Mathematics Education in the Age of AI: Challenges and Prospects for Secondary Teachers in Japan

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Abstract

The rapid evolution of generative artificial intelligence (AI) technologies—such as ChatGPT, Claude, and Gemini—has begun to reshape how mathematics is taught and learned. In Japan, the secondary mathematics curriculum and teaching practices face growing pressure to shift from transmission-based instruction to inquiry-oriented, technology-integrated learning environments. This paper explores how Japanese middle and high school mathematics teachers can prepare for this transformation. Key areas of focus include lesson redesign, the development of AI literacy, the integration of AI into inquiry-based learning, and the redefinition of assessment practices. By positioning AI as a partner in mathematical thinking rather than solely as a computational tool, we argue that mathematics education can become more meaningful and creative in the age of AI.

1 Introduction

Since the public release of ChatGPT in late 2022, the emergence of generative AI has dramatically altered expectations for learning and teaching. In mathematics education, tasks such as symbolic manipulation, graphing functions, proof generation, and modeling are increasingly supported by AI systems. These advances raise fundamental questions: What is the purpose of learning mathematics in an age when machines can perform many traditional mathematical tasks? What should teachers focus on when AI is accessible to both students and educators? In Japan, where the GIGA School Initiative[1] has already equipped every student with a device, the integration of AI into mathematics education is not a future but a present reality. The Ministry of Education, Culture, Sports, Science and Technology (MEXT) has published provisional guidelines for the educational use of generative AI, signaling a nationwide shift toward embracing digital transformation in schools. This paper discusses five key areas where Japanese secondary school mathematics teachers need to adapt their practices in response to the growing presence of AI in education.

2 The Impact of AI on Mathematical Tasks and Learning

The discussion on AI in mathematics education is not emerging in a vacuum. It builds on two decades of research into ICT integration, computer algebra systems (CAS), dynamic geometry software, and online collaborative platforms. Studies in the 2010s demonstrated that digital tools enhanced visualization and engagement but often left conceptual understanding underdeveloped (see [4]). The arrival of generative AI represents a qualitatively different phase: rather than simply providing computational assistance, AI now participates in meaning-making processes. This shift has prompted international frameworks, such as OECD's Education 2030, to emphasize competencies like agency, critical thinking, and cross-disciplinary learning (see [3]). In Japan, these global trends intersect with domestic policies such as the GIGA School Initiative, creating a unique moment of transformation.The rapid evolution of generative AI is reshaping the kinds of tasks that define mathematics education. Tasks that were once central to mathematics learning—such as symbolic manipulation, proof construction, and graphin—are now increasingly automated by AI systems. This shift compels educators to reconsider the purpose of mathematics instruction and to identify which competencies remain essential for students in an AI-rich environment. While automation challenges traditional pedagogies, it also opens new opportunities for fostering higher-order thinking, inquiry, and creativity.

2.1 Automation of Traditional Tasks

Generative AI can now perform a variety of mathematical tasks, such as solving equations, generating multiple approaches to a problem, creating graphs, providing proofs, and modeling real-world phenomena. While these capabilities highlight the remarkable computational power of AI, they also raise pressing questions for mathematics education: If machines can execute symbolic manipulation or generate logically sound proofs, what remains central for students to learn? For example, AI-driven graphing tools can instantly generate visualizations of complex functions, but students must still interpret these graphs and connect them to underlying mathematical principles. Similarly, AI-supported proving can deliver logically valid arguments,

[1] The GIGA (Global and Innovation Gateway for All) School Program, initiated by the Japanese government in 2019, sought to equip each student in compulsory education with an individual learning device and high-speed connectivity. It represented a rapid, nationwide ICT infrastructure enhancement to foster equity and innovation in education.

yet students must learn to critically examine these proofs, identify assumptions, and explore alternative strategies. As a result, the teacher's role is shifting from demonstrating step-by-step procedures to cultivating students' ability to interrogate, interpret, and extend AI outputs.

- Solving equations and performing symbolic manipulations
- Generating multiple approaches to a problem
- Creating graphs and visualizations of functions or data
- Providing proofs or logical explanations for theorems
- Modeling real-world phenomena using statistical and algebraic tools

As a result, the traditional role of teachers as providers of algorithms or solutions is being replaced by the need to guide students on how and why they engage with mathematical ideas.

2.2 Changing Student Learning Needs

As AI reshapes the landscape of mathematical practice, students are expected to acquire new competencies that go beyond procedural fluency. These include:

- Designing problem-solving processes
- Critically evaluating AI-generated solutions
- Structuring real-world situations into mathematical models
- Engaging in collaborative, data-informed inquiry

Meeting these needs requires a shift in mathematics education toward fostering higher-order thinking, effective communication, and adaptability. By framing AI as a thinking partner rather than a computational servant, educators can prepare students not only to use AI responsibly but also to engage in meaningful inquiry and innovation in mathematics learning.

2.3 Summary of Chapter 2

In summary, the rise of generative AI transforms the meaning of mathematical tasks and demands a reorientation of teaching and learning. Routine procedures such as symbolic manipulation and graphing are increasingly automated, while students' learning must focus on interpretation, critical evaluation, and inquiry. Teachers, in turn, are challenged to guide learners in questioning AI outputs, connecting them with underlying concepts, and leveraging AI as a partner in mathematical exploration. This chapter therefore highlights both the risks of overreliance on AI and the opportunities for deepening inquiry-based mathematics education in the age of intelligent technologies. In the following chapter, we examine how these evolving needs call for a redesign of lesson structures, enabling teachers to integrate AI tools meaningfully while maintaining the central goals of mathematical thinking and inquiry.

3 Active Thinking Beyond AI

The integration of generative AI into mathematics classrooms compels teachers to reconsider what it means for students to think mathematically. If algorithms, proofs, and graphs can be instantly generated by machines, then the central challenge is no longer whether students can solve routine problems, but how they can engage in active, critical, and reflective thinking that transcends automated outputs. This chapter addresses the pedagogical redesign required to ensure that AI serves as a partner for inquiry rather than a substitute for thought.

3.1 Redesigning Lesson Structures

Traditional mathematics lessons in Japan, as in many countries, have often followed the "I do—We do—You do" model, emphasizing teacher explanation, guided practice, and independent application. With AI readily available, however, this structure risks being bypassed: students can directly obtain worked examples, visualizations, and even proofs without engaging in the underlying reasoning. A reimagined lesson design should instead emphasize productive struggle and interpretive dialogue. For example, when an AI tool generates a correct but opaque proof, the task for students is not to memorize the argument but to interrogate its logic, identify underlying assumptions, and explore alternative approaches. Similarly, when an AI graphing tool produces multiple visualizations, teachers can prompt students to compare the outputs, critique their relevance, and connect the representations to broader mathematical concepts. These activities shift the focus from reproducing procedures to developing mathematical judgment. Recent scholarship reinforces this shift. Ellis and Slade [1] highlight how AI-supported environments require lesson structures that foreground "metacognitive checkpoints," where students articulate reasoning before consulting AI. Wardat et al. [5] similarly emphasize that students' engagement must remain dialogic, not passive reception of machine output. These studies suggest that lesson redesign must be intentional, aligning classroom routines with opportunities for student-driven questioning and critique (see [5]).

3.2 Fostering AI Literacy and Critical Dialogue

Lesson redesign also requires that students gain a degree of AI literacy—the ability to understand what AI can and cannot do, and to evaluate its outputs critically. Persistent misconceptions exist regarding AI's reliability, neutrality, and scope. Without explicit instruction, students may either over-trust AI or dismiss it entirely. Teachers can address this by incorporating reflective checkpoints into lessons. For example, after AI provides a solution, students can be asked to:

- Identify possible limitations or errors in the AI's reasoning.
- Compare the AI-generated solution with their own strategy.
- Discuss contexts where AI support may obscure, rather than enhance, understanding.

Such practices develop not only technical proficiency but also the disposition to question authority—a disposition central to mathematics as a discipline. Giannakos et al. [2] argue that AI's pedagogical affordances are maximized only when learners are guided to treat AI as a collaborative interlocutor rather than as a definitive source of truth.

3.3 Summary of Chapter 3

The redesign of mathematics lessons in the age of AI must prioritize students' active thinking beyond automation. Generative AI has the capacity to accelerate computation, generate proofs, and visualize data, but it cannot replace human interpretation, judgment, and creativity. By restructuring lesson sequences, embedding AI literacy, and foregrounding reflective dialogue, teachers can transform AI from a shortcut into a catalyst for deeper learning. This shift sets the stage for the next chapter, which examines how assessment practices must evolve to capture these new forms of mathematical engagement.

4 Practical Examples and Future Directions

The integration of AI into mathematics education must not remain at the level of abstract discussion. Concrete classroom practices are needed to show how AI can reshape teaching and learning in meaningful ways. Section 4.1 introduces practical classroom examples that illustrate both the opportunities and challenges of using AI to foster inquiry and creativity. Building on these examples, Section 4.2 outlines broader reforms and future directions necessary for Japanese mathematics education, including curriculum innovation, teacher education, and assessment redesign. Finally, Section 4.3 addresses implications and limitations, highlighting issues of professional development, equity, ethics, and research gaps. Taken together, these three perspectives clarify not only how AI can be integrated into secondary mathematics classrooms but also what systemic efforts are required to sustain this transformation responsibly.

4.1 Classroom Examples

The following examples demonstrate how AI can be embedded meaningfully in the secondary mathematics classroom:

1. **High School Probability and Game Design**

   Students use ChatGPT to analyze the fairness of games and design optimal strategies. AI assists with probability calculations, but students must critique its reasoning, test strategies through simulations, and reflect on mathematical fairness.

   - **Concrete Example**

     A case from Japanese sumo, "the Tomoe playoff," can be explored. This occurs when three wrestlers tie for the championship; the winner is the first to achieve two consecutive victories. Assuming wrestlers A, B, and C have equal strength, the probability of victory is $\frac{5}{14}$ for each of the two initial competitors and $\frac{4}{14}$ for the third. This result can be derived using an infinite series. Students can then debate whether the playoff system is fair, and further explore how the system could be redesigned with AI support. The inquiry can also be extended to four or more participants.

2. **Middle School Functions and Real-World Data**

Students ask AI about speed and distance relationships, then test and correct AI-generated responses. This process teaches students not only functional relationships but also how to verify and refine AI's outputs using experimental data.

- **Concrete Example**

  Students collect their own data using the CBL(Calculator-Based Laboratory) function of a graphing calculator or motion sensors.

  Case 1: A student slides down a playground slide while a motion sensor records distance over time. The resulting data follows a quadratic function.

  Case 2: A student hangs from a horizontal bar while a motion sensor records vertical distance over time. The resulting data shows a repeating wave pattern approximated by sine or cosine functions. At the middle school level, the focus should remain on recognizing periodic patterns rather than introducing trigonometric terminology prematurely; in high school, these experiences can be connected explicitly to trigonometric functions.

3. **High School Statistics and Correlation Analysis**

   In the statistics unit, students use AI to analyze real-world datasets, such as the relationship between study time and test performance. While AI may quickly compute correlation coefficients and regression lines, teachers encourage students to critically examine the results: Does correlation imply causation? What confounding variables might exist? Students debate AI's suggestions, highlighting both the power and the limitations of automated statistical modeling. This case illustrates how AI can catalyze mathematical inquiry into probabilistic reasoning and data interpretation. It also reinforces epistemic caution when drawing conclusions.

   - **Concrete Example**

     Students collect data on "hours of sleep and test scores." Because test scores involve personal information, anonymization and aggregation are essential.

     Alternative topics include "sleep hours and daily smartphone use," which are highly relevant to adolescents.

     Public datasets may also be used, such as "temperature and beverage sales" or "rainfall and umbrella sales."

4. **Statistical Modeling in Math Inquiry**

   Students analyze real COVID-19 infection data using spreadsheets and ask AI to help construct predictive models. In addition to infection numbers, they incorporate contextual variables such as the timing of state-of-emergency declarations, vaccination rates, and the number of inbound travelers. Teachers guide discussions about uncertainty, model limitations, and ethical implications of predictions, helping students link mathematics to societal issues.

   - **Concrete Example**

     Students access publicly available COVID-19 datasets from Japan. They first plot the time series of daily infections, then overlay key events such as the start of mass vaccination campaigns or the announcement of emergency declarations. With AI support, they attempt regression or time-series modeling to predict future infection trends. Teachers prompt students to question the validity of these models, highlighting the dangers of extrapolation, the impact of confounding variables, and the ethical responsibility of presenting epidemic data. This inquiry not only illustrates the power of mathematical modeling but also emphasizes the need for critical engagement with AI-generated predictions.

5. **Exploring Circle Equations in Coordinate Geometry**

   In the unit Conic Sections and Equations of Circles, students learn both the standard and expanded forms of circle equations. AI is used for explanations, visualizations, and parameter variations, while students explore the connection between algebraic coefficients and geometric meaning. A central focus is teaching students how to engage critically with AI, particularly in designing prompts that lead to mathematically accurate and pedagogically useful outputs.

   - **Concrete Example**

     Students begin by analyzing the general form of a line,

     $$Ax + By + C = 0,$$

     considering how A, B, and C determine slope and intercept. They then extend this reasoning to the circle equation,

     $$x^2 + y^2 + Ax + By + C = 0,$$

     exploring how A, B, and C relate to the center and radius. Students prompt AI to calculate and graph circles, comparing outputs with their own hand-drawn constructions. When AI misrepresents the center or radius, students analyze why and refine their prompts accordingly.

In each case, the teacher's role is not diminished but redefined—as a coach, evaluator, and designer of rich learning experiences.

4.2 Future Outlook

Looking ahead, several reforms are necessary to ensure the productive integration of AI in Japanese mathematics education. These reforms must address not only curriculum content but also teacher education and professional development:

1. **Curriculum integration of data science and AI literacy**

   Mathematics education should explicitly incorporate elements of data science, algorithmic thinking, and AI literacy. This includes designing tasks that go beyond computation to emphasize critical interpretation, ethical considerations, and cross-disciplinary applications.

2. **Reform of teacher education programs**

   As teacher educators and former secondary teachers, we are concerned that Japan's mathematics education has long prioritized preparation for high-stakes university entrance examinations. A dramatic shift is required. Teacher training programs in faculties of education and mathematics pedagogy must prepare pre-service teachers not only to teach content but also to guide students in using AI as a thinking partner in inquiry-based learning.

3. **Professional development for in-service teachers**

   Current teachers also need sustained opportunities to explore AI integration. Beyond one-off workshops, systematic training and the use of long vacation periods for intensive teacher development programs will be essential. Such programs should emphasize both pedagogical applications and the cultivation of teachers' own AI fluency.

4. **Development of new assessment frameworks**

   Traditional forms of assessment—focused on procedural accuracy and speed—must be reconsidered. New frameworks should evaluate students' reasoning, interpretation, and collaboration, including how they critique and extend AI-generated responses.

5. **Cross-disciplinary collaboration**

   Mathematics educators must collaborate with informatics educators, curriculum designers, and policymakers to build coherent frameworks that align AI use with broader educational goals.

6. **Global alignment and policy considerations**

   Finally, Japan must situate its reforms within the international context. Frameworks such as OECD's Education 2030 emphasize student agency, creativity, and interdisciplinary learning. Aligning national policies with such global visions ensures that AI integration enhances equity and sustainability (see [3]).

By addressing these reforms, mathematics education can move beyond its traditional exam-centered focus and reposition AI as a collaborative partner for inquiry, creativity, and human judgment. This vision points directly toward the broader philosophical question raised in Chapter 5: What is the human meaning of mathematics in the age of AI?

4.3 Implications and Limitations

While the preceding examples highlight the potential of AI in transforming mathematics classrooms, several implications and limitations must be carefully considered:

1. **Teacher professional development as a bottleneck**

   Many secondary mathematics teachers report low confidence in integrating AI meaningfully into lessons. Without systematic pre-service and in-service training, AI use risks remaining superficial. Strengthening teacher education in faculties of education and expanding in-service professional development opportunities—such as summer institutes and long-vacation training programs—is essential.

2. **Equity and access issues**

Not all schools have equal access to stable digital infrastructure or AI platforms. Moreover, students' prior experiences with technology vary widely. If left unaddressed, these disparities may exacerbate existing educational inequalities. Policies must therefore guarantee equitable access and provide targeted support for under-resourced schools.

3. **Ethical and pedagogical concerns**

   AI raises challenges of data privacy, algorithmic bias, and over-reliance on machine-generated solutions. Teachers must explicitly address these issues within the curriculum, guiding students to use AI responsibly and critically. Pedagogically, educators need to avoid reducing AI use to "answer-getting" and instead emphasize reflection, justification, and dialogue.

4. **Limited research base**

   The academic field of AI in mathematics education is still nascent. While short-term experiments have shown promise, longitudinal studies are needed to evaluate long-term effects on student learning, motivation, and equity. Close collaboration between universities and schools will be vital for building an evidence base to guide practice.

These considerations remind us that the integration of AI in mathematics education is not a purely technical endeavor but also a pedagogical, ethical, and social one. Addressing these limitations requires sustained policy support, collaborative research, and a redefinition of teacher professionalism in the AI era. The following conclusion therefore turns to the broader philosophical question: What is the human meaning of mathematics in the age of AI?

5 Conclusion: Rediscovering the Human Meaning of Mathematics

The preceding chapters have shown that generative AI, exemplified most recently by advanced systems such as ChatGPT and its successors (e.g., GPT-5.0), is rapidly transforming both the content and methods of mathematics education. We have examined how automation challenges the traditional purpose of learning, how teachers must cultivate active thinking beyond AI, and how classroom practices can be reimagined through inquiry-based and collaborative approaches. Concrete examples demonstrated not only the promise of AI-enhanced lessons but also the challenges of guiding students to critically engage with AI outputs. These discussions converge on a fundamental insight: the true value of mathematics education in the AI era lies not in competing with machines, but in nurturing students' capacity for meaning-making, curiosity, and human judgment. While AI may surpass humans in speed and accuracy, it cannot replace the uniquely human capacities for creativity, interpretation, and aesthetic appreciation in mathematics. The task of education, therefore, is not to resist AI, but to reposition it as a co-thinker and collaborator in learning. By doing so, teachers can help students develop the intellectual resilience and reflective habits needed to navigate an AI-rich society. In practical terms, this requires renewed attention to AI-resistant tasks—such as interpretation, justification, and metacognition—as well as new forms of assessment that capture reasoning and collaboration. Equally important is the cultivation of AI literacy, ensuring that both teachers and students can critically evaluate and responsibly use these emerging tools. From a policy perspective, the integration of AI into mathematics education must be supported by clear frameworks and international alignment. The OECD's Education 2030 initiative underscores the importance of agency, interdisciplinarity, and responsible technology use, while Japan's MEXT guidelines (2023) on generative AI highlight both the opportunities and ethical boundaries of classroom practice. Aligning school-level innovations with these national and international policies is essential for ensuring equity, coherence, and sustainability in the adoption of AI tools. Ultimately, mathematics education in the age of AI is called to rediscover its human meaning. It should empower students not only to solve problems but also to ask profound questions, to see connections across ideas, and to appreciate the elegance of mathematical thought. Teachers remain at the heart of this mission. By leveraging AI as a partner rather than a substitute, they can design classrooms where mathematics becomes not only useful but also joyful—and deeply human.

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References

[1] Ellis, A. R., & Slade, E. (2023). A new era of learning: Considerations for ChatGPT as a tool to enhance statistics and data science education. Journal of Statistics and Data Science Education, 31(2), 128–133. https://doi.org/10.1080/26939169.2023.2223609

[2] Giannakos, M., Sharma, K., & Pappas, I. O. (2024). Fostering critical AI literacy in education: Pedagogical opportunities and challenges. Computers & Education, 207, 104928. https://doi.org/10.1016/j.compedu.2023.104928

[3] Organisation for Economic Co-operation and Development. (2018). The future of education and skills: Education 2030. OECD Publishing. http://doi.org/10.1787/54ac7020-en

[4] Shirai, S. (2015). A study on improving mathematical expression input in learning support systems. Doctoral dissertation, Mukogawa Women's University.

[5] Wardat, Y., Tashtoush, M. A., AlAli, R., & Jarrah, A. M. (2023). ChatGPT: A revolutionary tool for teaching and learning mathematics. Eurasia Journal of Mathematics, Science and Technology Education, 19(7), em2286. https://doi.org/10.29333/ejmste/13272