Trends in Artificial Intelligence Research for Geometry Education: Educational Applications and System-Oriented Approaches

Yiru Chen [1], Yin Yang [2*],
[1, 2] The Education University of Hong Kong
s1146375@s.eduhk.hk
[*] yyin@eduhk.hk

Abstract: Artificial intelligence (AI) has increasingly been introduced into mathematics education research, with geometry attracting particular attention due to its reliance on visualization and reasoning. However, existing studies remain fragmented, with limited synthesis of how AI applications relate to instructional practice. This paper presents a focused review to clarify research orientations in AI-supported geometry education. A PRISMA-informed screening of 1,468 publications (2015–2025) resulted in 80 studies for analysis. Using qualitative content analysis, the studies were categorized by research orientation and educational focus. The preliminary analysis revealed two dominant orientations. Educationally oriented AI applications were embedded in instructional contexts to support conceptual understanding and exploratory learning. In contrast, system-oriented studies focused on the development and evaluation of AI techniques for geometric problem solving, automated reasoning, or representation. Still, they rarely reported classroom implementation or pedagogical design considerations. The findings highlight the need to connect AI capabilities with instructional design better to support meaningful geometry learning.

Keywords: artificial intelligence, mathematics education, geometric education, instructional design

1. Introduction

The integration of Artificial Intelligence (AI) into mathematics education has advanced rapidly, yet its application in geometry education remains challenging (Yunianto et al., 2024). Despite advances in AI systems for formal proof generation and geometric problem solving, a significant gap remains between their technical sophistication and meaningful integration into student-centered learning environments (Recio et al., 2019). Existing research on AI in geometry education has developed along two largely parallel. One strand emphasizes educationally oriented applications in which AI is embedded within structured, teacher-mediated instructional settings to support conceptual understanding and exploratory learning (Recio et al., 2019; Thampitak & Junpeng, 2024). A second strand focuses on system-oriented AI developments, including large language models and automated reasoning systems, which are primarily evaluated based on their performance in formal proof generation or competition-level geometric problem solving (Wei, 2024; Zou et al., 2024). Although these studies demonstrate advances in formal reasoning capabilities, they are often conducted outside instructional settings and pay limited attention to how students interpret or learn from AI-generated reasoning (ICMI, 2024). Against this backdrop, a focused synthesis is needed to clarify how AI has been conceptualized and operationalized in geometry education research. This review aims to answer one research question what trends are in artificial intelligence research for geometry education.

2. Method

Following PRISMA-informed procedures, 1,468 studies on artificial intelligence and geometry were identified from Web of Science, Scopus, Education Resources Information Center (ERIC), and the ACM Digital Library (2015–2025). Titles and abstracts were first screened to exclude studies that did not explicitly address geometry teaching or learning contexts. To enhance the reliability of the screening process, the inclusion decisions were independently reviewed by two researchers. Based on predefined criteria, 80 studies were retained for analysis. The studies were categorized into two orientations: (1) Educationally oriented AI applications emphasizing instructional design and learning outcomes; and (2) AI tools with potential educational relevance focusing on algorithm or system development without classroom implementation. A coding scheme was developed to capture key dimensions related to instructional integration, learning focus, and the role of AI in supporting geometric reasoning. Instructional context: Whether the AI system was implemented within formal instructional settings (e.g., school classrooms, curriculum-aligned platforms) or evaluated outside educational contexts.Learning focus: The primary geometric focus addressed by the AI system, including conceptual understanding (e.g., properties, relationships), spatial visualization, procedural computation, or formal deductive reasoning. Pedagogical Role of AI: The function of AI in the learning process, coded as instructional support (e.g., scaffolding, formative feedback, adaptive guidance), exploratory facilitation (e.g., conjecturing, visualization), or autonomous problem solving without pedagogical mediation (Zou et al., 2024; Wei, 2024; Zhang et al., 2025). Integration with instructional design was evaluated on three levels: (1)Technical evaluation only (e.g., accuracy or efficiency), (2) potential educational relevance without explicit instructional design, and (3) explicit integration into instructional tasks, activity sequences, or teacher-mediated learning.

3. Results

3.1. Educationally Oriented AI Applications in Geometry

Based on the coding scheme, educationally oriented AI applications in geometry exhibit a high degree of instructional integration and pedagogical alignment. 28 studies in this category were coded at Level 3 (explicit instructional integration).

3.1.1. Pattern 1: Strong coupling between AI and instructional context

Across the reviewed studies, educationally oriented AI applications in geometry are predominantly implemented within formal school-based learning contexts, including school classrooms, web-based learning platforms, and technology-enhanced instructional environments integrated into existing curricula (Cunha et al., 2025; Recio et al., 2019; Thampitak & Junpeng, 2024). In these studies, AI systems are embedded within structured instructional contexts aligned with grade-level objectives and classroom practices. For example, intelligent tutoring systems and AI-supported diagnostic platforms were used in middle and high school mathematics classrooms to support geometry and measurement learning (Thampitak & Junpeng, 2024). Similarly, GeoGebra-based automated reasoning tools were incorporated into task-based classroom activities, where students interact with dynamic geometry software during guided exploration sessions led by teachers (Recio et al., 2019). AI-enhanced immersive or extended reality environments were also used to support geometry instruction, typically as a complement to traditional teaching rather than a replacement (Cunha et al., 2025).

3.1.2. Pattern 2: Emphasis on conceptual and exploratory learning

In terms of learning focus, educationally oriented studies primarily emphasize conceptual understanding, spatial reasoning, and conditional geometric reasoning. AI is used to support students in exploring geometric properties, spatial relationships, and the conditions under which geometric statements hold. For instance, GeoGebra automated reasoning tools helped students explore when and under what conditions geometric properties hold, encouraging deeper conceptual engagement with geometry (Recio et al., 2019). In intelligent tutoring system–based studies, AI-supported diagnostic tools guided students through progressive levels of conceptual understanding as defined by structured learning outcome frameworks (Thampitak & Junpeng, 2024).

3.1.3. Pattern 3: AI as pedagogical support rather than autonomous problem solver

Pedagogically, AI-generated feedback is designed to scaffold students' reasoning processes, encourage reflection, or suggest next steps, instead of merely providing correct answers. For example, GeoGebra-based automated reasoning tools did not simply indicate correct or incorrect answers but prompted students to compare visual, numerical, and logical representations, supporting reflective geometric reasoning (Recio et al., 2019). Overall, AI functions as a teaching aid that supports exploration, understanding, and flexible instruction in geometry learning.

3.2. AI Tools with Potential Educational Relevance to Geometry

In addition to educationally oriented applications, a growing body of research focuses on AI-based tools that have not been implemented in instructional settings, but address problems closely related to geometry learning.

First, a number of 12 studies were coded at Level 1. These studies typically evaluated AI systems in non-instructional contexts, resulting in limited instructional integration. Performance was assessed through benchmarks, formal proofs, or competition-style problems, with little attention to how learners interact with or learn from AI-generated reasoning (Svičević et al., 2025; Zhang et al., 2025)

Second, 40 studies were coded at Level 2. Some studies assessed large language models using geometry-related problem sets from national assessments and mathematical competitions. Results from NAEP and AMC geometry items indicated that, despite strong performance in procedural or algebraic tasks, current language models exhibited systematic weaknesses in spatial reasoning and complex geometric problem solving (Teegavarapu & Sanghvi, 2023; Wei, 2024).

Other studies focused on the development of AI systems for formal geometric reasoning, including automated reasoning and deep reinforcement learning approaches (Zou et al., 2024). These systems were typically evaluated in technical or experimental settings rather than classrooms. Nevertheless, they targeted core difficulties in geometry learning, particularly the selection of appropriate theorems and the construction of coherent chains of deductive reasoning. In addition, some studies explored the combined use of multiple AI tools, such as integrating large language models with dynamic geometry software, to support geometric discovery and conjecturing. While these approaches did not report measured learning outcomes, they frame AI as a means to prompt exploration, verification, and reflection on geometric relationships (Botana et al., 2024).

4. Discussion

This review provided a focused and exploratory analysis of recent research on AI in geometry education by distinguishing two dominant research orientations: educationally oriented AI applications embedded in instructional contexts, and system-oriented AI tools evaluated primarily through technical performance. Rather than offering an exhaustive synthesis, the review aimed to clarify how AI had been conceptualized and positioned across these two strands and to identify recurring patterns in their relationship to geometry teaching and learning.

The analysis revealed a clear contrast between the two orientations. Educationally oriented studies tended to integrate AI into task-based instructional designs, emphasizing conceptual understanding, exploratory learning, and teacher mediation. In contrast, system-oriented studies primarily assessed AI capabilities in non-instructional contexts, focusing on formal correctness, automated reasoning, or benchmark performance, with limited attention to pedagogical design or learner interaction.

Due to its focused scope and space constraints, only a subset of representative studies was analyzed in depth, and the coding scheme was intentionally coarse-grained. As a result, the findings should be interpreted as indicative patterns rather than comprehensive mappings of the field. More fine-grained reviews could further examine variations across educational levels, geometric topics, AI techniques, and learning theories, as well as incorporate quantitative synthesis where appropriate.

References

Botana, F., Recio, T., & Vélez, M. P. (2024). On using GeoGebra and ChatGPT for geometric discovery. *Computers (Basel), 13*(8), 187. https://doi.org/10.3390/computers13080187

Cunha, C. R., Moreira, A., Coelho, S., Mendonça, V., & Gomes, J. P. (2025). Converging extended reality and machine learning to improve the lecturing of geometry in basic education. *Mağallaẗ Al-Abḥath al-Handasiyyaẗ, 13*(4), 3121 – 3131. https://doi.org/10.1016/j.jer.2024.10.016

International Commission on Mathematical Instruction (ICMI). (2024). *The 26th ICMI Study: Advances in geometry education* (Discussion Document). ICMI. https://www.mathunion.org/icmi/icmi-study-26

Recio, T., Richard, P. R., & Pilar Vélez, M. (2019). Designing tasks supported by GeoGebra automated reasoning tools for the development of mathematical skills. *International Journal for Technology in Mathematics Education, 26*(2), 81-88.

Svičević, M., Milenković, A., Vučićević, N., & Stanković, M. (2025). Evaluating the success of AI tools in supporting student performance in Mathematical Kangaroo Competition. *Computer Applications in Engineering Education, 33*(4). https://doi.org/10.1002/cae.70063

Teegavarapu, R. R., & Sanghvi, H. (2023, December). Analyzing the competitive mathematical problem-solving skills of chatGPT. *In 2023 International Conference on Data Science, Agents & Artificial Intelligence (ICDSAAI)* (pp. 1-7). IEEE.

Thampitak, D., & Junpeng, P. (2024, July). Diagnosing structure of observed learning outcomes in measurement and geometry for gifted students of 7th grade through machine learning platform, Khon Kaen Wittayayon School, Thailand. *In 2024 International Technical Conference on Circuits/Systems, Computers, and Communications (ITC-CSCC)* (pp. 1-6). IEEE.

Wei, X. (2024). Evaluating chatGPT-4 and chatGPT-4o: performance insights from NAEP mathematics problem solving. *Frontiers in Education (Lausanne), 9*. https://doi.org/10.3389/feduc.2024.1452570

Yunianto, W., Lavicza, Z., Kastner-Hauler, O., & Houghton, T. (2024). Investigating the use of chatGPT to solve a GeoGebra based mathematics+computational thinking task in a geometry topic. *IndoMS-Journal on Mathematics Education, 15*(3), 1027 – 1052. https://doi.org/10.22342/jme.v15i3.pp1027-1052

Zhang, Z., Cheng, J.-K., Deng, J., Tian, L., Ma, J., Qin, Z., Zhang, X., Zhu, N., & Leng, T. (2025). Diagram formalization enhanced multi-modal geometry problem solver. Proceedings of the ... IEEE International Conference on Acoustics, *Speech and Signal Processing* (1998), 1–5. https://doi.org/10.1109/ICASSP49660.2025.10889286

Zou, J., Zhang, X., He, Y., Zhu, N., & Leng, T. (2024). FGeo-DRL: Deductive reasoning for geometric problems through deep reinforcement learning. *Symmetry (Basel), 16*(4),437. https://doi.org/10.3390/sym16040437