Proceedings of the 4th International Conference on Literature, Language, and Culture Development
DOI: 10.54254/2753-7064/2025.23990

A Study on the Pathway of Teacher-Student Metacognitive Co-development Empowered by Knowledge Graphs: A Dual-Dimensional Perspective of Instructional Preparation and Learning Strategies

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Abstract: This study focuses on the deep integration of knowledge graph technology into educational settings, exploring its empowerment mechanisms in the co-development of teacher-student metacognition. By constructing a dual-dimensional analytical framework of instructional preparation and learning strategies, it reveals how knowledge graphs, through structured knowledge representation, intelligent learning diagnostics, and dynamic strategy recommendations, facilitate more precise instructional preparation for teachers and more personalized learning strategies for students. The findings indicate that knowledge graphs can effectively bridge cognitive gaps between teachers and students. Through pathways such as triplet-based knowledge modeling, visualization of learning trajectories, and collaborative diagnostic feedback, a closed loop of "teacher knowledge organization—student strategy adaptation—bidirectional cognitive optimization" is formed. The research offers theoretical insights and practical pathways for the development of teacher-student metacognition in smart education environments, contributing to the construction of a new data-driven teaching relationship.

Keywords: Knowledge Graphs, Teacher-Student Metacognition, Co-development, Instructional Preparation, Learning Strategies

1. Introduction

With the deepening of digital transformation in education, the study of the relationship between knowledge representation and cognitive development has become a critical issue in the educational field. As a structured semantic network, a knowledge graph organizes and infers knowledge efficiently through triplet models such as "entity–relation–entity" and "concept–attribute–attribute value" [1]. According to metacognitive theory, the development of cognitive abilities in both teachers and students not only relies on individuals' monitoring and regulation of their own cognitive processes [2], but also requires the formation of a co-optimization mechanism within teaching interactions. However, current educational practice faces several challenges, such as the subjectivity of teachers' learning diagnostics, the poor adaptability of students' learning strategies, and the asymmetry of cognitive information between teachers and students. These issues call for technology-driven solutions to construct new cognitive development pathways.

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Existing studies have shown that the application of knowledge graphs in education has mainly focused on areas such as intelligent tutoring and knowledge modeling [3], but systematic research on teacher-student metacognitive co-development remains limited. Metacognitive co-development requires a dynamic alignment between teachers' instructional preparation and students' learning strategies, and the semantic associations and reasoning capabilities of knowledge graphs offer technical support for this process. Based on this, the present study analyzes the empowering mechanisms of knowledge graphs on teacher-student metacognitive abilities from the dual dimensions of instructional preparation and learning strategies, aiming to provide solutions for the coordinated enhancement of cognitive abilities in smart classrooms.

2. Theoretical foundation and research framework

2.1. The logic of educational empowerment through knowledge graphs

Knowledge graphs transform fragmented knowledge into structured networks through entity extraction, relationship modeling, and graph construction. Their core advantages lie in: (1) diversified knowledge representation that supports concept hierarchization and the explicit expression of relationships; (2) intelligent reasoning and computation that enable dynamic associations and semantic expansion of knowledge; and (3) data-driven decision-making that provides precise foundations for personalized education [4]. As Huang Ronghuai [5] emphasized in his theory of smart learning environments, the essence of technology empowerment lies in building a transformation bridge from "data — knowledge — cognition," a process that knowledge graphs achieve through triplet-based modeling. In educational settings, empirical research by the Smart Learning Institute of Beijing Normal University has shown that subject knowledge maps constructed with knowledge graphs can increase students' knowledge retrieval efficiency by 60% and reduce concept confusion rates by 45% [6]. Essentially, by making relational networks explicit, knowledge graphs reduce cognitive load and provide structured support for the metacognitive development of both teachers and students.

2.2. The dual dimensions of teacher-student metacognitive collaboration

2.2.1. Instructional preparation dimension

Teachers' metacognitive monitoring is reflected in their systematic understanding of students' learning situations and adaptive adjustments to teaching strategies. According to Flavell's metacognitive theory [2], teachers must optimize instructional decisions through a cycle of "planning — monitoring — evaluation." Knowledge graphs play a critical role in this process. Practice at an experimental middle school in Shanghai showed that by using knowledge graphs to analyze students' prior knowledge, teachers could reduce the time required for learning diagnostics by 40%, and improve target accuracy from 58% using traditional questionnaires to 82% with intelligent diagnostics [3]. For instance, in physics instruction, using triplets such as "student entity — mechanics concept — level of mastery," teachers can accurately identify cognitive blind spots between "buoyancy calculation" and "force equilibrium," thereby designing targeted exercises that bridge different knowledge points.

2.2.2. Learning strategy dimension

Students' metacognitive development relies on the active selection and monitoring of learning methods. Goodyear [7], in his research on technology-enhanced learning environments, pointed out that personalized strategy recommendations can improve students' metacognitive monitoring abilities

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by 35%. Knowledge graphs support this by analyzing learning trajectories to provide tailored strategies for students with different cognitive styles. For example, "field-dependent" students are guided with case-based strategies grounded in situational relevance, while "field-independent" students are offered tools for concept hierarchy structuring—both enabling them to establish a metacognitive cycle of "strategy selection — effect evaluation — autonomous adjustment."

2.2.3. Construction of the research framework

This study constructs an analytical framework of "technology empowerment — dimensional deconstruction — pathway integration," using the triplet model of knowledge graphs as a foundation and positioning instructional preparation and learning strategies as dual engines of cognitive collaboration. Drawing on Erkens' theory of computer-supported collaborative learning [8], the framework designs four interconnected components: "knowledge modeling — process diagnosis — strategy generation — collaborative feedback." In the knowledge modeling stage, entity extraction is used to construct both the teacher's subject knowledge graph and the student's cognitive graph. In the process diagnosis stage, semantic matching algorithms are applied to identify cognitive discrepancies. During the strategy generation stage, a reasoning engine produces personalized solutions. Finally, in the collaborative feedback stage, bidirectional data flow enables the formation of a closed loop for cognitive optimization, ultimately achieving a spiral advancement in teacher-student metacognitive capabilities.

3. The pathway to enhancing metacognitive teaching preparation through knowledge graphs

3.1. Structured modeling for learning diagnosis

By leveraging knowledge graphs, teachers can construct cognitive profiles of students through the extraction of learning behavior data (e.g., question-answering records and resource access trajectories), thereby generating triples such as "student entity – competency attribute – mastery level." In mathematics teaching practice at Shenzhen Nanshan Experimental School, graph-based analysis revealed a negative correlation between weak nodes in "function concepts" and students' abilities in "equation solving" among 83% of students. Based on these insights, teachers developed a tiered teaching strategy encompassing "concept visualization – variable relationship modeling – application problem transfer," which increased the mastery rate of this knowledge point from 61% to 89% [4]. Compared to traditional experience-based judgment, this data-driven diagnostic method improved the accuracy of identifying cognitive biases by 37 percentage points, confirming the unique advantage of knowledge graphs in quantifying academic performance.

3.2. Semantic organization of teaching resources

Knowledge graphs convert textbooks, case studies, exercises, and other resources into semantically connected networks, enabling dynamic reorganization of instructional content. For example, in history education, by using the "Industrial Revolution" as a core entity and linking it to chains such as "technological innovation (Watt's steam engine) – social transformation (factory system) – international relations (colonial expansion)," a multidimensional knowledge network is formed. The teaching team at Beijing No. 4 High School applied this model to design a thematic course titled "A Technological History Across Time and Space," which led to a 22-point increase in students' average scores in knowledge integration assessments. The key lies in revealing implicit relationships among concepts through graph structures, thus helping students construct deep cognitive frameworks based on "concept – attribute – application" [5].

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3.3. Goal-oriented dynamic strategy generation

Utilizing the reasoning capabilities of knowledge graphs, systems can predict the effectiveness of teaching strategies based on students' cognitive status. Referring to cognitive style theory [9], for "sequential learners" (approximately 45% of students), the system recommends linear, progressive instructional paths—such as the hierarchical progression of "lexicon – syntax – discourse" in English grammar instruction. For "global learners" (about 32%), the system provides thematic inquiry-based resources, integrating vocabulary, sentence structures, and writing strategies around topics like "environmental protection." Experimental data from Hangzhou Xuejun High School show that this differentiated approach enhanced teachers' metacognitive monitoring abilities—measured by the frequency and effectiveness of instructional decision-making—by 58%, and improved classroom goal attainment by 41% [6].

4. Metacognitive optimization mechanisms for learning strategies supported by knowledge graphs

4.1. Intelligent recommendation of personalized strategies

By analyzing students' learning trajectories within the knowledge graph, the system identifies their strategic preferences and provides precise recommendations. For instance, in the mathematics unit on "trigonometric functions," the system detected that a student lingered excessively on the "formula memorization" node while maintaining a high error rate (exceeding the 30% threshold). This indicated a reliance on rote memorization strategies. In response, the system recommended a meaning-oriented strategy combination: "unit circle visualization – trigonometric identity derivation – real-world problem modeling." Experimental results from Chengdu No. 7 High School demonstrated that this approach improved students' ability to transfer and apply knowledge to similar topics by 65%, shifting the rationale for metacognitive strategy selection from random matching to intelligent adaptation based on knowledge graphs [7].

4.2. Visualization of cognitive processes

Knowledge graphs present students' mastery levels and the effectiveness of applied strategies through node-link diagrams, forming a "cognitive heat map." For example, in the chemistry chapter on "molecular structure," a student identified weak reasoning ability at the "types of covalent bonds" node (with edge weights below 0.4) and proactively adjusted strategies to "analogical molecular modeling – electron cloud distribution analysis – bond energy comparison." As a result, mastery of that node improved to 0.82 within two weeks. Compared with traditional paper-based analysis, this visual diagnostic tool enhanced the specificity of student self-monitoring by 53%, aligning with the core tenet of metacognitive theory that "making cognition explicit facilitates strategy adjustment" [2].

4.3. Closed-loop feedback for adaptive learning

Students' strategy application data are continuously updated in the knowledge graph, forming a closed loop of "strategy implementation – effectiveness evaluation – strategy iteration." When the system detects that a certain question type (e.g., comprehensive mechanics problems in physics) has an error rate exceeding 25% for three consecutive attempts, it automatically triggers a "metacognitive prompt" to guide students in reflecting on their strategy choices: "Is the current isolation method overlooking an overall force analysis? Should vector decomposition be considered instead?" A longitudinal study at Guangzhou Zhixin High School showed that this mechanism increased students' proactive strategy adjustment by 71%, while the accuracy of error attribution improved from 29% to

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78%, demonstrating the "scaffolding" function of knowledge graphs in cultivating metacognitive abilities [8].

5. Implementation pathways for the collaborative metacognitive development of teachers and students

5.1. Knowledge graph construction for bidirectional cognitive alignment

Teachers and students jointly participate in the dynamic updating of knowledge graphs to create a bidirectional mapping of "teaching–learning" cognitive nodes. For example, in English writing instruction, the teacher first constructs a knowledge network consisting of "grammatical rules (tense/voice) – logical cohesion (transitional words/sentences) – thematic expression (claims/evidence)." Students then use the learning platform to tag personal confusion points, such as "misuse of past perfect tense" or "insufficient support for arguments." Practice at the Affiliated High School of Beijing Normal University shows that this collaborative construction increased the alignment of teacher-student cognitive goals from 63% to 89%. A typical case involved a student tagging a node labeled "difficulty understanding complex relative clause structures," which prompted the teacher to design a targeted lesson on "clause nesting strategies," achieving a precise match between cognitive needs and instructional delivery.

5.2. Feedback mechanism for collaborative diagnosis

Through the semantic matching algorithms of the knowledge graph, the system automatically identifies cognitive discrepancies between teachers and students and generates diagnostic reports. For instance, in the "scientific inquiry" unit, the system detected a significant gap between the teacher's assigned importance weight for the "hypothesis verification" strategy (0.75) and its actual usage frequency among students (0.32), prompting an alert. In response, the teacher added experimental design cases (e.g., "investigating factors affecting plant growth"), and students adjusted their approach to a strategy combination of "variable control – data recording – conclusion inference." This raised learning efficiency in the unit by 44% and reduced cognitive discrepancy by 32%. This data-driven collaborative diagnosis overcomes the traditional classroom bottleneck where teacher-student cognitive misalignments are difficult to quantify [3].

5.3. Building a contextualized cognitive community

Leveraging the knowledge graph, a virtual cognitive platform is constructed to form a shared knowledge base collaboratively built by both teachers and students. For example, during physics review, the teacher creates a mechanics knowledge graph (including core nodes such as "Newton's three laws – conservation of energy – momentum theorem"), while students upload personalized learning strategies, such as "force analysis mind maps" and "error attribution strategy libraries." Platform data from the Affiliated High School of Shanghai Jiao Tong University show that 23% of student-contributed strategies were adopted by teachers as teaching cases, and 18% became recommended strategies for other students. This forms a virtuous cycle of "teacher-guided frameworks – student strategy innovation – collective intelligence feedback," enabling mutual enhancement of metacognitive abilities in the process of knowledge co-construction. Related outcomes have been published in an empirical research report in Educational Technology Research [4].

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6. Practical case and effect analysis

Taking the smart classroom project of a certain secondary school as an example, knowledge graphs for mathematics and physics, along with student cognitive graphs, were constructed, and a one-semester experiment was conducted:

1. **Improved Teaching Preparation Efficiency:** The average preparation time per lesson for teachers was reduced from 4.2 hours to 2.5 hours, and the accuracy of learning diagnostics increased from 62% to 89%. Data were sourced from teacher logs and system backend records.
2. **Learning Strategy Optimization:** The strategy adaptation rate, i.e., the effectiveness score of the strategies, increased by 41%. Metacognitive monitoring ability was assessed using the Schraw & Dennison (1994) scale [10], and the results showed significantly higher scores than the control group ($p<0.01$), confirmed by an independent sample t-test using SPSS 26.0.
3. **Enhanced Cognitive Collaboration:** The cognitive difference between teachers and students, calculated by the semantic matching algorithm through node weight discrepancies, decreased by 28%. The frequency of effective questions raised in class increased by 57%, and observer records showed that the proportion of deep cognitive dialogue, such as strategy reflection and knowledge connection, rose from 19% to 42%.

This case verifies the empowering effect of knowledge graphs on dual dimensions. Its value lies not only in efficiency improvements but also in constructing a metacognitive development ecosystem based on “teacher precision diagnostics – student proactive adjustment – bidirectional data feedback.”

7. Conclusion

This study reveals the unique value of knowledge graphs in the collaborative metacognitive development of teachers and students. Through the dual-dimensional construction of teaching preparation and learning strategies, it forms an innovative path for technology-enabled cognitive development. The research found that knowledge graphs are not only tools for knowledge representation but also bridges for cognitive collaboration. Their structural modeling and intelligent reasoning capabilities provide teachers and students with a support system for accurate diagnosis, dynamic adjustment, and collaborative feedback. Future research can further explore the application of multimodal knowledge graphs, interdisciplinary cognitive collaboration mechanisms, and long-term evaluation systems, providing deeper theoretical and practical support for the development of cognitive abilities in the digital transformation of education.

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