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Digital Interactive Tools and Classroom Integration: Practical Reflections on Immersive Learning for Primary School Students

Haosheng Lu, Wuting Huang, Lulu Shao, Shirui Hong, Ziyi Xie

College of Teacher Education, Zhejiang Normal University, Jinhua, China
Email: qishi_0611@qq.com

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Abstract

Against the backdrop of in-depth advancement in educational digital transformation, digital interactive tools, as crucial carriers for creating immersive learning scenarios and stimulating students' learning initiative, are gradually being integrated into primary school classrooms. However, current applications generally suffer from single forms, insufficient alignment with students' cognitive laws, and unsatisfactory immersive learning effects. The gaps in hardware and teaching resources between urban and rural schools further restrict the effectiveness of technology-enabled teaching. Targeting primary school students aged 5 - 12, this study draws on flow theory, constructivism, Piaget's cognitive development theory, and embodied cognition theory. Through literature review, classroom observation, and typical case analysis, it clarifies the internal logic and practical value of integrating digital interactive tools with immersive learning. On this basis, a theory-driven, tiered and classified design framework for digital interactive tools is constructed, and systematic optimization paths covering six dimensions—teaching philosophy, classroom design, teacher training, resource integration, evaluation reform, and long-term guarantee—are proposed. To verify the feasibility of the strategies, comparative analysis and transformation practices were conducted on typical mathematics lessons in urban and rural primary schools. The results show that tiered and classified interaction design can adapt to different school-running conditions, effectively extend students' attention spans, and promote deep learning. This study provides practical reference for primary school teachers to scientifically use digital tools and build normalized immersive classrooms, and has positive significance for bridging the urban-rural digital divide in education and improving the quality and efficiency of primary school digital classrooms.

Subject Areas

Educational Technology, Primary Education, Digital Learning

Keywords

Digital Interactive Tools, Immersive Learning, Primary School Teaching, Interaction Design, Urban-Rural Equity

1. Introduction

This chapter systematically elaborates the overall research foundation of this paper. Starting from the realistic background of global educational digital transformation and the practical dilemma of primary school classroom teaching, it clarifies the theoretical and practical significance of integrating digital interactive tools into immersive learning. On this basis, it sorts out domestic and foreign research progress on related topics, explains the research logic and specific research methods adopted, and finally summarizes the innovations of the study, so as to lay a solid logical foundation for the subsequent construction of design framework and proposal of optimization paths.

1.1. Research Background and Significance

The deep integration of digital technology into education provides new technical possibilities for the reform of primary school classroom teaching models, but it also brings practical challenges such as formalized tool application and unbalanced development between urban and rural schools. This section first analyzes the realistic background from three dimensions: policy guidance, cognitive characteristics of primary school students and current application status, and further expounds the research value of this topic from theoretical and practical levels.

1.1.1. Research Background

The application of digital interactive tools in primary school immersive classrooms is jointly driven by top-level policy promotion, internal demands of teaching reform and realistic conditions of educational digitalization. This subsection unfolds the analysis of research background from three interrelated dimensions: policy leadership, practical contradiction of traditional classrooms, and current situation of digital application in primary schools.

1) Policy Leadership: Educational Digitalization as a Core Direction of Educational Development

Promoting educational digitalization is an important strategic measure for China to achieve educational modernization and build a powerful education country. The 20th National Congress of the Communist Party of China explicitly proposed "advancing educational digitalization". Subsequently, a series of policies such as the Outline for Building a Powerful Education Country (2024-2035) and the "AI

+ Education" Action Plan were issued, clearly requiring the deep integration of artificial intelligence and digital technologies with all scenarios and elements of education [1] [2]. These policies also emphasize continuously optimizing the allocation of urban and rural educational resources and supporting rural education development through forms such as "delivery classrooms" and "master teacher classrooms". As a pioneer in educational digitalization reform, Zhejiang Province has also issued special plans to promote the universal access of intelligent educational resources across the region, striving to narrow the urban-rural education gap [3]. The No. 1 Central Document has focused on rural education for two consecutive years, putting forward requirements such as optimizing the allocation of urban and rural resources and promoting the construction of urban-rural school communities [4] [5]. The top-down policy system provides clear guidance and policy support for digital interactive tools to enter primary school classrooms and enable immersive teaching.

2) Practical Contradiction: Mismatch between Primary School Students' Cognitive Characteristics and Traditional Classroom Models

Primary school students mainly think in concrete terms and have limited effective attention spans, relying on intuitive, operable, and interactive classroom activities to maintain learning engagement [6]. However, the traditional one-way classroom model of "teacher lecturing + blackboard writing" has weak interactivity. Students are in a passive state of receiving knowledge for a long time and find it difficult to enter a state of deep learning engagement. Relevant classroom observation data show that problems such as distracted attention and unequal participation opportunities are prominent in traditional classrooms [7] [8]. A single teaching form is not only difficult to mobilize students' thinking participation but also restricts the generation of classroom cognitive interaction [9]. Therefore, reconstructing classroom forms and extending students' attention spans through digital interactive tools has become a practical demand for primary school teaching reform.

3) Practical Status Quo: Shallow Application of Digital Interactive Tools and Unbalanced Urban-Rural Development

At present, various intelligent terminals and interactive software have basically been popularized in urban and rural primary schools, but most digital applications only stay at the level of multimedia display. Although teachers generally use digital teaching tools, they often weaken the interactive attribute, simplifying technology into a means of classroom display. Interactive activities are divorced from teaching objectives and cannot promote students' deep thinking [10]. Meanwhile, the gap in digital development between urban and rural schools objectively exists, with significant imbalances in the configuration of hardware equipment and intelligent teaching systems [11]: rural schools have a high proportion of outdated equipment and low coverage of intelligent teaching systems, while urban schools are better equipped with new interactive hardware. Multiple gaps in hardware, teachers, and resources easily lead to a "Matthew effect" of digital empowerment, further widening the urban-rural education divide [12]. The gap in infrastructure such as networks and intelligent equipment between urban and rural schools is a common problem in the global development of educational digitalization. Rural teachers often need to adjust teaching plans according to local conditions to adapt to limited digital resources [13]. In this context, exploring low-cost, easy-to-implement digital interactive tools that adapt to different school-running conditions is the key to solving application dilemmas and promoting educational equity.

1.1.2. Research Significance

The integration of digital interactive tools and immersive primary classroom teaching not only has complementary theoretical construction value for the research system of smart education, but also provides targeted practical solutions for current teaching reform and the balanced development of urban and rural education. This subsection elaborates the research significance of this study from two dimensions: theoretical value and practical value.

1) Theoretical Significance

Existing research on immersive learning mostly focuses on language subjects, with relatively limited research on primary school general subjects, especially science subjects [14]. This paper combines immersive learning theory and multimodal interaction theory with primary school teaching scenarios, builds an analytical framework based on children's cognitive development laws and embodied cognition theory, and refers to existing research results such as multimodal interactive teaching aid design and collaborative learning engagement analysis [15] to expand the application scenarios of immersive learning. At the same time, combined with the application status of domestic intelligent technologies, it sorts out the theoretical logic of the integration of digital technology and primary school classrooms, enriches the theoretical system of digital interactive tool design in the field of smart education, and provides theoretical reference for similar studies.

2) Practical Significance

Combining literature review and frontline classroom observation, this paper summarizes the common problems of current digital interactive tool classrooms, proposes tiered implementation strategies based on the differentiated school-running conditions of urban and rural schools, and helps frontline teachers clarify the application ideas of digital interactive tools. It distinguishes between lightweight and diversified application modes according to different hardware conditions in urban and rural areas, lowers the threshold for digital teaching implementation in rural schools, and relies on digital transformation to help innovate the supply model of urban and rural educational services. Based on typical lesson examples, it demonstrates the implementation path of integrating digital interactive tools with immersive classrooms, providing a reference paradigm for the majority of primary school teachers.

1.2. Domestic and Foreign Research Status

Academic circles at home and abroad have accumulated rich research results on immersive learning and digital teaching tools, providing important theoretical reference and practical experience for this study. This section first sorts out the development context and core viewpoints of relevant foreign research, then summarizes the research progress and practical exploration in China's educational technology field, and finally conducts a comprehensive review of existing studies to clarify the research gaps and breakthrough points of this paper.

1.2.1. Foreign Research Status

Immersive teaching originated from the language teaching program in Canada in the 1960s and was later widely promoted in countries such as the United States. Many practical studies on primary school immersive teaching have shown that immersive learning environments can not only improve students' language abilities but also promote their comprehensive cognitive development. With the iteration of intelligent technologies, foreign academic circles have begun to focus on the correlation between multimodal interaction and learning engagement, analyzing students' learning status through multi-dimensional data such as voice, expression, and eye movement [15]. At the same time, low-power, offline AI teaching systems have been developed for remote areas to eliminate the digital divide. European and American primary schools also integrated virtual simulation and gamified interactive tools into classrooms earlier, confirming that diverse interactive forms can improve the classroom concentration of young students. Many foreign studies have explored the application of mobile multimedia interactive tools in primary school classrooms, confirming that the design of digital interactive tools close to teaching objectives can improve classroom participation, but most teachers face the practical dilemma of insufficient integration of technology and teaching [16]. Overall, however, foreign studies mostly focus on the application of general digital tools, and research on exclusive interactive design for different grades and subjects in primary schools still needs to be supplemented.

In particular, some recent studies in developing countries have also begun to explore low-cost digital teaching solutions suitable for rural areas, confirming that lightweight interactive tools can achieve good teaching effects even with limited hardware conditions.

1.2.2. Domestic Research Status

Domestic scholars have carried out a lot of research on educational digital transformation and urban-rural educational equity. It is generally believed that digital technology can optimize the supply of educational resources, but there are also problems such as "emphasizing policies over practice" and insufficient digital application ability of teachers. It is necessary to be alert to the new educational divide caused by the abuse of technology [17]. At the classroom application level, the academic circle has explored the practical paths of digital tools in primary school mathematics and other subjects, and developed classroom observation scales and human-machine collaborative teaching design schemes, which provide support for the quantitative analysis and practical implementation of digital classrooms

[12]. In terms of interactive form design, relevant studies have discussed design ideas of school-age children's teaching aids from the multimodal interaction perspective, providing reference for the form construction of digital interactive tools [6]. Meanwhile, domestic scholars have also systematically sorted out the challenges and implementation approaches of generative artificial intelligence empowering educational innovation [18]. With the development of generative AI and domestic intelligent technologies, China has gradually carried out explorations of human-machine collaborative teaching and intelligent education systems, discussing the changes and challenges brought by AIGC to education models, laying a technical foundation for the innovation of classroom digital interactive tools.

1.2.3. Research Review

Based on existing research results, current relevant theoretical and practical explorations have formed a certain accumulation, but there are still obvious shortcomings: First, immersive learning research has a narrow subject coverage, with relatively few studies on non-language subjects in primary schools; Second, research on digital interactive tools tends to focus on tool application, with insufficient systematic interactive design combined with subject characteristics and grade differences; most subject-specific classroom interaction studies only summarize practical effects through video case analysis, and have not yet constructed a targeted design system for digital interactive activities [19]; Third, research on inclusive and low-cost digital application solutions from the perspective of urban-rural differences is relatively scarce; Fourth, there is a disconnect between cutting-edge interaction theories and frontline classroom practice, lacking replicable implementation paradigms.

1.3. Research Ideas and Methods

This section clarifies the overall logical framework and specific implementation paths of this study to ensure the standardization of the research process and the reliability of the conclusions. It first expounds the progressive research ideas from theoretical sorting to practical verification, and then introduces the specific research methods adopted in this study and their application scenarios in detail.

1.3.1. Research Ideas

This paper follows the research logic of "theoretical combing - status quo judgment - framework construction - countermeasure proposal - case verification". First, define core concepts through literature research and integrate relevant theories to build the full-text research framework; Second, combine existing literature results, frontline classroom observations, and typical cases to sort out the practical dilemmas and analyze the causes of the integration of digital interactive tools and immersive learning in current primary schools; Third, based on the previous theoretical basis, deductively form a tiered and classified design framework for digital interactive tools; Then, propose optimization strategies adapted to urban and rural schools from multiple dimensions; Finally, select typical lesson examples from urban and rural primary schools to explain the practical feasibility of the strategies.

1.3.2. Research Methods

Literature Research Method: Retrieve Chinese and foreign databases and official policy documents, sort out research results and policy requirements related to digital interactive tools, immersive learning, and primary school smart classrooms, define core concepts, and consolidate the theoretical foundation.

Classroom Observation Method: Combined with daily frontline classroom observations, record the application forms of digital interactive tools and students' classroom performance in different primary schools and grades in urban and rural areas, and summarize common problems in practice. The design of classroom observation indicators in this paper refers to the coding analysis ideas of interactive behaviors in smart classrooms (see Table 1).

Table 1. Indicator system of classroom observation record form.

First-level indicator	Examples of second-level indicators
Basic classroom information	Subject, grade, class size, teaching topic
Interaction forms and duration	Interaction type, single duration, proportion of total duration
Student participation status	Proportion of participating students, interaction frequency, distraction situation, fluency of technical operation
Immersive learning performance	Attention span, active operation, cooperative communication, emotional state
Teaching effect	Goal achievement degree, knowledge mastery, thinking development

Case Analysis Method: Select typical cases of different subjects and lesson types in urban and rural primary schools, analyze the design ideas, application effects, and existing problems of digital interactive tools, and test the rationality of the design framework and optimization strategies. The case analysis logic refers to the video analysis paradigm of information-based classrooms.

1.4. Research Innovations

Research Perspective Innovation: From Tool Use to Subject Adaptation Previous studies mostly focused on the classroom application of general digital tools, and rarely carried out targeted designs combined with the knowledge structure of primary school subjects and children's cognitive development characteristics. This paper breaks away from the technology-first tool-oriented thinking, explores the path of deep integration of digital interactive tools and subject teaching based on the teaching characteristics of various primary school subjects and the cognitive development laws of students aged 5 - 12, and constructs a grade-tiered interaction design system, allowing technology to serve the essence of teaching and student development, filling the gap of grade-specific interactive design for primary school non-language subjects.

Practical Path Innovation: Design Tiered Implementation Plans for Urban and Rural Scenarios Most existing digital classroom solutions rely on the perfect hardware conditions of urban schools and are difficult to promote in weak rural schools. Taking into account the principle of educational equity, this paper divides two application modes: the basic version (for rural/weak schools) and the advanced version (for urban/smart campuses). The basic version focuses on lightweight interaction with weak network, offline availability, and zero cost, adapting to the hardware shortcomings of rural schools; The advanced version makes full use of high-end intelligent equipment to create multimodal virtual-real integration scenarios. The tiered promotion of the two schemes conforms to the compensatory principle of educational equity [20] and is also a concrete practice of digital transformation to promote urban-rural educational equity, taking into account both technical feasibility and educational inclusiveness, which is the first systematic tiered solution specifically designed for the significant urban-rural hardware gap in Chinese primary schools.

System Construction Innovation: Build a Six-Dimensional Whole-Process Optimization System Breaking through the fragmented research limitations of single tools and single teaching links, this paper builds a whole-process optimization system from five dimensions: concept leadership, classroom design, teacher development, resource construction, and evaluation guarantee, forming a systematic construction plan for classroom digital interactive tools and providing a complete reference for the normalized operation of primary school immersive digital classrooms, and breaking through the limitation of previous fragmented research that only focused on single tools or links.

2. Core Concepts and Theoretical Basis

Clarifying core concepts and sorting out theoretical foundations are important prerequisites for carrying out this research. This chapter first defines three core concepts closely related to the research topic, then systematically expounds the four core theories supporting this study and their internal logical relationship, so as to lay a solid theoretical foundation for the subsequent construction of the design framework of digital interactive tools and the proposal of optimization paths.

2.1. Definition of Core Concepts

Accurate definition of core concepts is the basis for ensuring the rigor of research and unifying analytical dimensions. This subsection respectively clarifies the connotation, characteristics and classification of digital interactive tools, immersive learning for primary school students, and the integration of the two, so as to clarify the research boundary and core research object of this paper.

2.1.1. Digital Interactive Tools

Refer to the general term for tools, operation forms, and classroom activities that realize two-way interaction between human and machine, teachers and students, and students and students relying on digital technology around subject teaching objectives. Different from one-way multimedia playback and pure entertainment games, digital interactive tools have three characteristics: subjectivity, two-wayness, and cognition. Their core function is to serve the breakthrough of teaching key and difficult points and the development of students' thinking, specifically including touch screen dragging, dynamic deduction, virtual simulation, real-time feedback, online collaboration, and other types (see **Figure 1**).

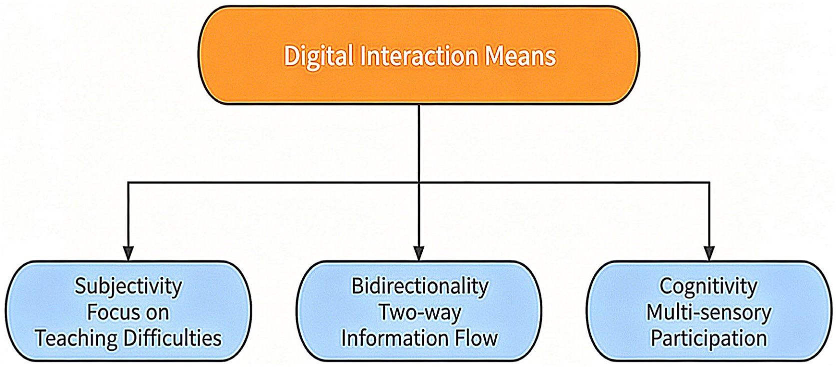

Figure 1. Functional complementary relationship between digital interaction and immersive learning.

2.1.2. Immersive Learning for Primary School Students

Refers to the learning state in which primary school students aged 5 - 12 are deeply attracted by classroom interactive activities, inquiry tasks, and learning scenarios, with highly concentrated attention and wholehearted devotion to thinking, practice, and communication. According to the degree of engagement, it can be divided into three levels: primary immersion is manifested as following the classroom rhythm and completing basic tasks; intermediate immersion is manifested as active inquiry and in-depth thinking; advanced immersion points to higher-order learning behaviors such as critical thinking and creative expression (see **Figure 2**).

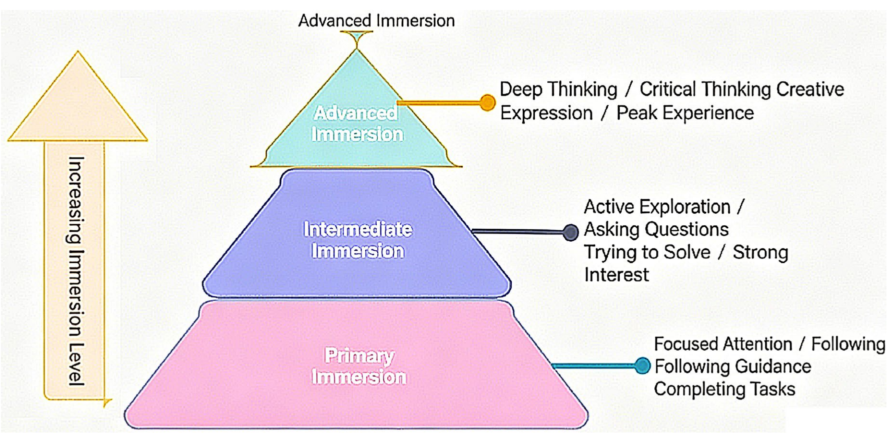

Figure 2. Level classification and performance characteristics of pupils' immersive learning.

2.1.3. Digital Interactive Tools Empowering Immersive Learning

Means taking digital technology as the carrier, creating learning scenarios, designing inquiry tasks, providing real-time feedback and multi-sensory interaction, stimulating students' internal motivation, guiding them to gradually enter an immersive learning state, and finally realizing knowledge understanding, ability improvement, and thinking development.

2.2. Theoretical Basis

The four core theories of this paper support each other and jointly form the theoretical framework of the research:

2.2.1. Flow Theory

This theory proposes that when the difficulty of an activity matches the learner's ability, and there are clear goals and immediate feedback, individuals are prone to enter an immersive state [21]. Digital interactive tools can help primary school students form immersive experiences by clarifying learning tasks, providing real-time feedback on operation results, and setting gradient inquiry content.

2.2.2. Constructivist Learning Theory

Learning is a process in which students actively construct knowledge, and situation, collaboration, and communication are the key elements for learning to occur. Digital interactive tools provide a carrier for students' independent inquiry and cooperative communication, allowing students to complete knowledge internalization in operation and interaction.

2.2.3. Piaget's Cognitive Development Theory

Primary school students are in the transition period from the concrete operational stage to the formal operational stage. Lower grades rely on concrete things, while abstract thinking gradually develops in higher grades [22] [23]. This characteristic determines that the design of digital interactive tools must be tiered according to grades to match the thinking characteristics of students at different stages.

2.2.4. Embodied Cognition Theory

Cognition is the result of the interaction between the body and the environment, and hands-on operation and sensory experience directly affect learning effects [24] [25]. Digital interactive tools support students to participate in learning through touch screens, gestures, dragging and other actions, realizing "learning by doing", which conforms to the core requirements of embodied cognition [26].

The above four theories are not isolated from each other, but jointly form the theoretical analysis framework of this study around the core proposition of "immersive learning supported by technology".

Among them, flow theory starts from the generation conditions of learning state and provides the generation logic of "clear goals - immediate feedback - difficulty matching" for digital interaction design; Constructivist learning theory starts from the essence of knowledge acquisition and establishes the classroom interaction orientation centered on situation, collaboration and communication; Piaget's cognitive development theory focuses on the learners' own thinking characteristics and provides a developmental basis for the grade-tiered design of interactive activities; Embodied cognition theory starts from the embodied root of cognition and emphasizes the basic role of multi-sensory participation and physical operation in meaning construction. The four correspond to the state triggering, process organization, object adaptation and cognitive mechanism of digital interactive classrooms respectively, forming a logical closed loop of "why interact - how to interact - for whom to interact - with what cognition". This theoretical framework lays the academic foundation for the construction of the tiered and classified digital interaction design framework below, and also provides a comprehensive analytical perspective for the subsequent proposal of classroom optimization strategies.

3. Internal Logic and Value of Integrating Digital Interactive Tools with Immersive Learning

On the basis of clarifying core concepts and theoretical foundations, this chapter deeply analyzes the internal operating mechanism and multi-dimensional practical value of the integration of digital interactive tools and immersive learning. It first demonstrates the inherent consistency and mutual support relationship between the two from three logical levels, and then elaborates the positive significance of integrated application from four dimensions: students, classrooms, teachers and regional education, so as to fully demonstrate the necessity and feasibility of promoting the integration of digital interactive tools and immersive learning in primary schools.

3.1. Internal Logic of the Integration

The integration of digital interactive tools and immersive learning is not a simple superposition of technology and teaching form, but has a tight internal logical connection. This subsection demonstrates the rationality and inevitability of the integration from three interrelated dimensions: consistent goal orientation, complementary functional relationship and adaptive implementation path.

3.1.1. Consistent Goals: Jointly Pointing to the Development of Students' Core Literacy

Digital interactive tools aim to optimize the teaching process, break through teaching difficulties, and cultivate students' thinking abilities [27]; Immersive learning focuses on improving classroom participation and promoting deep learning [28]. Both are closely linked to the general goal of core literacy cultivation proposed in the Compulsory Education Curriculum Plan (2022 Edition) [29]. Digital interactive tools are technical support, and immersive learning is the process form. The integration of the two jointly promotes the transformation of classrooms from knowledge indoctrination to literacy cultivation.

3.1.2. Complementary Functions: Dialectical Unity of Carrier and Learning State

Digital interactive tools are the core carrier for creating immersive learning. Relying on the three elements of situation, task and feedback, they mobilize students' multi-sensory participation and provide basic conditions for immersive learning; Immersive learning is the ideal form of application of digital interactive tools [30]. Only when students are truly engaged in learning can digital technology exert its value and avoid becoming a formal tool [31]. The two are interdependent and mutually reinforcing, forming a virtuous cycle from technical carrier to learning state (see Figure 3).

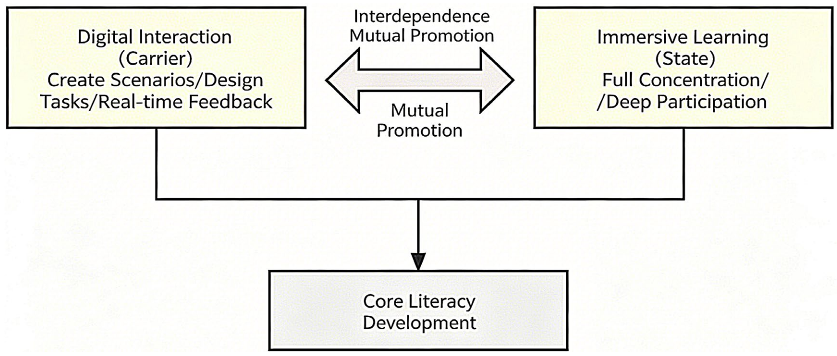

Figure 3. Functional complementary relationship.

3.1.3. Implementation Adaptation: Realizing Grade Gradient Implementation Based on Classroom Activities

Both digital interactive tools and immersive learning take classroom inquiry activities as the main implementation form, emphasizing students' active participation [32]. Combined with the tiered design ideas of artificial intelligence education in primary and secondary schools issued by the Ministry of Education [33], gradient implementation paths can be set according to students' cognitive characteristics: lower primary grades rely on interesting interactions to cultivate basic immersion habits; middle grades use inquiry interactions to form a stable immersion state; higher grades use speculative interactions to create high-level immersion experiences, realizing the progressive integration effect(see Figure 4).

3.2. Value Implication of the Integration

3.2.1. For Students: Optimizing Learning Experience and Promoting Deep Learning

Digital interactive tools visualize abstract knowledge and dynamize static content, fitting the concrete thinking characteristics of primary school students and enriching learning experiences. Immersive learning can effectively extend students' attention spans, promote the transformation from passive listening to active inquiry, help develop comprehensive abilities such as logical reasoning, cooperative communication and innovative practice, and realize the transformation from shallow learning to deep learning [33]. Teaching practice based on embodied cognition can further consolidate students' knowledge mastery [34].

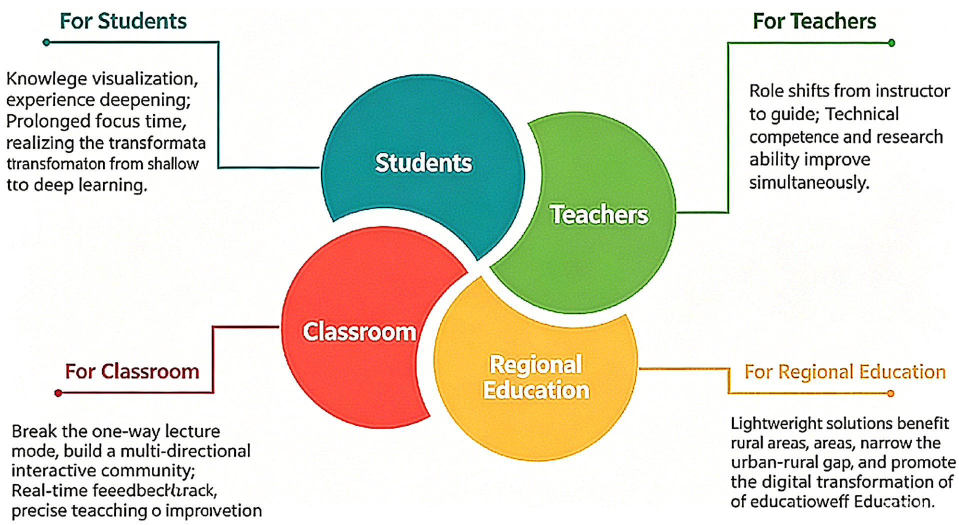

Figure 4. Value dimensions of digital interactive tools empowering immersive learning.

3.2.2. For Classrooms: Reconstructing Interactive Forms and Improving Teaching Efficiency

The integration breaks the traditional one-way teaching model and builds a classroom community of multi-directional interaction between teachers and students, students and students, and human and machine. Digital interactive tools can simplify repetitive teaching links, collect learning situation data in real time, help teachers adjust teaching strategies in real time, realize individualized teaching, and improve overall classroom teaching efficiency [35].

3.2.3. For Teachers: Transforming Teaching Philosophy and Promoting Professional Growth

Integrated application promotes teachers to transform from "knowledge disseminators" to classroom organizers and learning guides. Classrooms using digital interactive tools put forward higher requirements for teaching design, digital technology application and classroom management, forcing teachers to continuously learn and polish their teaching abilities, and also providing new directions for teachers' teaching research and professional development [36].

3.2.4. For Regional Education: Bridging Urban-Rural Gaps and Promoting Balanced Educational Digitalization

Lightweight and low-cost digital interactive tool solutions allow rural schools to enjoy the dividends of digital education and narrow the gap in urban and rural classroom teaching [37]. The deep integration of digital interactive tools and immersive learning is also an important starting point for regional educational digital transformation, which can comprehensively improve the quality of primary school education [38].

4. Theoretical-Based Design Framework and Principles of Digital Interactive Tools

Combined with the four core theories above, based on the characteristics of primary school grades, classroom teaching scenarios and urban-rural school-running differences, this paper constructs a theory-driven design framework for digital interactive tools in primary school classrooms from three dimensions: overall design goals, tiered and classified design principles, and scenario adaptation requirements.

4.1. Overall Design Goals

Taking cultivating students' core literacy as the fundamental, relying on digital interactive tools to create immersive learning scenarios adapted to primary school students; Taking into account both interestingness and knowledge, technicality and practicality, designing interactive forms according to urban-rural hardware conditions and grade cognitive levels; Making digital interactive tools serve the breakthrough of teaching key and difficult points, extend students' effective attention spans, and promote students at different levels to achieve deep learning.

4.2. Core Design Principles (Combined with Theoretical Deduction)

Guided by the four core theories mentioned above and combined with the actual needs of primary school classroom teaching, this study summarizes six core design principles covering learner adaptation, immersion generation, cognitive mechanism, teaching orientation, educational equity and subject integration. These principles run through the whole process of digital interactive tool design, providing clear value criteria and operational guidelines for tiered and classified interactive design adapted to different grades and school-running conditions.

4.2.1. Cognitive Adaptation Principle (Based on Piaget's Cognitive Development Theory)

Strictly design interactive activities according to the thinking characteristics of students in the lower, middle and upper grades of primary school, and reject the "one-size-fits-all" approach.

Lower Grades (Grades 1-2): Focus on interesting lightweight interactions, select simple operations such as touch screen clicking and graphic dragging, with simple pictures and low operation thresholds, control the proportion of entertainment elements, and avoid distracting attention.

Middle Grades (Grades 3-4): Focus on inquiry-based interactions, add forms such as dynamic deduction, group collaboration and real-time answering, and guide students to verify by hands and think cooperatively.

Higher Grades (Grades 5-6): Focus on speculative deep interactions, use forms such as virtual simulation, project-based collaboration and open inquiry to help students develop abstract logical thinking.

4.2.2. Immersion Generation Principle (Based on Flow Theory)

Design interactive tasks following the three immersion generation conditions of "clear goals, immediate feedback, and difficulty matching": Each interactive activity clearly corresponds to the learning objectives; Realize real-time feedback on operation results with digital tools; Set task difficulty between students' existing abilities and potential development levels, and set gradient subtasks so that students of all levels can continue to engage.

4.2.3. Embodied Participation Principle (Based on Embodied Cognition Theory)

Strengthen "hands-on operation + sensory experience", give priority to interactive forms that can mobilize the coordinated participation of hands, eyes and brain such as touch screens, dragging and gesture operations, integrate knowledge learning into practical experience, and avoid simple "passive interaction" such as picture playback and video viewing, allowing students to complete cognitive construction in "learning by doing".

4.2.4. Constructivist Orientation Principle (Based on Constructivist Learning Theory)

Interaction design is carried out around real classroom situations and inquiry tasks, and more collaborative and discussion-based interactive links are set up. Relying on digital tools to build platforms for communication, sharing and inquiry, guide students to think independently, discuss cooperatively, and actively complete knowledge construction, rather than indoctrinating knowledge points directly through technology.

4.2.5. Urban-Rural Tiered Principle (Based on Educational Equity Theory)

Combined with the differences in hardware, network and resources between urban and rural schools, two design standards are divided:

Basic Level (Rural/Weak Schools): Adapt to ordinary multimedia, mobile phones and outdated terminals, support weak network and offline use, give priority to free tools and simple interactive forms, and control hardware and capital costs.

Advanced Level (Urban/Smart Campuses): Rely on touch whiteboards, student tablets, VR/AR and other equipment to create multimodal and virtual-real integrated complex interaction scenarios, and tap the high-level application value of technology (see Table 2).

Table 2. Comparison of basic information of lesson examples.

Comparison dimension	Lesson example 1: "learning perimeter in the fields"	Lesson example 2: "angle measurement"
School type	Rural primary school	Urban primary school
Grade	Grade 3 (middle primary school)	Grade 4 (middle primary school)
Teaching content	Understanding and measurement of perimeter	Angle measurement, concept of 1-degree angle
Hardware conditions	Ordinary multimedia, mobile phones, physical teaching aids (basic version environment)	Interactive tablets, virtual simulation systems (advanced version environment)

4.2.6. Subject Integration Principle

Put an end to formal interaction divorced from teaching content, and all digital activities are closely linked to subject key and difficult points and classroom teaching objectives. Entertainment and ornamental elements serve teaching, do not one-sidedly pursue classroom liveliness, and ensure that interactive activities have clear subject value.

4.3. Classroom Scenario Adaptation Design

Combined with conventional primary school teaching links, form scenario-based interaction design matching the above principles:

New Lesson Introduction Link: Focus on situational interactions, use animations, interesting quizzes and virtual scenarios to quickly attract students' attention and lay the groundwork for learning content.

New Knowledge Teaching Link: Focus on inquiry and deduction interactions, visualize abstract knowledge points, and cooperate with practical operations to help students understand core concepts.

Classroom Practice Link: Focus on real-time feedback interactions, use online answering, breakthrough exercises and other forms to quickly detect learning situations.

Group Cooperation Link: Focus on collaboration and sharing interactions, use functions such as file sharing, work upload and online discussion to support student-student interaction.

5. Optimization Countermeasures for Integrating Digital Interactive Tools with Immersive Classrooms

Combined with the previous design framework, literature research and practical problems found in classroom observation, this paper proposes implementable optimization countermeasures from six aspects: philosophy, classroom, teachers, resources, evaluation and guarantee, taking into account the tiered implementation requirements of urban and rural areas throughout the process.

5.1. Update Teaching Philosophy, Clarify Interaction Positioning, and Abandon Formal Application

Carry out normalized school-based teaching research with subject teaching and research groups as units, clarify the boundaries between digital interactive tools, entertainment games and one-way multimedia playback, and establish the core principle of "interaction serving teaching, focusing on thinking cultivation". Organize teachers to observe high-quality lesson examples in urban and rural areas, and transform traditional teaching thinking. In terms of tiered guidance, teaching research in rural schools focuses on "making good use of existing equipment and tapping the interactive potential of simple tools", while teaching research in urban schools focuses on "moving from technology superposition to teaching reconstruction", fundamentally avoiding the blindness and formalization of technology use.

5.2. Implement Tiered Design and Build a Gradient Immersive Classroom System Based on the Interaction Framework

Strictly follow the interaction design principles in Part IV, and plan classroom interaction processes by grade and scenario. Rural schools implement the basic version of lightweight interaction solutions and carry out teaching based on existing equipment and free tools; Urban schools implement the advanced version of multimodal interaction solutions, and give full play to the advantages of intelligent equipment to create virtual-real combined immersive scenarios. In classroom practice, teachers can build four interaction nodes of "situation triggering - inquiry construction - practice feedback - summary sublimation" in one lesson according to the design framework in Part IV: In the introduction link, situational interactions are used to quickly focus attention; In the new teaching link, inquiry and deduction interactions are used to support the understanding of core concepts; In the practice link, real-time feedback interactions are used to detect learning situations in real time and adjust teaching rhythm; In the summary link, reflective and sharing interactions are used to help students sort out knowledge structures. The four nodes are closely linked to avoid the fading of students' immersion state due to interrupted interaction.

5.3. Build a Tiered Training System to Make up for Teachers' Shortcomings in Digital Interactive Tool Design Ability

Construct a teacher development system integrating "tiered training + school-based teaching research + urban-rural linkage". Carry out basic equipment operation and free teaching tool use training for middle-aged and elderly teachers and zero-based teachers; Offer special courses on interactive design and scenario creation for young backbone teachers, deeply integrating technical operation with subject teaching design. Improve the overall ability through in-class lesson polishing and collective lesson preparation, and carry out cross-school exchanges relying on urban-rural school communities, master teacher classrooms and delivery classrooms to exchange application experience and narrow the ability gap between urban and rural teachers. At the same time, build an online micro-video resource library classified by tools, equipped with common troubleshooting guides, to lower the technical threshold for teachers' independent practice after class and alleviate their fear of difficulties.

5.4. Integrate Global Digital Resources to Solve the Problem of Uneven Allocation of Urban and Rural Resources

Regional education funds should be appropriately tilted towards rural and remote schools, set up special funds for digital teaching in rural schools, include them in the annual budget according to the per capita standard, and give priority to updating outdated intelligent terminals and optimizing the network environment. At the same time, establish a recycling mechanism for idle equipment. After passing the inspection, interactive tablets and tablet computers replaced by urban schools should be preferentially allocated to weak rural schools, and do not engage in "one-size-fits-all" hardware configuration. Build a regional resource sharing library with districts, counties and school districts as units, organize teachers to jointly develop interactive courseware, activity cases and other resources by grade and subject, which are open to the public for free and dynamically updated. Make full use of free resources from official smart education platforms at the national, provincial and municipal levels, reduce dependence on commercial paid resources, and realize the circulation of high-quality resources across the region.

5.5. Improve the Diversified Comprehensive Evaluation System and Establish the Orientation of Immersive Learning

Break the single evaluation model dominated by summative examination scores, and build a comprehensive evaluation system combining process evaluation and summative evaluation. Expand evaluation dimensions to include classroom participation, concentration state, inquiry ability and collaborative performance; Enrich evaluation methods, and record students' comprehensive performance through classroom observation, learning files and digital learning situation data. Among them, the digital interactive platform itself can provide rich accompanying evaluation data: The online answering system automatically generates correct rate distribution and error type analysis, helping teachers immediately locate teaching weaknesses; The collaborative whiteboard records students' operation tracks and discussion processes, providing process evidence for evaluating collaborative ability; The virtual simulation experiment platform tracks students' inquiry paths and trial-and-error times, reflecting their problem-solving strategies.

These data complement each other with classroom observation and learning files, forming a comprehensive evaluation basis that pays equal attention to process and summation. In terms of evaluation subjects, implement a multi-subject model combining student self-evaluation, peer evaluation and teacher evaluation. At the same time, adjust the teacher assessment orientation, include the design and implementation effect of digital classrooms in the evaluation, and guide teachers to attach importance to the construction of immersive classrooms.

5.6. Improve the Multi-Dimensional Guarantee Mechanism and Build a Long-Term Operation System for Digital Classrooms

Schools should incorporate digital classroom construction into the annual teaching work plan, clarify the minimum class hour ratio of digital interactive teaching and the frequency of teaching research activities each semester, so as to ensure plans, records and feedback. Establish a special incentive mechanism for digital teaching, and give preference to information-based teaching backbone teachers in merit evaluation and professional title assessment. Carry out home-school collaboration work, popularize the value of immersive teaching to parents through parent-teacher meetings and classroom open days, and strive for home-school cooperation. Establish a normalized classroom supervision mechanism, regularly inspect and review classroom application situations, continuously optimize implementation plans, and ensure the long-term implementation of various strategies.

6. Typical Lesson Example Analysis

Typical mathematics lesson examples from two urban and rural primary schools were selected for analysis combined with the previous interaction design framework and optimization countermeasures, to illustrate the rationality and implementability of the relevant design ideas and practical strategies. The lesson example analysis in this paper uses the "Five-Dimension Observation" framework for classroom diagnosis.

6.1. Basic Information of Lesson Examples

This section selects two typical mathematics lesson examples from rural and urban primary schools respectively as case analysis objects to verify the applicability of the digital interactive tool design framework and optimization countermeasures proposed above. The basic information of the two lesson examples, including school type, grade, teaching content and hardware configuration, is sorted out and compared (see **Table 3**).

Table 3. Basic background comparison of the two teaching examples.

Comparison dimension	Lesson example 1: "learning perimeter in the fields"	Lesson example 2: "angle measurement"
School type	Rural primary school	Urban primary school
Grade	Grade 3 (middle primary school)	Grade 4 (middle primary school)
Teaching content	Understanding and measurement of perimeter	Angle measurement, concept of 1-degree angle
Hardware conditions	Ordinary multimedia, mobile phones, physical teaching aids (basic version environment)	Interactive tablets, virtual simulation systems (advanced version environment)

6.2. Application Status and Problem Analysis of Original Lesson Examples

Before proposing targeted transformation and optimization schemes, this section first conducts a diagnostic analysis of the application status of the two selected original lesson examples. Combined with the classroom observation framework, it sorts out the practical advantages and existing shortcomings of rural and urban primary school mathematics classrooms in the application of digital interactive tools respectively, so as to clarify the entry points for subsequent transformation and provide realistic basis for the verification of the design framework and optimization strategies.

6.2.1. Lesson Example 1 (Rural Primary School)

This lesson creates a real situation based on the school vegetable garden, with physical operation, group collaboration and teacher-student Q&A as the main interactive forms. Students showed strong interest in the embodied operation link, but there were obvious shortcomings: There was no effective digital interactive means throughout the whole process, making it difficult to visually explain the abstract concept of "closed figures"; Lack of immediate feedback links, teachers cannot fully grasp the learning situation; Tasks were not tiered, making it difficult to take into account students of different levels; When switching from practical operation to theoretical explanation, students' immersive learning state was interrupted, and the classroom participation showed a significant contrast before and after: All students actively participated in the practical operation link, while about one-third of students showed distracted attention in the theoretical explanation link. This phenomenon is highly consistent with the problem of "fragmented interaction design and incomplete whole-process penetration" found in literature review and classroom observation, and generally conforms to the common dilemma of digital application in rural schools.

6.2.2. Lesson Example 2 (Urban Primary School)

This lesson carries out inquiry-based interaction relying on tablet operation and 1-degree angle dynamic tiling virtual simulation technology, which intuitively presents the abstract measurement principle. Students have high classroom concentration and strong initiative in inquiry, and the high-level immersive learning effect is outstanding. However, this lesson is highly dependent on high-end equipment and high-speed networks, with high technical thresholds, and cannot be directly replicated in rural schools. In addition, the evaluation link only takes the correct rate of exercises on the tablet as the basis, fails to make full use of the platform's process data (such as operation tracks, inquiry paths, number of attempts, etc.), pays insufficient attention to students' thinking processes and collaborative performance, and the evaluation dimension of individual learning effects is relatively single.

6.3. Lesson Example Transformation and Feasibility Explanation

Based on the problem diagnosis of the original lesson examples and following the tiered design framework and optimization countermeasures proposed above, this section carries out targeted transformation and optimization for the two typical lesson examples of rural and urban primary schools respectively. It verifies the feasibility and practical effect of the relevant strategies through comparative analysis of classroom performance before and after adjustment, so as to provide replicable practical paradigms for primary schools with different school-running conditions.

6.3.1. Transformation of Lesson Example 1 (Adapted to Rural Basic Version Solution)

Combined with the principles of cognitive adaptation, embodied participation and urban-rural tiering, a zero-cost, weak-network available lightweight transformation plan is adopted:

Add free courseware to complete figure judgment interaction, strengthen the core concept of "closed figures", and realize immediate feedback.

Use mobile phone photography and class albums to display group measurement results, simplifying the equipment use threshold.

Design three levels of gradient tasks to match the abilities of different students and implement tiered design requirements.

Reconstruct the classroom process, connect each link with micro-videos and interactive quizzes, and maintain a continuous immersion state.

The transformation plan completely relies on the existing equipment of rural schools, requires no additional capital investment, and is simple and easy to operate, proving that the strategy of lightweight digital interactive tools is feasible in rural classrooms and can effectively make up for the shortcomings of traditional classrooms.

From the comparison of classroom observations before and after the transformation, the improvement effects are mainly reflected in three aspects: First, the mastery of the concept of "closed figures". Before the transformation, most students relied on mechanical memorization of definitions. After the transformation, through the figure judgment interactive activity, most students can accurately distinguish closed and non-closed figures. Second, the continuity of classroom concentration. Before the transformation, there was an obvious attention interruption when switching from practical operation to theory. After the transformation, micro-videos and interactive quizzes were interspersed, the transition between each link was smooth, and students' concentration state remained consistent. Third, the immediacy of learning situation feedback. Before the transformation, teachers needed to correct exercises after class to understand the mastery of the whole class. After the transformation, with the help of free online answering tools, the correct rate distribution can be obtained in class, providing an immediate basis for subsequent teaching adjustments.

Quantitative observation data further confirmed this improvement: Before the transformation, the average effective attention span of students in the theoretical explanation stage was only 8 minutes, accounting for 32% of the total class time; after the transformation, this indicator increased to 15 minutes, accounting for 60% of the total class time. The correct rate of post-class closed figure concept tests also increased from 62% to 89%.

6.3.2. Optimization of Lesson Example 2 (Adapted to Urban Advanced Version Solution)

Combined with the design framework and evaluation optimization countermeasures, improve on the basis of the original advantages: Simplify basic operation steps to reduce the technical use difficulty of some students; Supplement process evaluation based on platform learning situation data to improve the diversified evaluation system. This optimization idea fits the hardware advantages of urban schools and further amplifies the integration effect of digital interaction and immersive learning. After optimization, students' inquiry processes have visual records, and teachers can conduct multi-dimensional evaluation combined with operation tracks and final correct rates, rather than judging based on a single exercise result. This improvement proves that the advanced version of interaction design combined with process evaluation strategies is not only feasible in smart campus scenarios but also can more comprehensively reflect students' learning quality.

6.4. Lesson Example Summary

The two lesson examples correspond to different school-running conditions in urban and rural areas respectively, and the transformation and optimization processes strictly follow the previous theoretical framework, design principles and optimization countermeasures. Practical effects show that the tiered and classified design idea of digital interactive tools can adapt to different urban and rural scenarios; The various optimization strategies proposed in this paper can effectively improve the problems of formalized classroom interaction, insufficient immersion experience and lagging learning situation feedback, and have universal practical reference value.

7. Conclusions and Prospects

On the basis of theoretical analysis, framework construction and case verification, this chapter systematically summarizes the core research conclusions of this study, objectively points out the limitations existing in the current research, and looks forward to the future development direction and optimization space of related research, so as to provide reference for subsequent in-depth exploration and practical promotion of digital interactive tools in primary school immersive classrooms.

7.1. Research Conclusions

First, the form and design method of digital interactive tools directly affect the effect of immersive learning for primary school students. Interactive activities that fit the cognitive characteristics of grades and subject characteristics can effectively extend students' attention spans, help students understand abstract knowledge, and promote the occurrence of deep learning.

Second, the common problems of current primary school digital classrooms are concentrated in: formalized interaction design with emphasis on form over content, unimplemented grade tiering, insufficient teacher interaction design ability, significant urban-rural resource and hardware gaps, and lagging evaluation systems. These problems are interrelated and need to be solved systematically through a framework and tiered strategies.

Third, the tiered and classified interaction design framework built based on flow theory, constructivism, cognitive development theory and embodied cognition theory has clear logic and fits the actual situation of primary school teaching. The two sets of basic and advanced solutions formulated according to urban-rural differences can adapt to the school-running conditions of different schools.

Fourth, the transformation and optimization practices of typical urban and rural lesson examples prove that the six countermeasures proposed in this paper—concept updating, classroom design, teacher construction, resource integration, evaluation reform and long-term guarantee—have low implementation thresholds and strong adaptability, can effectively improve the application status of digital interactive tools, and have promotion value.

7.2. Research Limitations

This paper mainly conducts analysis based on existing literature, classroom observation and typical cases, and has not carried out large-scale empirical research and long-term controlled experiments; Research on personalized interaction design for students with different learning styles and academic levels, as well as detailed adaptation research for different subjects and lesson types, still needs to be deepened.

7.3. Research Prospects

In the future, the interaction design framework and optimization strategies of this paper can be implemented in more regions and more subject classrooms, continuously summarizing experience and improving the plan. Combined with emerging technologies such as AIGC and VR/AR, explore new interaction forms such as human-machine collaboration and virtual-real integration. Relying on multimodal learning analysis technology, explore personalized and precise interaction design paths. Continuously promote the co-construction and sharing of regional digital resources, empower immersive classrooms with digital interactive tools, and contribute to the balanced and high-quality development of educational digitalization in urban and rural primary schools.

Conflicts of Interest

The authors declare no conflicts of interest.

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