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Generative AI Supports Path Exploration for Deep Learning in Middle School Science

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Abstract

The Compulsory Education Curriculum Plan (2022 Edition) emphasizes the integration of scientific deep learning and digitalization, and generative artificial intelligence injects new momentum into classroom reform. At present, junior high school science teaching faces bottlenecks such as limited experimental conditions, shallow cognition, and lagging feedback, which restricts the development of students' higher-order thinking. In this study, a three-path model of "phenomenon visualization-problem ladder-feedback precision" was constructed, and a scientific inquiry task template was developed based on AI tools, and a controlled experiment was carried out in the eighth grade "Material Change" unit (AI support in the experimental class vs. traditional teaching in the control class). Empirical data show that this path significantly improves students' complex problem-solving rate, experimental design innovation and evidence correlation ability, and promotes the implementation of scientific literacy-based goals. In the future, we will deepen the dual-track integration of AI and physical experiments, build a regional shared task library, and provide a universal paradigm for the digital transformation of science education.

Keywords

Generative AI; Deep learning; Junior high school science; Teaching path; Empirical research; Academic literacy.

1. Introduction

1.1. Background

The curriculum objectives always keep pace with the changes in society and the development of the times [1]. Since the 18th National Congress of the Communist Party of China, our country has paid attention to the field of education, especially the basic stage of education, and has made targeted strategic innovation plans. The new curriculum standard emphasizes following the laws of students' physical and mental development, puts forward "three suitability" and "two compliance", and requires teachers to create challenging tasks to stimulate students' in-depth learning. Science courses should pay attention to the connection between kindergarten and primary school, and design the curriculum reasonably to meet the characteristics of students' school stages. In the classroom, the main position of students is highlighted, and teachers, as organizers and guides, reasonably arrange the teaching process and time to build an orderly classroom. Carry out evidence-based teaching, implement teaching based on evidence, emphasize rationality, science and visualization, and focus on students' independent inquiry and self-experience. Pay attention to synthesis and practice, follow the principle of "less but fine", strengthen practical requirements, and highlight scientific inquiry and "learning by doing". With the goal of cultivating core literacy, students are cultivated from four aspects: scientific concepts, thinking, inquiry and practice, and attitude and responsibility, and lead the revision of the curriculum and the determination of goals.

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At present, there are inevitable difficulties in junior high school science teaching. First of all, there are limitations in experimental conditions, and some experiments with harsh equipment conditions or strict environmental requirements are difficult to carry out. Secondly, due to insufficient resources and information or other undiscovered influencing factors, the exploratory experiment has a shallow phenomenon, which fails to meet the real experimental effect brought by the real inquiry experiment. In view of the increasingly prominent practical dilemma of teaching, in today's rapid development of science and technology, the national level has also given certain technical guidance and action help. In 2017, our country's Ministry of Education issued the "Education Informatization 2.0 Action Plan", which requires promoting the combination of AI, big data and other technologies with education to promote educational equity and quality improvement [2].

1.2. Core Questions

The essence of understanding things lies in seeing the root of the problem, and only by clarifying the key to the problem can we solve the problem from the root cause and avoid unnecessary troubles. Combined with the current issue of synergy and symbiosis between education and science and technology, how to promote students' higher-order thinking through AI design? How can teachers balance AI tools with traditional experiments? It became the two cores of this study. The research aims to realize the coordinated development of "education + artificial intelligence", create new vitality for science education at the junior high school level, and achieve a high-quality leap in technical bottlenecks and a breakthrough in shallow to deep exploration. On this basis, this study has important theoretical and practical value. First, the research aims to provide technology integration solutions for interdisciplinary practice. By optimizing curriculum design, we can achieve deep integration and collaborative innovation between disciplines, and provide practical technical support and strategic framework for educational practice. Secondly, this study is committed to exploring a feasible way to bridge the uneven allocation of science education resources. Through in-depth analysis of the current situation and problems of resource allocation, targeted solutions are proposed, aiming to promote educational equity, improve the overall quality of science education, and provide theoretical basis and practical guidance for the optimal allocation of educational resources. In general, this study not only provides innovative ideas for interdisciplinary educational practice, but also provides useful exploration for solving the problem of unbalanced educational resources, which has high academic value and practical significance.

2. Concept Definition and Design Logic

Generative Artificial Intelligence (GAI), as a new artificial intelligence technology based on production and innovation, has advantages in data processing, analysis and generation, providing a new perspective for the field of learning and analysis [3]. GAI technology, represented by ChatGPT, DeepSeek, etc., relies on the self-supervised learning paradigm of Transformer architecture, constructs a semantic association model through massive corpus pre-training, and optimizes the alignment of output content in combination with human feedback reinforcement learning technology, so as to have human-like natural language understanding, multimodal content generation and complex task reasoning capabilities, and promote artificial intelligence into a new stage of cognitive intelligence [4]. GAI is embedded in education and teaching, from one-way knowledge indoctrination education to collaborative and co-created teaching innovation, and educational resources have changed from primitive accumulation to rich various forms, which has also changed the function of education. With the assistance of GAI, the function of education benefits all kinds of education and teaching, from laboratory simulation teaching to the generation and application of theoretical courses, to the feedback of education and teaching to make targeted adjustment plans, reflection and summary.

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The embedding of GAI strengthens students' absorption of knowledge, promotes the practical application of knowledge, and promotes the improvement of the practical operation effect of science courses in the field of education and teaching.

Deep learning is a complex learning process that runs through the horizontal and vertical integration of learners' cognitive structures and ways of thinking, while also adapting to specific learning situations [5]. Learning motivation is the source of learning, based on the characteristics of deep learning, combined with SOLO classification theory, to maximize the effectiveness of education and teaching. SOLO classification theory provides new ideas for the integration of teaching, learning and evaluation with its hierarchical thinking, knowledge continuity, and learning circularity [6]. Using the ability level under the SOLO classification theory: single-point → association → abstraction, starting from the visualization of single-point AI phenomena, through the connection between related knowledge, to achieve the improvement of students' metacognitive level in the process of practical learning. The figure shows an AI-powered learning process model. First, the "single-point structure" realizes the visualization of AI phenomena to help learners understand specific phenomena. Then, the association structure is carried out through "breaking through the blind spot of cognition" to deepen the understanding of the phenomenon. Then, use "AI problem stepping" for systematic thinking training to guide learners to solve problems step by step. Subsequently, AI accurate feedback is provided through "abstract expansion" to evaluate the learning effect and provide suggestions for improvement. Finally, "metacognitive enhancement" is realized, that is, the improvement of learners' understanding and control of their own learning process. This model emphasizes the important role of AI in promoting learner cognitive development, see Fig. 1.

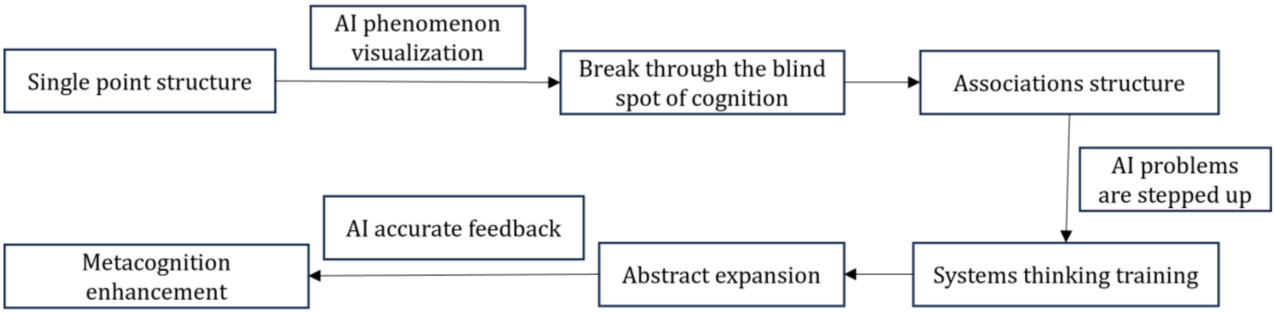

Figure 1. AI-powered learning process

The figure shows the interaction between deep learning paths and AI function support. The left side is the deep learning path, including phenomenon visualization, problem ladding, feedback accuracy, and finally relational construction and abstract migration. The right side is supported by AI functions, including dynamic simulation of microscopic phenomena, generating ladder problem chains, cognitive weakness diagnosis, and ultimately pointing to association construction and abstract migration. The two realize interaction through a single point of breakthrough, and jointly promote the improvement of learning effect. Phenomenon visualization and problem ladder are the foundation of deep learning, and feedback accuracy ensures the correctness of learning direction. AI assists learners in identifying cognitive weaknesses and achieving accurate learning by simulating microscopic phenomena and generating problem chains. Ultimately, deep learning paths and AI functions support the deepening and application of knowledge through associative construction and abstract transfer. This diagram highlights the synergy between deep learning and AI technology in education, providing a theoretical framework for personalized and precise learning, see Fig. 2.

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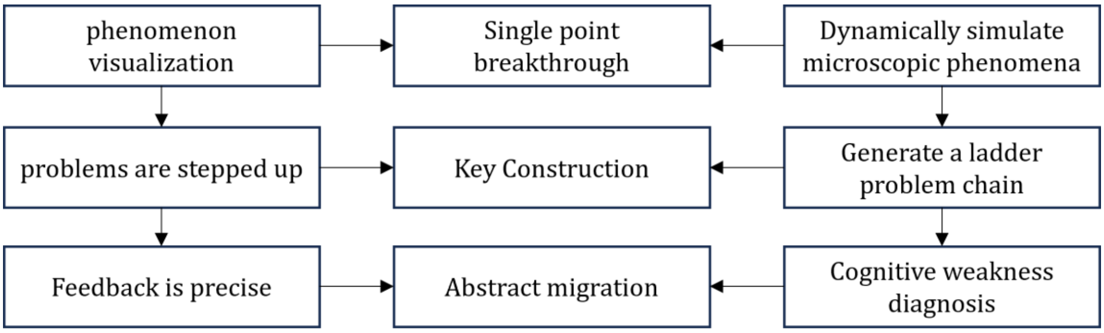

Figure 2. Interaction diagram between deep learning paths and AI functions

3. Support the Three-Dimensional Path of Scientific Deep Learning

Path 1: Visualization of phenomena (breaking through cognitive blind spots)

Case: Dynamic simulation of "molecular thermal motion" with AI

In science curriculum education and teaching, phenomenon visualization is a very powerful display tool, which can use the most intuitive visual way to help students break through the shortcomings in the cognitive field, so that students can more accurately capture abstract concepts in learning. Taking the movement of oxygen molecules in different temperature environments as an example, AI dynamic simulation technology can generate a map of the motion rate distribution of oxygen molecules at different temperatures, which not only makes up for the shortcomings of experimental conditions, but also concretizes the microscopic world, allowing students to intuitively observe the impact of temperature changes on molecular motion.

The experiment is carried out from three aspects: "instruction input, student tasks, and migration applications". First, enter the command "Generate a map of the motion rate of oxygen molecules at different temperatures", and after the instruction is released, the AI system simulates and displays the movement changes of oxygen molecules under different temperature conditions according to the instructions. Relying on the visualizations obtained from AI simulations, students can see how temperature affects the kinetic energy of molecules and thus their rate of motion. Secondly, after observing the visual AI simulation experiment, students need to complete the task of "correlating temperature→ molecular kinetic energy → combustion efficiency" to learn abstract knowledge. In this process, students need to relate the observed molecular motion rate to temperature, molecular kinetic energy, and combustion efficiency. Through this association, students can better understand the effect of temperature on the rate of chemical reactions. After that, students can transfer the knowledge they have learned to similar or highly relevant abstract knowledge principles, draw inferences from one example, and achieve the goal of efficient learning.

This method of visualizing phenomena not only makes up for the lack of experimental conditions, but also allows students to conduct scientific exploration even in environments with limited resources. And it concretizes the microscopic world, allowing students to intuitively understand phenomena at the molecular level, which is essential for cultivating scientific thinking and understanding complex scientific concepts. Finally, by combining theoretical knowledge with practical application, students can better understand and memorize scientific principles, thereby improving learning efficiency and interest.

Path 2: Problem ladder (train systematic thinking)

Case: AI-generated "metal rust" exploration problem chain

In science education, problem ladder is an effective teaching strategy that aims to guide students to train systems thinking through hierarchical problems. Taking metal rust as an

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example, AI can generate a series of inquiry problem chains, from the basic layer to the innovation layer, gradually improving students' cognitive level.

The problem chain level of this experiment is divided into three levels: basic layer, reasoning layer and innovation layer. The basic layer is mainly used for students to initially understand and distinguish the color and composition of rust. At this level, students need to understand the basic properties, composition, and chemical composition of rust, and also need to distinguish colors, so as to provide a preliminary understanding for students to carry out the core experimental part and lay a theoretical foundation for subsequent experiments. At this level, students learn the relationship between the rust process and environmental variables by exploring environmental factors and observation records of the experimental process, and cultivate their own learning, analysis and reasoning ability. The innovation layer is mainly used to improve experiments, solve problems, and design rust prevention solutions. At the innovation level, teachers are required to actively encourage and cooperate with students to combine theory and practice to design practical rust prevention solutions, and cultivate students' ability to think innovatively and actively handle problems when dealing with problems.

Teachers play a crucial role in this process. They need to screen out high-level questions, build cognitive scaffolding for students, and help students gradually build a knowledge system. By guiding students to start with basic problems and gradually transition to more complex ones, teachers can promote the development of students' systems thinking and improve their ability to solve practical problems. This approach not only helps students gain a deep understanding of abstract scientific principles, but also cultivates their critical thinking and innovation skills, laying a solid foundation for future studies and careers.

Path 3: Feedback precision (promoting metacognition)

Case study: AI corrects experiment reports and generates heat maps of cognitive weaknesses

In education, accurate feedback is crucial for promoting students' metacognitive development. Metacognitive knowledge refers to the general knowledge of cognitive activities of cognitive subjects, involving the subject's understanding of which factors affect cognitive activities and how these factors affect each other [7]. By correcting experimental reports and generating heat maps of cognitive weaknesses through AI technology, students can more accurately and intuitively understand the essence of experiments and the concretization of abstract theoretical knowledge applications, and can provide students with more accurate and intuitive feedback, thereby promoting the improvement of their metacognitive abilities. Compared with traditional teacher comments, the AI-generated cognitive weakness heat map can visually show students' performance in the report, so that students can see their shortcomings more intuitively. Traditional comments are often more abstract and may contain some general guiding opinions, but lack specificity and pertinence. Students may find it difficult to accurately identify their mistakes and deficiencies from comments, which can affect learning effectiveness. AI feedback visually displays students' performance in the report in the form of colors and graphics through heat maps and other forms. This visual feedback method can help students quickly identify their cognitive weaknesses and make targeted improvements.

By using AI to grade experiment reports and generate heat maps of cognitive weaknesses, students can more clearly recognize their shortcomings in experimental design, data analysis, and report writing. This precise feedback helps students self-assess and self-regulate, thereby promoting the development of their metacognitive abilities. In addition, this feedback method can also improve students' learning efficiency, help them master scientific methods and experimental skills faster, and lay a solid foundation for future academic research and career development.

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4. An Empirical Analysis of Junior High School Science Teaching

In this empirical analysis, two parallel classes in the second grade of junior high school were used as experimental objects, with 45 students in each class. The experimental period is set at 4 weeks, focusing on the teaching content of the unit "Changes in Matter". In order to ensure the scientificity and effectiveness of this experiment, strict variable control was carried out during the experimental process. Specifically, the two classes are taught by the same teacher, using the same teaching materials and teaching the same knowledge points, with the only difference being the form of tasks: the experimental class uses AI-assisted deep learning paths, while the control class uses traditional teaching methods.

After the experiment, the researchers conducted a series of evaluations of the overall performance of students in both classes to verify the effect of AI-assisted teaching. The evaluation indicators include complex problem solving rate, experimental design innovation, and scientific reasoning rigor. The experimental data show that the students in the experimental class are significantly better than the control class in solving complex problems, and the problem-solving effect is significantly better than that of the control class. This shows that AI-assisted teaching can effectively improve students' ability to solve complex problems. In terms of the rigor of scientific reasoning, the students in the experimental class underwent multiple iterations through AI feedback, while the students in the control class only determined its reliability through teacher correction. This shows that AI-assisted teaching can promote students to self-reflect and revise more frequently, thereby improving the rigor of scientific reasoning.

In addition, during the experiment, we observed a typical case that fully demonstrated the advantages of AI-assisted teaching. A student discovered an interesting phenomenon during an AI simulation experiment: when the salt water concentration exceeded 10%, the rust rate decreased. This discovery sparked the curiosity of the students, who independently proposed the "concentration threshold" hypothesis and designed a validation experiment to explore this phenomenon. During the experimental design process, students used AI tools to conduct multiple simulations and iterations, constantly adjusting the experimental conditions to verify their hypotheses. Through this process, students learn not only how to design and execute scientific experiments, but also how to analyze data and draw conclusions. In the end, the students successfully verified their hypothesis and presented it in class, which was recognized by teachers and classmates.

Through this empirical analysis, it can be seen that the performance of students in the experimental class in complex problem solving, experimental design innovation and scientific reasoning rigor is better than that of the control class, which shows that AI-assisted teaching can effectively improve students' scientific literacy. Through AI simulations and feedback, students can independently discover problems, formulate hypotheses, and design experiments, which helps stimulate students' innovative thinking and exploration. Through AI feedback, students can engage in more frequent self-reflection and revisions, thereby improving the rigor of scientific reasoning. Compared with traditional teaching methods, AI-assisted teaching can achieve more efficient teaching results in a short period of time, which is of great significance for improving teaching quality and efficiency.

5. Reflection and Suggestions on Path Implementation

In junior high school science teaching, the implementation of AI-assisted teaching paths has achieved certain results, but there are also some limitations and challenges.

Through empirical analysis, it is found that AI-assisted teaching paths have significant effects on improving students' scientific literacy. Specifically, students' hypothesis formulation ability

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and evidence correlation ability have been improved. This shows that AI-assisted teaching can effectively stimulate students' innovative thinking and critical thinking, improving their analytical and problem-solving skills. Although AI-assisted teaching has shown significant advantages in this experiment, we should also see its limitations. First of all, the application of AI technology requires certain technical support and resource investment, which can be a challenge for schools with limited resources. Secondly, the effectiveness of AI-assisted teaching may be affected by individual student differences, and the learning habits and abilities of different students may affect the effectiveness of AI teaching. Finally, the implementation of AI-assisted teaching requires teachers to have certain technical capabilities and instructional design capabilities, which puts forward new requirements for teachers' professional development.

In order to avoid the risks that AI-assisted teaching may bring, in subsequent classroom practice applications, students can be encouraged to question and reflect on AI-generated content by setting up an "AI output questioning link". Through this method, students can recognize the limitations of AI simulation and avoid over-reliance on AI. Therefore, any data generation and application need to follow data ethics and morality, and teachers should desensitize student data to protect students' privacy. At the same time, the AI-generated content should be labeled to clarify its source and nature to avoid misleading students.

Depending on the school's resource conditions and student needs, different AI promotion methods can be used for schools at different levels of development. For schools with weak resources, priority can be given to the "phenomenon visualization" path with lower cost but higher benefits to help students understand scientific phenomena more intuitively and stimulate their interest in learning. For schools in developed areas, the dual-track model of "AI simulation + physical verification" is adopted, in which students can not only learn theory through AI simulation, but also explore practical operations through physical experiments, so as to achieve the organic combination of theory and practice.

In the process of implementing AI-assisted teaching paths, further reflection and improvement are still needed in terms of teaching design, teacher training, student engagement, and evaluation mechanisms. In the process of instructional design, AI-assisted teaching requires a well-designed teaching plan to ensure the achievement of teaching goals. Teachers need to design appropriate teaching activities and assessment methods according to the characteristics and needs of students. Teachers are key implementers of AI-assisted teaching, and they need to have certain technical skills and instructional design capabilities. Therefore, strengthening the training and guidance of teachers and improving their professional abilities is an important guarantee for the implementation of AI-assisted teaching. Improving student engagement is key to the success of AI-assisted teaching. Teachers need to stimulate students' interest and enthusiasm in learning by designing interesting teaching activities and providing timely feedback. Establish a scientific and reasonable evaluation mechanism to regularly evaluate and feedback the effectiveness of AI-assisted teaching. This helps to identify and solve problems in a timely manner and continuously optimize the teaching plan. Therefore, educational researchers and practitioners should strengthen the research and practice of AI-assisted teaching and explore more effective teaching strategies and methods. The education department has established a cooperation mechanism with schools, enterprises and society to jointly promote the development of AI-assisted teaching. This helps to integrate resources and improve teaching effectiveness. In addition, in the process of implementing AI-assisted teaching, we should always pay attention to the development of students, respect their individuality and needs, and provide them with personalized learning support. Finally, based on the evaluation results and feedback, the implementation plan of AI-assisted teaching is continuously improved to achieve higher quality teaching results.

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6. Conclusion

The closed-loop support model of "phenomenon visualization→ problem stepping→ and feedback accuracy" proposed in this study has shown its potential and effect in junior high school science teaching. The model forms a complete teaching closed loop through three stages, aiming to improve students' scientific literacy and critical thinking ability. First, the phenomenon visualization stage uses AI technology to concretize abstract scientific concepts to help students intuitively understand scientific phenomena. Secondly, the question ladder stage guides students to gradually explore and cultivate their systematic thinking through hierarchical question design. Finally, the feedback precision stage promotes students' self-reflection and learning adjustment through AI-generated personalized feedback, thereby improving metacognitive abilities.

Looking ahead, we believe there are several important development directions worth paying attention to. First, the development of subject-specific AI tools, such as chemical equation generators, can further enhance the application of AI in specific subject teaching. These tools will be more tailored to the characteristics of the subject and provide students with more accurate and efficient learning support. Secondly, the construction of a regional shared task library can avoid teachers from repeatedly developing teaching resources and improve the utilization efficiency of teaching resources. Through the shared task library, teachers can easily obtain high-quality teaching tasks, and at the same time, they can also share their innovative teaching designs with their peers to realize the co-construction and sharing of teaching resources.

In general, the implementation of AI-assisted teaching paths has achieved certain results, but there is still broad room for development. We look forward to further optimizing the teaching path, developing more practical teaching tools, and building a more efficient teaching resource sharing mechanism through continuous research and practice, so as to achieve continuous innovation and progress in science teaching.

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