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Human-Machine Collaboration Perspective: Analysis on the Development Path of Primary and Secondary School Teachers' Digital Competence

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Abstract: With the accelerated transformation of digital and intelligent education, primary and secondary school teachers are required to develop digital competence beyond basic technical operation. From the perspective of human-machine collaboration, this paper examines how intelligent technologies can support teachers' instructional design, data-informed decision-making, ethical judgment, and continuous professional development. Through integrative literature analysis, the study clarifies the conceptual relationship between human-machine collaboration and teachers' digital competence, identifies major development dilemmas, and proposes a systematic pathway for competence improvement. The study argues that teachers' digital competence should be developed through tiered diagnosis, scenario-based practice, AI-assisted instructional routines, evidence-based reflection, professional learning communities, and ethical governance. The proposed framework emphasizes teacher agency, responsible technology use, and sustainable school-based support, offering theoretical and practical references for the professional development of primary and secondary school teachers in the intelligent era.

1. Introduction

Digital transformation has become a structural force reshaping educational systems, teaching relations, and teachers' professional competence. In the intelligent era, digital technology is no longer merely an auxiliary tool for presentation or administration. It increasingly participates in lesson preparation, resource generation, learning analytics, instructional feedback, classroom interaction, and teacher professional learning. The 2025 World Digital Education Conference emphasized that artificial intelligence is promoting systemic transformation in teaching, learning, management, evaluation, and research, which requires teachers to reconstruct their professional roles in a more open, inclusive, and intelligent educational ecosystem [1].

For primary and secondary school teachers, this transformation is especially significant. Basic education directly concerns students' foundational knowledge, learning habits, social development,

and future adaptability. Teachers' digital competence therefore affects not only classroom efficiency but also educational equity, learning support, value guidance, and students' digital citizenship. Existing research has shown that teacher digital competence has shifted from tool-based digital literacy to comprehensive professional competence involving digital resources, teaching design, learning assessment, student empowerment, and ethical responsibility [2]. A review of Chinese studies from 2004 to 2023 also indicates that the field has gradually focused on conceptual connotation, current status, influencing factors, and development strategies, while still facing limitations in research depth, methodological rigor, and differentiated attention to educational stages [3].

However, the development of primary and secondary school teachers' digital competence remains uneven. Some teachers still understand digital technology as an external instrument rather than a pedagogical partner. Some training programs focus on general platform operation while neglecting classroom transformation, subject integration, student development, and ethical issues. Evaluation research further points out that teachers' digital competence development is constrained by delayed digital awareness, weakened evaluation functions, vague evaluation content, and insufficiently diversified evaluation subjects [4].

Human-machine collaboration offers a useful analytical perspective for addressing these problems. In this perspective, teachers and intelligent systems do not form a replacement relationship. Teachers retain professional judgment, emotional care, value guidance, and pedagogical creativity, while intelligent systems provide resource generation, data analysis, adaptive feedback, and decision support. Research on future teachers' artificial intelligence instructional competence emphasizes AI teaching knowledge, AI teaching capability, AI teaching value ethics, intrinsic motivational traits, and AI teaching development, which provides theoretical support for examining digital competence in the intelligent era [5].

Accordingly, this paper focuses on the following question: from the perspective of human-machine collaboration, how can primary and secondary school teachers develop sustainable digital competence? To answer this question, the paper first clarifies the core concepts of human-machine collaboration and teacher digital competence. It then analyzes existing development dilemmas, explains the internal empowering mechanisms, proposes multiple development paths, and discusses implementation guarantee strategies.

2. Conceptual Basis of Human-Machine Collaboration and Teacher Digital Competence

2.1 Human-machine collaboration in education

Human-machine collaboration in education refers to a professional interaction mode in which teachers, students, and intelligent technologies jointly participate in teaching activities under the guidance of educational goals. Its core feature is not teaching automation, but the coordinated distribution of educational tasks between human intelligence and machine intelligence. Machines are suitable for information retrieval, content generation, learning data analysis, pattern recognition, and personalized recommendation. Teachers are responsible for educational interpretation, contextual judgment, emotional communication, ethical guidance, and creative instructional design.

This relationship makes the teacher's role more complex rather than weaker. Teachers need to understand how intelligent systems generate outputs, how learning data are collected and interpreted, and how algorithmic recommendations should be judged according to students' actual needs. Therefore, human-machine collaboration is both a technological practice and a professional competence structure.

2.2 Teacher digital competence in primary and secondary education

Teacher digital competence refers to the comprehensive capacity of teachers to appropriately, effectively, critically, and responsibly use digital technologies to solve educational problems, optimize teaching processes, support students' learning, and promote their own professional development. It includes digital awareness, digital knowledge and skills, digital instructional design, digital resource use, data-based evaluation, professional collaboration, student empowerment, information security, and digital ethics.

For primary and secondary school teachers, digital competence must be understood within basic education contexts. It is connected with curriculum standards, classroom interaction, learning differences, student protection, home-school communication, and school-based teaching research. The digital teaching competence model for primary and secondary school teachers identifies dimensions such as digital-intelligent preparation, digital-intelligent education, digital-intelligent cognition, digital-intelligent development, digital-intelligent responsibility, and personal traits, showing that competence development involves both external skills and internal values [6].

2.3 Relationship between human-machine collaboration and digital competence

Human-machine collaboration provides a practical environment for teachers' digital competence development, while digital competence determines whether teachers can participate effectively in such collaboration. If teachers only possess operational skills, they may use intelligent tools superficially, such as generating worksheets or slides without improving learning design. If teachers develop comprehensive digital competence, they can transform machine-generated content into pedagogically meaningful resources, use learning data to diagnose student difficulties, evaluate AI outputs critically, and redesign teaching strategies according to classroom evidence.

Thus, the relationship between the two concepts is mutually constitutive. Human-machine collaboration expands the task field of teacher competence, while teacher digital competence ensures that human-machine collaboration remains educationally valuable, ethically responsible, and contextually appropriate.

3. Existing Dilemmas in the Development of Teachers' Digital Competence

3.1 Lagging digital cognition

The first dilemma lies in teachers' digital cognition. Some teachers regard digital tools as temporary aids for presentation, communication, or administrative work, but do not recognize their deeper value in reshaping learning processes. Under this view, technology decorates traditional teaching rather than supporting inquiry, interaction, differentiation, and reflection. Research on teachers' digital competence in the digital-intelligent era shows that teachers face challenges in cognitive awareness, autonomous construction, lifelong learning, technology iteration, teaching integration, equipment support, and institutional guarantee [7]. These problems suggest that competence development must begin with conceptual transformation.

3.2 Fragmented training and weak classroom transfer

The second dilemma is fragmented training. Many training programs emphasize general technical skills, such as platform login, resource downloading, software operation, and multimedia production. Although these skills are necessary, they cannot automatically lead to instructional transformation. Studies on digital competence cultivation in the Web3.0 era point out that the

external educational environment has changed significantly and that teachers need more professional information technology skills to support educational reform [8]. However, if training remains separated from curriculum design, classroom interaction, and student development, teachers may not transfer what they learn into daily teaching.

This problem is also reflected in insufficient differentiation. Primary school teachers, junior secondary teachers, senior secondary teachers, subject teachers, class advisers, and school administrators have different digital tasks and competence needs. Research on digital competence cultivation in the digital-intelligent era suggests that teacher development should be supported by standards, intelligent resources, scenario application, environmental atmosphere, diversified training courses, practical activities, and innovative evaluation [9].

3.3 Superficial technology integration

The third dilemma is superficial technology integration. In some classrooms, digital tools are used frequently, but their use does not necessarily improve learning quality. Teachers may rely on ready-made resources, automated exercises, or AI-generated content without redesigning learning objectives, activities, feedback, and assessment. Research on digital transformation argues that teachers' existing competence structures often struggle to meet the requirements of digital education, and that digital competence improvement is necessary for teaching innovation and professional development [10].

Weak data use further limits competence development. Intelligent platforms can provide abundant learning data, but data do not automatically become educational evidence. Teachers must know how to select meaningful indicators, interpret learning processes, identify misconceptions, and adjust instruction. Without data literacy, digital platforms may become administrative systems rather than teaching support systems.

3.4 Evaluation weakness, ethical uncertainty, and insufficient motivation

The fourth dilemma concerns evaluation, ethics, and motivation. If teacher evaluation systems do not recognize digital competence, teachers may lack incentives for long-term development. Evaluation should not only measure tool use frequency but also examine instructional design quality, student learning support, data-informed reflection, ethical practice, and teaching research outcomes. Generative AI can support personalized teaching and efficient interaction, but it also brings challenges related to technology dependence, data security, content reliability, and teachers' professional adaptation [11].

Motivational mechanisms are equally important. Research integrating technology acceptance theory and self-determination theory argues that the key to improving teachers' digital competence lies not only in external resources but also in the transformation from external regulation to internal identification [12]. Teachers need to move from "being required to use technology" to "wanting to use technology for better teaching." Without such internalization, human-machine collaboration cannot become a sustainable professional practice.

4. Internal Mechanisms of Human-Machine Collaboration Empowering Teachers' Digital Competence

4.1 Resource generation and instructional design enhancement

Human-machine collaboration can enhance teachers' instructional design by improving access to resources and expanding design possibilities. Generative AI can help teachers search materials,

generate examples, draft questions, differentiate tasks, and create multimodal resources. However, the educational value of these outputs depends on teachers' professional redesign. Teachers must align AI-generated materials with curriculum goals, students' cognitive levels, subject logic, and classroom conditions.

This mechanism transforms teachers from resource consumers into resource designers. When teachers compare, modify, and reconstruct AI-generated resources, they develop digital resource evaluation ability, pedagogical design ability, and reflective judgment. AI-assisted resource generation should therefore be embedded in a cycle of goal analysis, content generation, pedagogical adaptation, classroom implementation, and reflective revision.

4.2 Data-driven diagnosis and decision support

Human-machine collaboration also supports data-driven teaching decisions. Intelligent systems can record students' learning behaviors, assignment performance, interaction patterns, and feedback responses. These data can help teachers identify learning difficulties that are not easily visible in traditional classrooms. Teachers may detect which concepts cause repeated errors, which students need additional support, and which tasks generate meaningful engagement.

Nevertheless, data-driven decision-making cannot replace teacher judgment. Teachers must interpret data in relation to classroom observation, student background, emotional state, and learning history. The AI instructional competence framework highlights data-driven teaching decisions as an important feature of future teachers' competence [5]. In this sense, data use should be integrated with instructional reflection rather than treated as mechanical measurement.

4.3 Motivation transformation through successful experience

Human-machine collaboration can promote competence development by increasing teachers' sense of efficacy. When teachers use digital tools to solve real classroom problems, such as reducing repetitive work, improving feedback efficiency, or supporting students with different learning levels, they are more likely to experience the value of technology. This positive experience can transform external requirements into internal motivation.

Therefore, schools should not simply require teachers to use platforms or submit digital evidence. Instead, they should create opportunities for teachers to experience successful technology-supported teaching, reflect on student learning improvement, and gradually build professional confidence. Motivation is not a by-product of competence development, but a central mechanism of sustainable growth.

4.4 Collaborative knowledge construction

Human-machine collaboration is not limited to interaction between an individual teacher and a digital tool. It also includes collaboration among teachers, experts, students, platforms, and intelligent systems. Digital communities can support lesson sharing, collaborative lesson preparation, teaching observation, resource co-construction, and action research. Research trends indicate that future studies should focus on differentiated framework construction, digital awareness reconstruction, and intelligent technology-driven cultivation [2]. A national review also suggests that future research should enrich studies across educational stages, expand depth, and optimize methods [3]. These findings imply that teacher development should be organized through communities that connect theory, practice, technology, and evidence.

4.5 Ethical alignment and professional responsibility

Human-machine collaboration empowers teachers only when it is ethically aligned. Teachers must understand the limitations of AI-generated content, protect student data, prevent algorithmic bias, and maintain fairness. In primary and secondary education, ethical issues are particularly sensitive because students are minors. Teachers must protect privacy, avoid discriminatory algorithmic classification, ensure age-appropriate technology use, and maintain emotional and moral care. Ethical competence is therefore not an external constraint but an internal component of teacher digital competence.

5. Development Paths and Implementation Guarantees

5.1 Establish competence diagnosis and tiered advancement

The first path is to establish a regular diagnosis and tiered advancement mechanism. Schools and regional teacher development institutions should diagnose teachers' digital competence according to dimensions such as digital awareness, instructional design, digital resource use, data literacy, collaborative teaching, ethical responsibility, and professional development. Diagnosis should not be used for labeling teachers, but for identifying development needs and designing targeted support.

Based on diagnosis results, tiered training can be organized into basic, applied, advanced, and innovative levels. At the basic level, teachers master platform operation, digital resource retrieval, information security, and classroom technology use. At the applied level, teachers integrate digital tools into lesson design, learning activities, feedback, and assessment. At the advanced level, teachers use data analysis, generative AI, adaptive learning tools, and collaborative platforms to support differentiated instruction. At the innovative level, teachers conduct action research, develop school-based digital resources, and share transferable teaching models.

5.2 Promote scenario-based and problem-oriented practice

The second path is to embed competence development in real teaching scenarios. Teachers should not learn digital tools in isolation; they should learn them through authentic instructional problems. For example, teachers may explore how AI tools support reading feedback, how learning analytics diagnose mathematical misconceptions, how digital portfolios record project-based learning, or how collaborative platforms support home-school communication.

Scenario-based practice helps overcome superficial technology use. Teachers can follow a cycle of problem identification, tool selection, activity design, classroom implementation, evidence collection, and reflective improvement. This cycle connects technology with curriculum goals and student needs, allowing digital competence to grow through situated practice.

5.3 Build AI-assisted instructional routines and data reflection

The third path is to build stable human-machine collaborative routines in lesson preparation, teaching implementation, feedback, and evaluation. In lesson preparation, teachers can use AI to generate alternative explanations, examples, learning tasks, and assessment items. In classroom teaching, teachers can use intelligent tools to support interaction, collect responses, and provide differentiated resources. In homework and feedback, AI can assist with preliminary analysis, while teachers provide final judgment, emotional encouragement, and personalized guidance.

The key is to clarify role boundaries. Machines can support efficiency and pattern recognition, but teachers must decide educational relevance, value orientation, and student suitability. Data

literacy should also be strengthened. Teachers need to understand what data can and cannot explain, collect learning evidence appropriately, interpret platform reports, and redesign instruction based on evidence.

5.4 Construct professional learning communities and ethical governance

The fourth path is to construct teacher learning communities supported by intelligent platforms. At the school level, subject groups can conduct AI-assisted collective lesson preparation, shared resource evaluation, classroom observation, and action research. At the regional level, platforms can support inter-school sharing of lesson cases, digital resources, expert guidance, and teaching research outcomes. At the individual level, teachers can build professional development portfolios that record digital practices, reflective notes, student feedback, and competence progress.

At the same time, digital ethics and human-centered values must be integrated into all stages of teacher development. Training should include cases involving AI-generated misinformation, data privacy, biased recommendations, excessive screen time, and inappropriate student profiling. School governance should clarify rules for data collection, platform use, content review, and human supervision. The ultimate aim is to ensure that technology supports students' holistic development rather than replacing educational relationships.

5.5 Strengthen policy, school support, and evaluation mechanisms

Implementation requires institutional guarantees. First, national and regional policies should provide general standards for teacher digital competence, while schools should transform these standards into school-based competence frameworks. Such frameworks should be connected with curriculum reform, classroom teaching, teacher evaluation, and professional development plans.

Second, schools should build digital teaching support systems that include technical assistance, instructional consultation, data analysis, resource development, and ethical guidance. A school-level digital teaching support group can help teachers select tools, solve problems, interpret data, and redesign activities.

Third, evaluation and incentive mechanisms should be reformed. Evaluation should combine self-assessment, peer review, student feedback, expert observation, and evidence portfolios. It should recognize not only technical use but also teaching quality, student support, reflective improvement, and responsible innovation. Finally, differentiated support should be provided for teachers in different regions, schools, subjects, and career stages to prevent digital transformation from widening educational inequality.

6. Discussion

This study contributes to existing research in three aspects. First, it places teacher digital competence within the perspective of human-machine collaboration. Previous studies have examined digital competence, AI instructional competence, evaluation mechanisms, and development paths from different angles. This paper integrates these discussions and argues that teacher competence development should be understood as a process of collaborative intelligence construction. The key is not whether teachers use AI tools, but whether they can transform intelligent support into educationally meaningful decisions.

Second, the study emphasizes the unity of competence, motivation, and ethics. Technical training alone cannot guarantee sustainable improvement. Teachers need internal motivation, successful experience, community support, and ethical judgment. This view responds to studies on

motivation transformation and generative AI-supported teacher development, while also emphasizing that human-machine collaboration must remain human-centered.

Third, the study proposes a systematic path that connects diagnosis, scenario-based practice, AI-assisted routines, evidence-based reflection, professional communities, and ethical governance. Compared with fragmented training models, this path emphasizes continuity, contextualization, and school-based implementation.

However, this paper also has limitations. It is mainly based on conceptual analysis and literature integration, and does not provide empirical data from large-scale teacher surveys, classroom observations, or intervention experiments. The proposed paths require further verification in different regions, school types, subject domains, and teacher groups. Future research may conduct longitudinal studies to examine how teachers' motivation, competence, and professional identity change through sustained human-machine collaborative practice.

7. Conclusion

From the perspective of human-machine collaboration, primary and secondary school teachers' digital competence is a comprehensive professional capacity that integrates digital awareness, instructional application, data-informed decision-making, collaborative learning, ethical responsibility, and continuous development. Its development is shaped by both technological conditions and teachers' internal agency.

At present, teachers face dilemmas such as lagging digital cognition, fragmented training, superficial integration, weak data use, inadequate evaluation, insufficient motivation, and ethical uncertainty. Human-machine collaboration can empower competence development through resource generation, instructional design enhancement, data-driven diagnosis, motivation transformation, collaborative knowledge construction, and ethical alignment.

Therefore, a sustainable development path should include competence diagnosis and tiered advancement, scenario-based practice, AI-assisted instructional routines, data literacy improvement, professional learning communities, ethical governance, and institutional guarantees. Ultimately, the goal of human-machine collaboration is not to replace teachers, but to help them become more reflective, creative, responsible, and capable professionals in the intelligent era.

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