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Research on Interactive Design of Digital-Human Teachers in Smart Classroom Contexts

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Abstract: Digital-human teachers offer new ways to strengthen interaction in smart classrooms, yet current designs are often scripted, one-way, and weakly grounded in pedagogy. This study integrates constructivist theory, social presence theory, and Long's (1996) Interaction Hypothesis to derive actionable principles and a design framework for high-quality interaction. Four principles are specified: learner agency and constructive engagement, social presence enhancement, meaningful interaction through negotiation and feedback, and contextual adaptability to classroom constraints. Based on these principles, a three-dimension framework is proposed, comprising knowledge-construction interaction (inquiry questioning, scaffolding, misconception diagnosis, collaborative facilitation), affective resonance interaction (personalized motivation and multimodal socio-emotional cues), and contextual adaptability interaction (phase-, subject-, and school-stage adaptation). The framework translates theory into operational elements that guide how digital-human teachers elicit, guide, respond, and reflect across instructional phases, aiming to improve engagement, reduce interactional distance, and support deeper learning in technology-mediated classrooms.

1. Introduction

Against the backdrop of the ongoing digital transformation of education, the deep integration of new-generation information technologies with teaching and learning has accelerated the shift from conventional classrooms toward smart classrooms, which are increasingly regarded as a pivotal arena for reconstructing the instructional ecosystem[5]. Distinguished by personalization, interactivity, and intelligence, smart classrooms move beyond the traditional one-way paradigm of teacher-dominated instruction and passive student reception, and instead promote deeper learning that is co-constructed through sustained teacher–student collaboration [12,14]. In this policy and practice context, improving the quality of classroom interaction has become a central objective for smart classroom development.

Within this trajectory, digital-human technologies have emerged as a promising technological vehicle for addressing a persistent challenge in smart classrooms. Enabled by anthropomorphic appearance, multimodal interaction, and contextualized expression [1,4], they help alleviate the lack of social presence that often occurs when interaction is mediated by digital systems. By providing

richer social cues through speech, facial expression, gesture, and situational responses, digital humans have the potential to strengthen interpersonal perception, increase engagement, and optimize the interactive experience of teaching and learning [1]. Accordingly, they offer new possibilities and technical support for innovating interaction patterns and for extending the pedagogical affordances of smart classrooms.

Nevertheless, the application of digital humans in education remains at an early stage of technological adaptation and scenario exploration [1,4]. Current practices are still largely confined to surface-level and often one-directional knowledge delivery, and they have not sufficiently engaged with the core logic of classroom interaction as a process of meaning-making, negotiation, and shared construction. More importantly, existing interactive designs for digital-human teachers frequently lack guidance from a systematic theoretical framework, resulting in interaction behaviors that are often formalized, homogeneous, and fragmented. Such interaction designs may function as demonstrations of technological capability, yet they tend to fall short in aligning with teachers' and students' deeper needs related to knowledge construction, emotional resonance, and cognitive engagement. This misalignment constrains the realization of the core value of digital technologies in empowering classroom interaction, and it limits the pedagogical effectiveness of digital-human teachers in authentic instructional contexts.

From a theoretical perspective, three lines of theory provide particularly relevant explanatory and design foundations. Constructivist theory emphasizes the pivotal role of interaction and social participation in learners' active knowledge construction, highlighting the importance of context, collaboration, scaffolding, and learner agency [9,13]. Social presence theory explains how media convey social cues that shape interpersonal perception, relational closeness, and the feeling of "being with others," thereby influencing motivation, engagement, and communication quality in mediated environments [8,10]. Interaction Hypothesis further highlights the driving role of meaningful interaction in language acquisition and the internalization of knowledge, especially through interactional processes such as negotiation of meaning, feedback, and modification [3,7]. Together, these theories address complementary dimensions of classroom interaction—cognitive construction, socio-emotional connection, and interaction-driven learning mechanisms—and thus constitute a robust theoretical foundation for the interactive design of digital-human teachers.

However, existing research has not yet achieved an organic integration of these three theoretical perspectives, nor has it formed a systematic and context-sensitive interactive design solution tailored to smart classroom ecosystems. In particular, there remains a gap in translating theory into operational design principles, specifying how digital-human teachers should enact interaction strategies across instructional phases (e.g., elicitation, guidance, feedback, and reflection), and clarifying how design elements (e.g., multimodal cues, dialogue moves, scaffolding patterns) can be aligned with the situated needs of teachers and learners. As a result, the field still lacks a coherent framework that is both theoretically grounded and practically adaptable to real classroom constraints and affordances.

In response to this theoretical and practical gap, the present study systematically explores pathways for the interactive design of digital-human teachers in smart classrooms, grounded in constructivist theory [13], social presence theory [10], and Interaction Hypothesis [7]. This inquiry not only addresses the dual deficiencies of insufficient theoretical integration and limited actionable design solutions in current research, but also aims to provide usable guidance for enhancing teacher–student interaction quality and improving instructional effectiveness in smart classrooms. Situated within the teaching ecosystem of smart classrooms and centered on the core needs of teachers and students, this study focuses on the key logic, principle system, and implementation essentials of digital-human teacher interaction design, with the goal of developing an interactive design framework that is both theoretically sound and contextually applicable, thereby offering

theoretical references and a practical paradigm for innovating and optimizing interaction models in smart classroom settings.

RQ1: From an integrative perspective combining constructivist theory, social presence theory, and the Interaction Hypothesis, what core theoretical principles and practical guidelines should guide the interactive design of digital-human teachers in smart classrooms?

RQ2: How can an interactive design framework for digital-human teachers be constructed to align with the smart classroom teaching ecosystem and the deeper needs of teachers and students? What are its key interaction dimensions, content elements, and design focal points?

2. Literature Review

Interaction has been widely recognized as a central issue in the digital transformation of education, and smart classroom interaction has accordingly become a major research focus. Existing studies generally converge on the view that smart classroom interaction is distinguished by technology-enabled personalization, immediacy, and collaboration, which differentiates it from the predominantly unidirectional interaction patterns typical of traditional classrooms [15]. Within this line of inquiry, scholars have proposed and examined a range of interaction models, including data-driven precision interaction informed by learning analytics, as well as multimodal and collaborative interaction supported by intelligent platforms and classroom response systems. Empirical evidence has largely confirmed the positive role of educational technologies in improving interaction quality and stimulating students' active engagement [11].

Despite these advances, limitations remain prominent. Much of the literature has prioritized the deployment, usability, and adaptation of technological tools, while offering comparatively less attention to the theoretical grounding and mechanism-based logic of interaction design. In particular, in-depth investigation of interaction involving anthropomorphic technological agents—such as digital humans—remains underdeveloped. As a result, existing interaction designs may improve operational efficiency or participation rates, yet they often struggle to address teachers' and students' needs for deeper forms of interaction related to meaning-making, emotional connection, and cognitive engagement in smart classroom settings.

Research on the educational application of digital-human technologies is still emerging, but it has already demonstrated considerable potential [1]. Current studies have primarily focused on functional positioning and scenario exploration, conceptualizing digital humans as tools for knowledge delivery, facilitators of personalized learning, or designers of immersive instructional contexts. A number of works also explore surface-level design elements—for example, visual appearance, voice and expression design, and scripted dialogue optimization—and suggest that anthropomorphic representations may enhance learners' interest, attention, and willingness to participate [6]. However, the existing literature still tends to remain at the level of describing application phenomena or reporting short-term effects, rather than systematically analyzing the interaction mechanisms and design rationales that explain *why* and *under what conditions* digital-human interaction supports learning. Moreover, findings regarding the relationship between digital-human interaction and learning outcomes are not yet consistent, and theory-driven, operational design solutions for digital-human teachers remain scarce. This gap indicates that the field has not yet moved from "technology demonstration" to "interaction design grounded in pedagogy."

In this regard, constructivist theory, social presence theory, and Interaction Hypothesis provide well-established theoretical resources for understanding and designing instructional interaction. From a constructivist perspective, interaction is a key pathway through which learners actively construct knowledge; thus, interaction design should emphasize learner agency, scaffolding, and contextualized participation, often operationalized through inquiry-oriented tasks and collaborative

learning activities [2]. Social presence theory, widely applied in online and technology-mediated learning, posits that a medium's capacity to convey social cues influences interpersonal perception, participation, and learning experience; enhancing social presence is therefore crucial for improving interaction quality in mediated environments [10]. Long's Interaction Hypothesis [7], particularly influential in language education, highlights that meaningful interaction—through negotiation of meaning, feedback, and modification—facilitates comprehension and the internalization of knowledge, offering an outcome-oriented rationale for designing effective interaction.

Although these three theories have been broadly used in instructional interaction research, existing studies have not yet achieved organic integration among them. A substantial body of work relies on a single theoretical lens—for example, optimizing online course interfaces primarily through social presence theory, or designing language-learning tasks mainly through the Interaction Hypothesis—without developing an interaction design framework supported by multi-theory synergy. The literature lacks systematic argumentation regarding the theoretical suitability of these perspectives for digital-human–mediated classroom interaction, and there is no widely accepted interaction design framework derived from such theoretical integration. This unresolved gap aligns with the practical challenges identified in the Introduction and provides a clear entry point for the present study: to construct an interactive design framework for digital-human teachers in smart classrooms through an integrative theoretical perspective, thereby addressing the limitations of existing research and advancing both conceptual understanding and design practice.

3. Research Design

The core objective of this study is to from an integrative perspective combining constructivist theory, social presence theory, and the Interaction Hypothesis [7], distill the core principles for the interactive design of digital-human teachers and construct an interaction design framework adaptable to smart classroom contexts, thereby addressing the two central research questions. The study follows a logic of "theoretical deconstruction → dimensional integration → framework construction → logical validation." The research proceeds in four steps. First, theoretical deconstruction and element extraction: the study reviews key literature on the three theories and extracts core elements directly related to instructional interaction. Second, theoretical integration and principle refinement: it analyzes the complementary relationships among the theories and, in conjunction with application contexts, refines core interaction design principles to address RQ1. Third, framework construction: guided by these core principles and informed by typical interaction scenarios in smart classrooms, the study specifies the framework's key dimensions, content elements, and design focal points to address RQ2. Fourth, framework validation and optimization: the framework is examined and revised in terms of theoretical coherence and contextual adaptability, leading to the finalized framework.

4. Deriving the Core Principles for the Interactive Design of Digital-Human Teachers

Building on an integrative logic that combines constructivist theory, social presence theory, and Long's [7] Interaction Hypothesis, and taking into account both the instructional ecosystem of smart classrooms and teachers' and students' expectations for deep, high-quality interaction, this study derives four core principles for the interactive design of digital-human teachers through theoretical deduction and contextual fit analysis. In this study, "contextual fit" refers to aligning theoretical constructs with the practical realities of smart classrooms—such as technology-mediated communication, time constraints within instructional phases, heterogeneous learner profiles, and the need for interaction that is both pedagogically meaningful and operationally feasible.

These four principles are formulated to be conceptually distinguishable yet functionally

interdependent. Specifically, the *Learner Agency and Constructive Engagement Principle* clarifies the cognitive and epistemic orientation of interaction (i.e., interaction as active knowledge construction rather than passive reception); the *Social Presence Enhancement Principle* addresses the socio-emotional conditions that sustain willingness to participate and reduce interactional distance; the *Meaningful Interaction Principle* specifies the mechanism through which interaction supports comprehension and internalization (e.g., negotiation, feedback, and adaptive adjustment); and the *Contextual Adaptability Principle* ensures that the above principles can be translated into design choices that are scalable across subjects, phases, and learner characteristics. Together, these principles jointly support both the theoretical soundness (clear grounding in established learning and communication theories) and the practical applicability (actionable guidance for real classroom implementation) of digital-human teacher interaction design. The details of each principle—including its core objective and corresponding design guidelines—are summarized in table 1.

Table 1. Core Principles and Design Guidelines for Digital-Human Teacher Interaction

Core Principle	Core Objective	Condensed Design Guidelines
Learner Agency and Constructive Engagement	To activate learners' interactive agency and support active knowledge construction	(1) Use inquiry-based scenarios and open-ended prompts to trigger cognitive conflict; (2) offer interaction choices (e.g., support depth, exploration paths); (3) prioritize scaffolded feedback over direct answers to foster independent thinking.
Social Presence Enhancement	To enhance learners' sense of social presence and reduce affective barriers	(1) Employ appropriate visual cues (e.g., facial expressions, gestures); (2) use natural, personalized language; (3) adapt tone and prosody dynamically to learners' emotional states.
Meaningful Interaction	To ensure interaction quality and avoid superficial or ritualized exchanges	(1) Focus interaction on key concepts, difficulties, and common errors; (2) align interaction difficulty with prior knowledge; (3) implement negotiation-based adjustments (e.g., examples, analogies, stepwise explanation).
Contextual Adaptability	To accommodate diverse instructional contexts and learner needs	(1) Differentiate interaction across instructional phases; (2) adapt to disciplinary characteristics; (3) align with learners' cognitive stages; (4) streamline interaction design to fit typical technology-use practices.

5. Constructing an Interactive Design Framework for Digital-Human Teachers

Building on the four core principles derived above and in consideration of the smart classroom instructional ecosystem and teachers' and students' needs for deep interaction, this study constructs a "three-dimension–multi-element" interactive design framework for digital-human teachers. The framework takes knowledge-construction interaction, affective resonance interaction, and contextual adaptability interaction as its core dimensions. For each dimension, it specifies concrete content elements and design focal points, forming a complete design logic of "principle-led → dimension-supported → element-implemented," ensuring both theoretical soundness and practical guidance.

Drawing on the integrative logic of the three theories and the key interaction needs of smart classrooms, this study defines the framework in terms of three core dimensions: (1) the knowledge-construction interaction dimension, guided by the Learner Agency and Constructive Engagement Principle and the Meaningful Interaction Principle, focusing on students' needs for active knowledge construction and serving as the primary value carrier of digital-human teacher interaction; (2) the affective resonance interaction dimension, guided by the Social Presence Enhancement Principle, focusing on building a sense of interpersonal "being there" in teacher–

student interaction and functioning as critical support for improving interaction quality and student engagement; and (3) the contextual adaptability interaction dimension, guided by the Contextual Adaptability Principle, focusing on alignment with different instructional scenarios and differentiated needs, and providing an essential foundation for practical feasibility. These three dimensions are interrelated and work synergistically, together constituting a comprehensive interactive design system for digital-human teachers.

To clearly present how the framework can be operationalized, this study further elaborates the content elements and design focal points of the three core dimensions, as shown in Table 2.

Table 2. Core Dimensions, Content Elements, and Design Focal Points

Dimension & Content Element	Design Focal Points
A. Knowledge-Construction Interaction	
A1. Inquiry-based questioning	(1) Scaffold questions from basic understanding to higher-order reasoning around key concepts; (2) support student-initiated inquiry through a question–scaffold–feedback cycle.
A2. Knowledge organization & Q&A	(1) Address misconceptions and concept links using chunking, examples, and analogies; (2) adapt interaction difficulty based on logged learning progress.
A3. Collaborative learning	(1) Design group tasks with clear roles and goals under digital-human facilitation; (2) scaffold negotiation, problem-solving, and peer feedback.
B. Affective Resonance Interaction	
B1. Personalized motivation	(1) Provide differentiated encouragement based on learner performance and effort; (2) tailor motivational style to individual learner characteristics.
B2. Anthropomorphic affective expression	(1) Align facial expressions, gestures, and tone with instructional context; (2) respond adaptively to affective cues in learner language.
B3. Learning atmosphere cultivation	(1) Use light warm-up and interactive prompts to encourage participation; (2) sustain a positive learning climate through guided sharing and peer interaction.
C. Contextual Adaptability Interaction	
C1. Instructional phase adaptation	(1) Adjust interaction strategies across pre-, in-, and post-class phases; (2) provide phase-appropriate scaffolding and feedback.
C2. Subject-type adaptation	(1) Emphasize experiential interpretation in humanities and reasoning scaffolds in STEM; (2) highlight cross-domain connections in interdisciplinary contexts.
C3. School-stage cognitive adaptation	(1) Use concrete and playful interaction for primary levels; (2) support abstract reasoning and personalized deep learning at higher levels.

6. Conclusions

Grounded in the instructional needs of teachers and students in smart classrooms, this study adopts an integrative perspective combining constructivist theory, social presence theory, and the Interaction Hypothesis to examine the interactive design of digital-human teachers. Through theoretical analysis and deductive reasoning, it distills core design principles and proposes a corresponding framework to address the research questions.

First, the study identifies four interrelated principles—learner agency and constructive engagement, social presence enhancement, meaningful interaction, and contextual adaptability—which jointly define the essential interactional qualities of digital-human teachers and provide a theoretically grounded response to the first research question.

Second, guided by these principles, a three-dimension, multi-element design framework is

proposed, encompassing knowledge-construction interaction, affective resonance interaction, and contextual adaptability interaction. The framework further clarifies an operational process of needs sensing, dimension matching, and dynamic adjustment, translating abstract principles into actionable design guidance and addressing the second research question.

The study contributes theoretically by integrating interactionist, constructivist, and affective perspectives into a coherent design-oriented account of digital-human teaching, and practically by offering conceptual guidance for improving interaction quality and instructional effectiveness in smart classrooms. At the same time, limitations remain, including the lack of empirical validation and limited consideration of differentiated instructional contexts. Future research may empirically test and refine the framework, incorporate emerging educational technologies to enhance adaptive interaction, and further explore its applicability across diverse instructional scenarios.

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