanding with coordinated task planning. The ID3 network exhibits thick, evenly distributed edges across all three nodes, supported by frequent epistemic co-activation. For example, utterances including "I'll document the timings so we can compare performance across versions" and "If the algorithm misfires, we'll analyze the signal flow step-by-step" contributed to the strong linkage between AI Concepts and Problem-Solving, while collaborative statements such as "Let's validate our results by collecting data and confirming the automation works consistently" reinforced the triadic integration. Across all three advanced participants, the ENA plots reveal dense and highly interconnected epistemic patterns, characterised by substantial and repeated co-activation of AI Concepts, Collaboration, and Problem-Solving throughout the task engagement.

Epistemic Network Analysis of the Novice Group

The ENA visualizations for the three novice students (ID4, ID5, and ID6) reveal less integrated and more fragmented epistemic networks compared to the advanced group (see Figure 5). ID4 shows a nontriangular structure, with two dominant connections between AI Concepts–Problem-Solving and Collaboration–Problem-Solving, while the link between AI Concepts and Collaboration is statistically less frequent within the observed interaction windows. This pattern aligns with utterances such as “Why doesn’t this turn on? Maybe we placed something wrong,” and “Let’s try copying the design and see what happens,” which frequently activated Problem-Solving without concurrent conceptual talk. Limited collaboration was evident in statements like “Let’s ask the other team how they made it work,” which did not co-occur with AI-related reasoning in the same interaction windows.

In ID5, the network exhibits a slightly more developed structure, with an observable but still weak link between AI Concepts and Collaboration. This is supported by utterances such as “If we change the order of the steps, the whole system behaves differently,” which reflects emerging algorithmic thinking, alongside “Maybe if we connect all the wires (Redstone dust), it will just produce everything,” which primarily activated Problem-Solving. Collaborative exchanges, including “Let’s remove everything and rebuild to see which part failed,” strengthened the connection between Collaboration–Problem-Solving but did not frequently co-occur with conceptual reasoning, resulting in an asymmetrical network.

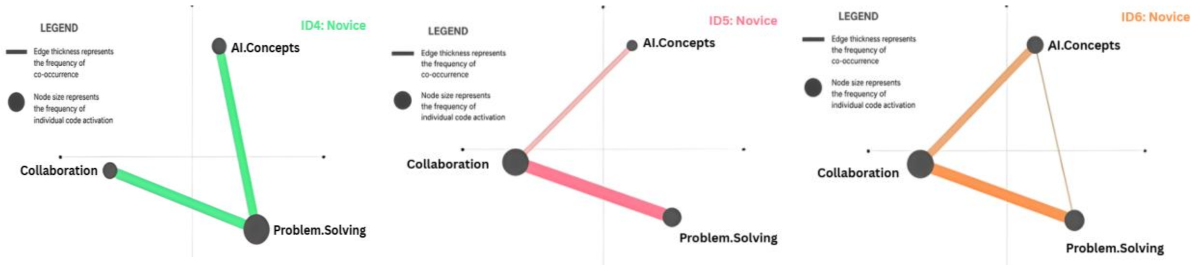

Figure 5. The ENA visualizations of the Novice Group

The ID6 displays the most integrated network among the novice participants, forming a triangular structure, although the edges remain weaker than those seen in the advanced group. Utterances such as “So we’re using algorithms and also thinking about fairness…” contributed to AI Concept activation, while “Maybe we should slow down the system, so players still need to farm sometimes,” activated both conceptual and ethical reflection alongside Problem-Solving. Similarly, statements like “We should compare data before and after to see if our redesign is better,” supported the co-occurrence of AI Concepts and Problem-Solving, and collaborative moments such as “This design is confusing, we need a plan,” reinforced group coordination. Despite these improvements, the connections between the three dimensions remain comparatively less dense, reflecting more tentative epistemic integration. In summary, across all three novice participants, the ENA results indicate emerging yet still developing epistemic connections, characterised by frequent Problem-Solving activity, intermittent AI Conceptual reasoning, and inconsistent integration of collaboration into conceptual discourse.

Comparative Epistemic Network Analysis between the Advanced and Novice Groups

A comparison of the ENA visualizations between the advanced (ID1–ID3) and novice (ID4–ID6) participants shows marked differences in the density and configuration of epistemic connections among AI Concepts, Collaboration, and Problem-Solving (see Figure 6).

Figure 6. The Comparative ENA Visualizations

All three advanced students produced fully triangular and highly interconnected networks, indicating frequent co-occurrence of conceptual reasoning, collaborative discourse, and computational action. In contrast, the novice group displayed less integrated network patterns, with ID4 showing only partial connectivity, ID5 demonstrating emerging algorithmic understanding. This reasoning rarely overlapped with collaboration, resulting in an asymmetrical structure. Only ID6 produced a triangular network, albeit with weaker edges. In summary, the advanced group showed denser, more balanced epistemic co-activation, while the novice group exhibited fragmented or emerging connections, with limited overlap between AI conceptual talk and collaborative problem-solving.

Summary of Findings

This study aimed to examine (i) how students engage with AI concepts through Minecraft-based learning tasks, and (ii) what epistemic patterns emerge in their discourse and actions. The findings show that students engaged with AI concepts in multiple meaningful ways as they designed, tested, and refined automated systems within the Minecraft environment. Advanced students consistently articulated algorithmic logic and applied data-driven reasoning to optimise their Minecraft builds, while novice students demonstrated emerging conceptual engagement, gradually shifting from trial-and-error strategies to recognizing algorithmic structure. Participants across both groups also began linking technical reasoning with ethical considerations after completing the tasks, as reflected in statements such as "Automation can replace jobs, thus what does that mean in real life?"

ENA provided a clear depiction of the patterns of co-occurrence among AI Concepts, Collaboration, and Problem-Solving. Advanced students produced dense triangular networks, indicating highly integrated epistemic engagement where conceptual reasoning, collaborative discussion, and computational action frequently occurred together. In contrast, novice learners displayed fragmented patterns in the early stages, with networks dominated by Problem-Solving and limited conceptual overlap, though post-task networks showed emerging triangulation as conceptual and ethical reasoning became more frequent. Across all participants, post-task networks exhibited a notable increase in the co-occurrence between algorithmic thinking and ethical considerations, demonstrating growth in students' ability to connect technical actions with reflective judgments. In summary, these findings address both research objectives by showing not only how students engaged with AI concepts during authentic constructionist activities but also how their conceptual, collaborative, and problem-solving processes became interconnected, yielding distinct epistemic patterns across novice and advanced learners.

Discussion

The findings suggest that Minecraft's constructionist affordances, specifically the physicalised logic of Redstone, serve as a multimedia bridge between abstract AI theory and tangible system design. The dense, triangular ENA networks observed among advanced students further suggest that these learners coordinated AI concepts, collaboration, and problem-solving in a highly integrated manner (Shaffer et al., 2016; Bressler et al., 2019). From a constructionist perspective, this pattern suggests that the open-ended design of Minecraft enabled advanced learners to externalise their thinking through iterative building, debugging, and system refinement. These activities closely mirror authentic computational and AI design processes (Papert, 1980; Kafai & Burke, 2015). Their tightly interconnected epistemic networks reflect the idea that knowledge is constructed through the creation of meaningful artifacts, in this study, automated farms, data tracking mechanisms, and other AI-aligned structures (Hébert & Jenson, 2020).

The results also highlight the crucial role of sociocultural learning processes. Advanced students consistently engaged in explanation, justification, and coordinated decision-making, producing strong AI Concepts–Collaboration links (Vandenberg et al., 2021; Bressler et al., 2019). These patterns align with the view that knowledge is co-constructed through dialogue, peer support, and shared reasoning (Vygotsky, 1978; Stahl, 2023). The collaborative discourse surrounding algorithmic logic, data interpretation, and system optimization provided a social space where students refined their understanding while negotiating the implications of their design decisions. This was especially evident in the ENA networks, where students began connecting algorithmic reasoning to ethical considerations, demonstrating the emergence of shared moral reflection grounded in their collaborative interactions (Allen & Kendeou, 2024; Zhou et al., 2025).

In contrast, the novice students' initial networks were less cohesive, reflecting fragmented or sequential processing rather than integrated epistemic work (Ko et al., 2025; Moshman, 2013). Their progression from linear patterns to more triangular structures in the post-task networks suggests a developmental shift: as they engaged with the tasks, novices gradually moved from trial-and-error manipulation to more conceptually grounded reasoning (Chakraburty et al., 2025; Zhang et al., 2024). This progression illustrates the activation of epistemic cognition, wherein learners increasingly understood not only what actions to take, but also how to link algorithms to data, fairness, and the societal implications of automation (Lin & Dai, 2025; Hummel, 2025). Their newfound connections between AI Concepts and Problem-Solving, and later between AI Concepts and Collaboration, indicate growing awareness of how knowledge elements relate within the broader context of AI literacy.

A key finding across both groups was the increased linkage between algorithmic thinking and ethical considerations in the post-task phase. This suggests that constructionist activities, when coupled with explicit opportunities for reflection, may support the integration of technical and ethical dimensions of AI literacy (Lin & Dai, 2025; Dai, 2025). Students shifted beyond procedural reasoning toward more mature, reflective thinking about the consequences of automation both in-game and in real-world contexts. This shift aligns with contemporary frameworks of AI literacy, which emphasise the need for learners to develop both the ability to use and understand AI technologies and the critical awareness to evaluate their societal impacts (Panagiotou, 2025; Tadimalla & Maher, 2025; Biagini, 2025). Reflection-based pedagogies further reinforce this integration by encouraging learners to interrogate assumptions and engage in ethical reasoning (Kim, 2025).

In summary, these findings highlight the value of combining constructionist learning environments with systematic analytic tools such as ENA. Minecraft's embedded affordances, such as agent-based automation, Redstone logic, and iterative building, serve as powerful contexts through which students can experience AI concepts in action (Schifter & Cipollone, 2015; Lehane et al., 2021). ENA, in turn, provides a lens for examining how students organise and connect these experiences cognitively and socially (Shaffer et al., 2016; Elmoazen et al., 2022). The observed differences between advanced and novice learners highlight the need for scaffolding that supports novices in linking their hands-on experimentation to conceptual and ethical reasoning, thereby strengthening the epistemic coherence of their learning (Ko et al., 2025; Kafai & Burke, 2015). This study contributes to growing evidence that game-based environments can effectively foster AI literacy when learning activities engage students’ social, cognitive, and constructionist processes in mutually reinforcing ways (Slattery et al., 2025). However, these developmental shifts should be interpreted with caution, given the small participant pool (N = 6), and future studies involving larger and more diverse cohorts are necessary to confirm the stability and generalizability of the observed epistemic patterns.

Practical and Theoretical Implications

The findings of this study generate significant implications for both educational practice and learning theory within the emerging field of AI literacy. From a practical standpoint, the strong epistemic integration demonstrated by advanced learners indicates that constructionist, game-based environments such as Minecraft provide fertile ground for cultivating deep and interconnected AI literacy skills (Dai, 2025; Du & Wang, 2023). By engaging students in the design, testing, and refinement of automated systems, such environments enable them to experience AI concepts in action, bridging the gap between abstract ideas and concrete computational behaviors. At the same time, the fragmented networks observed among novice learners highlight the need for targeted scaffolds, including structured prompts, teacher-led reflections, or peer-supported design strategies that scaffold the transition from 'trial-and-error' building to 'concept-first' design through structured logic templates, and algorithmic processes with collaborative reasoning and ethical considerations (Ng et al., 2024). Furthermore, the observed increase in co-occurrence between algorithmic thinking and ethical reflection suggests that AI literacy programs should prioritise interdisciplinary integration, weaving moral reasoning and discussions of societal impact into technical learning activities rather than treating them as peripheral add-ons (Lin & Dai, 2025; Biagini, 2025; Allen & Kendeou, 2024).

Theoretically, the study advances understanding at the intersection of constructionism, sociocultural learning, and epistemic cognition. The dense triangular networks produced by advanced learners offer empirical evidence that constructionist learning environments foster tightly interconnected knowledge structures when students engage in meaningful artifact creation (Papert, 1980; Kafai & Burke, 2015). The strong linkages between AI Concepts and Collaboration reinforce sociocultural perspectives that view learning as a socially negotiated process that emerges through shared explanation, coordination, and collective problem-solving (Vygotsky, 1978; Stahl, 2023). Meanwhile, the developmental trajectories observed in novice learners, which range from linear to more triangulated conceptual networks, underscore the importance of epistemic cognition in shaping how learners evaluate, connect, and organise knowledge related to AI (Shaffer et al., 2016; Moshman, 2013). The increased connections between algorithmic logic and ethical considerations further reveal that epistemic growth in AI literacy is multidimensional, spanning technical reasoning, social awareness, and reflective judgment (Allen & Kendeou, 2024; Lin & Dai, 2025). In summary, these implications highlight the need for learning environments that integrate hands-on creation, collaborative discourse, and structured opportunities for epistemic reflection, thereby advancing both theoretical understanding and practical approaches to AI literacy education.

Limitations and Suggestions

Several limitations should be acknowledged when interpreting the findings of this study. First, the sample sise was relatively small, involving only six secondary school students, which limits the generalizability of the ENA patterns observed (Hackshaw, 2008; Cao et al., 2024). While the purpose of the study was exploratory, larger and more diverse cohorts would provide a more representative distribution of AI literacy development across different learner profiles. Second, the study relied on Minecraft Education Edition as the primary learning environment; although its constructionist affordances aligned well with the research objectives, students' prior familiarity with Minecraft may have influenced their problem-solving efficiency and the structure of their discourse (Nebel et al., 2016; Baek et al., 2020). Consequently, the degree to which the observed epistemic patterns transfer to other AI learning contexts or platforms remains uncertain (Mills et al., 2024; Allen & Kendeou, 2024). Third, the segmentation and coding of discourse and action data, although guided by established ENA standards, carry the inherent limitations of qualitative judgment. Despite achieving acceptable inter-rater reliability, coding decisions may still introduce interpretive bias (O'Connor & Joffe, 2020; Halpin, 2024). Finally, the study focused primarily on conceptual co-occurrence patterns and did not directly measure learning outcomes such as knowledge gains, ethical reasoning proficiency, or transfer of AI literacy beyond the task environment.

Future work should address these limitations by expanding the participant pool and incorporating comparative analyses across multiple schools, age groups, and instructional settings (Ng et al., 2024). Longitudinal designs could further illuminate how students' AI literacy develops over time and how epistemic networks evolve with repeated exposure to constructionist AI learning tasks (Ko et al., 2025). To enhance ecological validity, future studies could examine additional game-based or simulation-based environments, enabling comparison of how different platform affordances shape epistemic engagement (Slattery et al., 2025). Methodologically, combining ENA with complementary approaches, such as eye-tracking, multimodal learning analytics, or automated discourse analysis, could yield richer insights into the interplay between students' cognitive, behavioral, and social processes (Viberg et al., 2024; Worsley & Blikstein, 2018). Finally, future research should explore how instructional scaffolds, such as teacher prompts, AI-augmented feedback, or structured ethical inquiry, might support novice learners in forming more integrated and reflective epistemic networks, thereby strengthening their AI literacy development in meaningful and sustainable ways (Lin & Dai, 2025; Ng et al., 2024).

Conclusion

In conclusion, this study examined how secondary school students engaged with core dimensions of AI literacy while completing constructionist, collaborative tasks in Minecraft, and used Epistemic Network Analysis (ENA) to model the structure of their conceptual connections. The analysis revealed that advanced learners exhibited dense and balanced networks linking AI Concepts, Collaboration, and Problem-Solving, demonstrating highly integrated epistemic engagement during the tasks. In contrast, novice learners displayed more fragmented networks, with conceptual integration emerging only in the later stages of their work. Across both groups, post-task networks showed increased co-occurrences between algorithmic thinking and ethical considerations, indicating that the activities supported students in connecting technical reasoning with reflective evaluation of automation’s broader social implications. Through these findings, the study contributes new insights into how constructionist environments like Minecraft can serve as effective platforms for fostering AI literacy, particularly when supported by collaborative inquiry and iterative design. By applying ENA, the study demonstrates the value of fine-grained analytic methods that capture not only what students learn but also how their knowledge elements become interconnected during authentic problem-solving. The results highlight the need for instructional scaffolds that help novice learners develop more cohesive conceptual networks, while affirming the potential of interdisciplinary, game-based learning experiences to cultivate both technical and ethical dimensions of AI literacy. As AI continues to shape the future of work, knowledge, and citizenship, this study underscores the importance of equipping young learners with the capacity to understand, apply, and critically reflect on intelligent systems in ways that are meaningful, collaborative, and responsible.

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