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From philosophical immersion to digital reality: A unified theoretical framework for understanding and classifying immersive technologies in education

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ABSTRACT

The rapid evolution of immersive technologies has created a fragmented landscape of definitions and frameworks that fail to connect philosophical foundations with practical educational implementations. This paper addresses this gap through a theoretical analysis proposing the Philosophical-Technical Immersion Framework (PTIF), which bridges pre-digital concepts of immersion with modern VR, AR, MR, and XR technologies. Through systematic philosophical inquiry and historical analysis, we develop a three-dimensional classification space integrating perceptual, cognitive, and embodied immersion. Our theoretical analysis synthesizes insights from phenomenology, cognitive science, learning theory, and human–computer interaction, grounded in extensive literature review of 127 empirical studies (2018–2024). Comparative analysis with eight established frameworks demonstrates PTIF's superior theoretical coherence and coverage. The framework maps philosophical concepts to technical parameters, providing theoretical guidance for educational technology design. Our analysis reveals that successful educational immersive experiences require dimensional balance aligned with learning objectives rather than technical maximization. PTIF offers researchers and educators a theoretical tool for understanding and designing immersive learning experiences that align with fundamental principles of human cognition and perception, addressing a critical need for theoretically-grounded frameworks in educational technology.

1. Introduction

The concept of immersion has captivated human imagination long before the advent of digital technologies. From the painted caves of Lascaux to the panoramic paintings of the 19th century, humanity has consistently sought to create experiences that transport individuals beyond their immediate physical reality (Cole, 2025; Lescop, 2017). Today, this ancient pursuit has evolved into a sophisticated technological ecosystem encompassing Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and the emerging paradigm of Extended Reality (XR) (Burke et al., 2025; Rauschnabel et al., 2022). In educational contexts, these technologies promise to revolutionize learning by creating unprecedented opportunities for experiential, embodied, and situated knowledge construction (Kuhail et al., 2025; Tene et al., 2024b). However, despite tremendous technological progress, numerous scholars have identified a significant gap between philosophical foundations and technical implementations in educational immersive technology research. Agrawal et al. (2019) note that engineering developments often proceed without deep consideration of phenomenological principles, while Nilsson et al. (2016) observe that theoretical discussions frequently lack grounding in practical implementation realities. This disconnect manifests in inconsistent terminology, fragmented frameworks, and educational implementations that prioritize technological novelty over pedagogically-grounded design (Kuhail et al., 2022; Mohsen & Alangari, 2024). While individual studies have made progress in specific domains, the field lacks a unified framework that systematically connects philosophical understanding of immersion with technical considerations for educational design.

The current landscape of immersive technology research in education reveals troubling fragmentation. While engineers develop increasingly sophisticated hardware and software solutions for classroom

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use, they often do so without deep consideration of the phenomenological and cognitive principles that underlie human learning through immersive experiences (Agrawal et al., 2019; Nilsson et al., 2016). Conversely, theoretical discussions of immersion in educational philosophy, learning sciences, and media studies frequently lack grounding in the practical realities of technological implementation in educational settings (Mystakidis & Lympouridis, 2023; Poupard et al., 2025). This divide has resulted in a proliferation of incompatible frameworks, inconsistent terminologies, and missed opportunities for creating truly transformative learning experiences.

Recent systematic reviews have identified significant gaps in our understanding of immersive technologies for education. Mohsen and Alangari (2024) analyzed two decades of immersive technology research in education and found that while the field has grown exponentially, it lacks unified theoretical foundations that connect diverse educational applications. The study revealed that educational implementations often prioritize technological novelty over pedagogical effectiveness, resulting in limited learning outcomes despite significant investment. Similarly, Kuhail et al. (2022) highlighted that despite widespread adoption in educational contexts, immersive technologies suffer from inconsistent definitions and evaluation criteria, making it difficult to assess their true impact on learning. These challenges are compounded by what Rauschnabel et al. (2022) describe as conceptual confusion in even basic terminology, with terms like XR being used inconsistently across academic and industry contexts, further complicating educational research and practice.

Recent evidence from 2024–2025 further emphasizes the need for a unified framework (Semerikov et al., 2023, 2024b). Tene et al. (2024b) found that AR was the most studied technology in STEM education (followed by VR), with most studies reporting positive effects on student engagement and performance. Their systematic review of 143 articles revealed that 36.4% of studies reported increased engagement, while 63.6% focusing on practical skills noted performance improvements. Similarly, Park et al. (2024) conducted a meta-analysis showing that immersive technology-based education for nursing students significantly improved theoretical knowledge ($SMD = 0.31$) and self-efficacy ($SMD = 0.51$), demonstrating the potential when properly implemented.

To address these challenges, this paper proposes the Philosophical-Technical Immersion Framework (PTIF), a unified theoretical model comprising three interconnected elements. First, PTIF is built upon five foundational principles derived from philosophical inquiry and learning sciences: (1) multidimensional experience, recognizing that immersion emerges from the interaction of perceptual, cognitive, and emotional dimensions; (2) user experience primacy, prioritizing learning outcomes over technological capability; (3) contextual embeddedness, acknowledging that immersive experiences are shaped by educational contexts; (4) temporal dynamics, understanding immersion as a dynamic process that unfolds over time; and (5) social learning integration, recognizing that educational immersion frequently involves collaborative and social knowledge construction. Second, the framework establishes a three-dimensional classification space consisting of perceptual immersion (sensory engagement with educational content), cognitive immersion (mental absorption and knowledge construction), and embodied immersion (physical agency and action-based learning). Third, PTIF provides systematic mapping between abstract philosophical concepts and concrete technical design parameters, enabling theoretically-grounded understanding of immersive educational technologies. Together, these components offer a comprehensive lens for analyzing, comparing, and understanding the effectiveness of immersive learning experiences.

The philosophical roots of immersion in education extend far beyond simple technological determinism. As documented in historical analyses (Adams, 2004; McLellan, 2004), the concept of immersive learning emerged from artistic and theatrical traditions that understood it as a complex interplay between sensory stimulation, cognitive engagement, and emotional involvement in the learning process. The Renaissance artist Leon Battista Alberti's pioneering work on perspective in 1462 represented an early attempt to create immersive visual experiences through mathematical precision, principles that continue to inform modern educational VR design (Rosenblum & Cross, 1997). This was followed by the panoramic paintings of Robert Barker in the late 18th century, which created 360-degree visual environments that prefigured modern VR experiences used in history and cultural education (VRrOOm, 2016). These historical precedents reveal that immersion has always been understood as more than mere technical achievement; it represents a fundamental mode of human experience that bridges the physical and the imagined, the known and the unknown.

Educational theorists have long recognized the power of immersive experiences for learning. John Dewey's emphasis on experiential learning, Jean Piaget's theories of cognitive development through interaction with the environment, and Lev Vygotsky's concepts of social constructivism all point to the importance of immersive, embodied experiences in knowledge construction (Bizami et al., 2023; Mystakidis & Lympouridis, 2023). The evolution from these pre-digital forms of educational immersion to contemporary XR technologies has been marked by both continuity and disruption. While modern head-mounted displays and spatial computing systems offer unprecedented technical capabilities for creating educational experiences, they often struggle to achieve the depth of engagement found in traditional immersive pedagogies (Dengel et al., 2024). This paradox suggests that technological sophistication alone cannot guarantee meaningful learning experiences. Instead, successful educational immersive technologies must align with deeper principles of human perception, cognition, and learning processes. Fig. 1 illustrates this evolutionary trajectory, highlighting how philosophical and pedagogical concepts have persistently influenced technological development in education across centuries. As shown in the figure, the ascending conceptual development layers demonstrate how each technological era builds upon its predecessors rather than replacing them: the philosophical insights about perspective, embodiment, and narrative engagement established in the pre-digital era continue to inform the design principles of modern XR systems, creating a cumulative knowledge base for immersive educational technology.

This paper addresses these challenges by proposing a unified theoretical framework that bridges philosophical understanding with technical implementation specifically for educational contexts. The PTIF synthesizes insights from phenomenology, cognitive science, learning theory, and human–computer interaction to provide a model for understanding immersive educational experiences. Unlike existing frameworks that focus primarily on either theoretical concepts or technical specifications, PTIF integrates both dimensions within a coherent theoretical structure that facilitates conceptual understanding and classification in educational settings while maintaining rigorous grounding in learning sciences.

Our contribution extends beyond mere taxonomy. By mapping philosophical concepts such as presence, embodiment, and narrative engagement to specific technical parameters, PTIF provides theoretical guidance for understanding how immersive technologies can support educational objectives. The framework reveals how fundamental aspects of human learning manifest in technological implementations and identifies critical factors that influence the educational effectiveness of immersive systems. Through systematic comparative analysis with existing frameworks, we demonstrate that PTIF offers superior theoretical coherence and explanatory power while maintaining relevance across diverse educational domains including STEM education, language learning, vocational training, and special education. Fig. 2 provides a visual summary of the framework's theoretical structure and relationships.

The significance of this work extends to multiple stakeholders in the educational technology ecosystem. For researchers, PTIF provides a theoretical foundation for investigating how immersive technologies

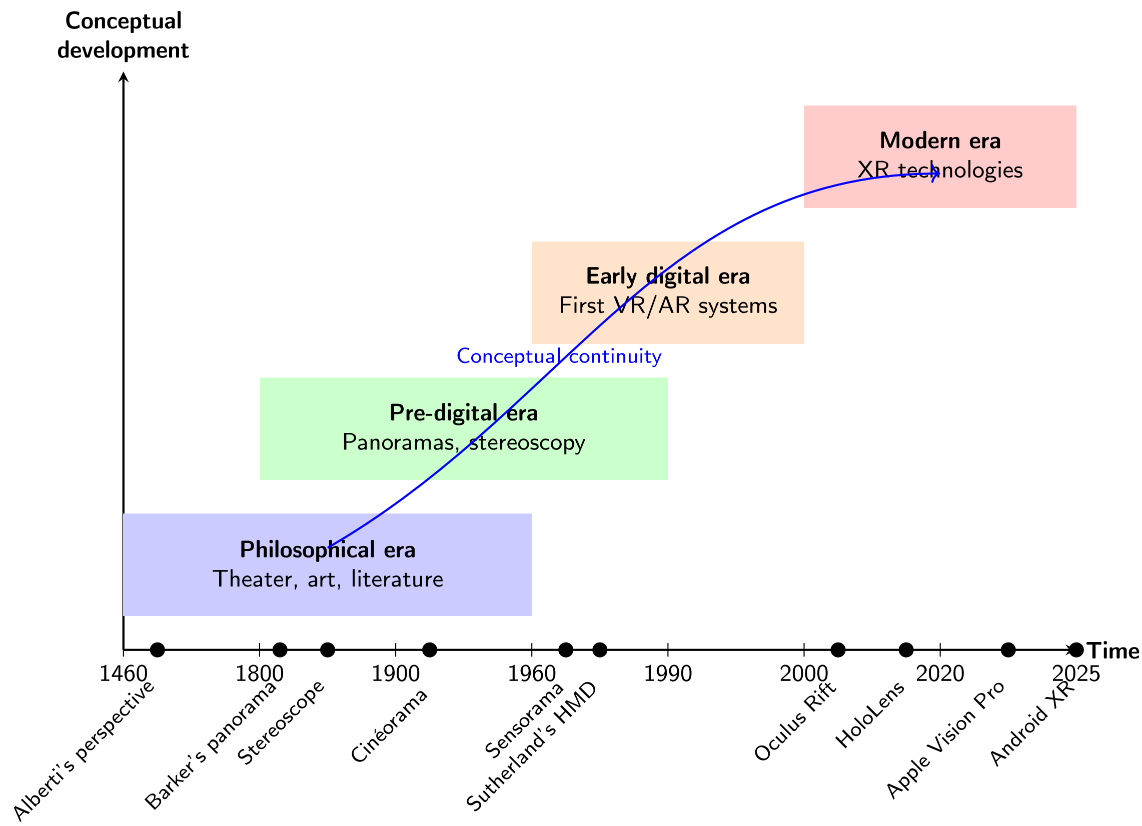

Fig. 1. Evolution of immersive technologies from philosophical concepts to modern XR systems. The Y-axis represents conceptual development layers, showing how each era builds upon previous foundations. The blue arrow illustrates conceptual continuity: fundamental principles established in the philosophical era (e.g., perspective, embodiment, narrative engagement) persist and inform each subsequent technological paradigm. The ascending trajectory reflects cumulative knowledge integration rather than replacement, as modern XR technologies incorporate insights from all preceding eras while adding new capabilities.

support different types of learning. For educators, it offers conceptual guidelines for understanding and evaluating immersive technologies that align with pedagogical goals. For developers, it presents design principles grounded in both learning theory and user experience research. By bridging the gap between philosophical understanding and technical implementation, PTIF contributes to the theoretical maturation of immersive educational technology as a field capable of advancing our understanding of technology-mediated learning.

This paper pursues three primary research objectives. First, we develop the PTIF through systematic philosophical inquiry and synthesis of empirical literature from multiple disciplines. Second, we conduct comparative analysis of PTIF against eight established frameworks to evaluate its theoretical coherence, explanatory power, and coverage of immersive educational phenomena. Third, we demonstrate PTIF's applicability through theoretical analysis of documented educational implementations, showing how the framework's dimensional structure can explain patterns of effectiveness and failure in immersive learning technologies. Through these objectives, we aim to provide researchers and practitioners with a theoretical tool for understanding and advancing immersive education. Fig. 3 presents our research design, illustrating the systematic five-phase approach employed in developing and validating PTIF.

2. Literature review

2.1. Philosophical foundations of immersion in learning

The philosophical investigation of immersion in educational contexts predates digital technology by centuries, rooted in fundamental questions about the nature of experience, reality, and knowledge acquisition. This rich intellectual tradition provides essential insights for understanding contemporary immersive educational technologies, yet remains underutilized in technical discussions of educational XR systems.

The phenomenological tradition, particularly the work of Merleau-Ponty on embodied perception, offers crucial insights into the nature of immersive learning experiences. Merleau-Ponty's concept of the body-subject challenges the Cartesian separation of mind and body, proposing instead that learning through perception is fundamentally embodied and that our sense of being-in-the-world emerges from the dynamic interplay between bodily sensation and cognitive interpretation (Biocca & Levy, 1995; Nilsson et al., 2016). This perspective has profound implications for educational immersive technology design, suggesting that effective immersive learning requires more than visual fidelity; it demands consideration of the full spectrum of embodied experience including proprioception, kinesthesia, and multimodal sensory integration in the learning process (Agrawal et al., 2019).

Building on phenomenological foundations, Bizami et al. (2023) identify constructivism and experiential learning as key theoretical frameworks in immersive education. These frameworks emphasize that immersive learning is not a passive state but an active process of meaning-making through interaction with educational content. The constructivist view aligns with historical concepts of immersion in educational theater and interactive museum exhibits, where learner participation and imaginative engagement were recognized as essential components of the educational experience (Mystakidis & Lympouridis, 2023). This understanding challenges purely technological approaches to educational immersion that focus exclusively on sensory

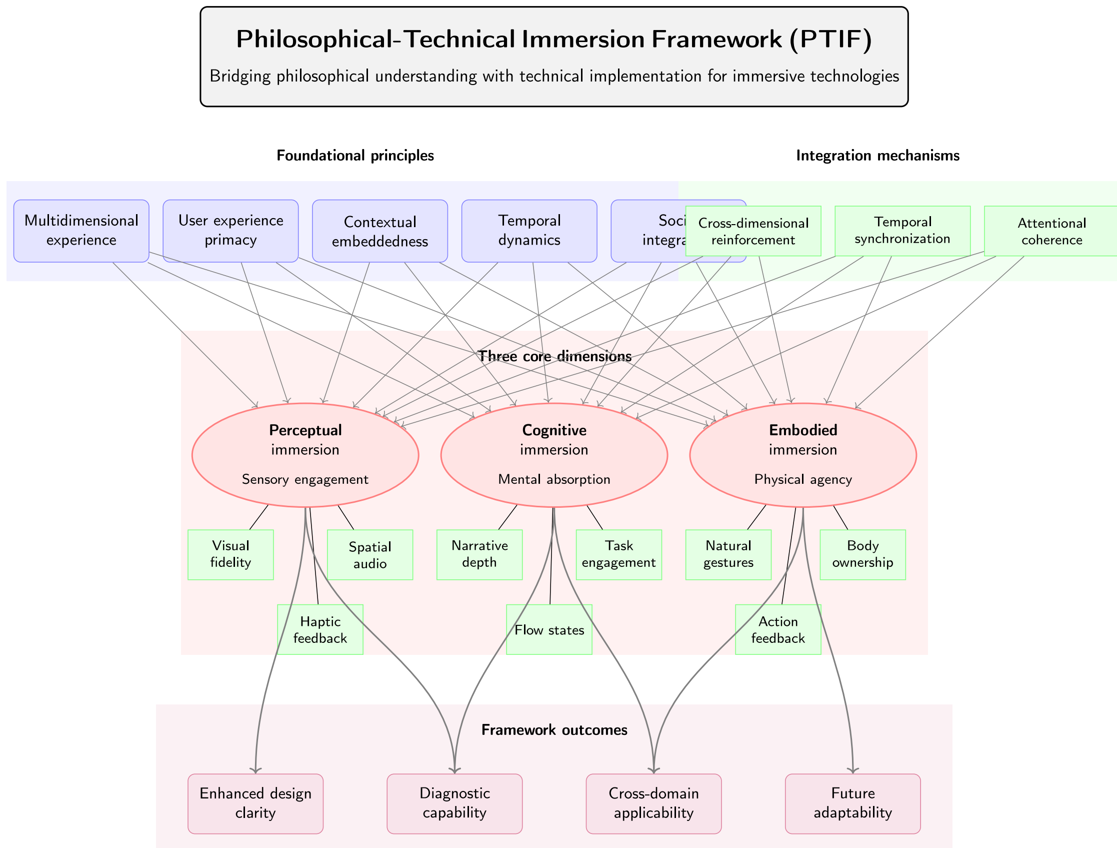

Fig. 2. Overview of the Philosophical-Technical Immersion Framework (PTIF) showing the relationships between foundational principles, core dimensions, integration mechanisms, and theoretical outcomes. The framework provides a unified approach to understanding and classifying immersive technologies across diverse applications.

fidelity while neglecting the active role of the learner in constructing knowledge through immersive experiences.

Educational psychology provides additional theoretical grounding for understanding immersive learning. The concept of flow, developed by Csikszentmihalyi, describes optimal learning states characterized by complete absorption in educational tasks (Lee et al., 2013). This psychological state shares fundamental characteristics with technological immersion, suggesting that effective educational XR must support not just perceptual presence but also cognitive and emotional engagement with learning material. Research on cognitive load theory by Sweller et al. (2011) further informs our understanding of how immersive environments can either facilitate or hinder learning depending on their design and implementation. Recent findings by Poupard et al. (2025) confirm that cognitive load and curiosity state are critical factors affecting learning performance in immersive environments.

The concept of presence, central to contemporary VR research in education, has deep philosophical roots that extend beyond its technical definitions. Slater (2003) distinguishes between place illusion (the sense of being in a virtual educational space) and plausibility illusion (the feeling that educational scenarios are really happening), but these technical concepts echo older philosophical discussions about the nature of reality and educational simulation. Ancient Greek concepts of mimesis in educational drama, medieval mystery plays as teaching tools, and Comenius's "Orbis Sensualium Pictus" all grappled with similar questions about the relationship between representation, reality, and learning (McLellan, 2004). Understanding these philosophical precedents helps contextualize current debates about the nature of virtual educational experiences and their relationship to authentic learning.

Narrative theories of immersion, developed primarily in literary studies but highly relevant to educational contexts, provide another crucial perspective often overlooked in technical discussions of educational XR. The concept of transportation, wherein learners become absorbed in an educational narrative world, shares fundamental characteristics with technological immersion in learning environments (Adams, 2004). This narrative dimension reveals that educational immersion involves not just sensory presence but also cognitive and emotional engagement with coherent educational content. The success of immersive educational experiences often depends less on technical sophistication than on the creation of compelling narratives that engage learners' imagination and emotion while conveying educational objectives.

2.2. Evolution of immersive technologies in education

Understanding the historical evolution of immersive educational technologies is essential for developing PTIF, as it reveals persistent patterns of how philosophical concepts of learning have been translated into technological implementations. This historical analysis informed our framework's foundational principles, particularly the recognition that successful immersive education has always required balance between perceptual engagement, cognitive scaffolding, and embodied interaction – the three dimensions that would become central to PTIF. By examining how different eras approached immersive learning, we can identify both enduring principles and evolving capabilities that shape contemporary educational XR design.

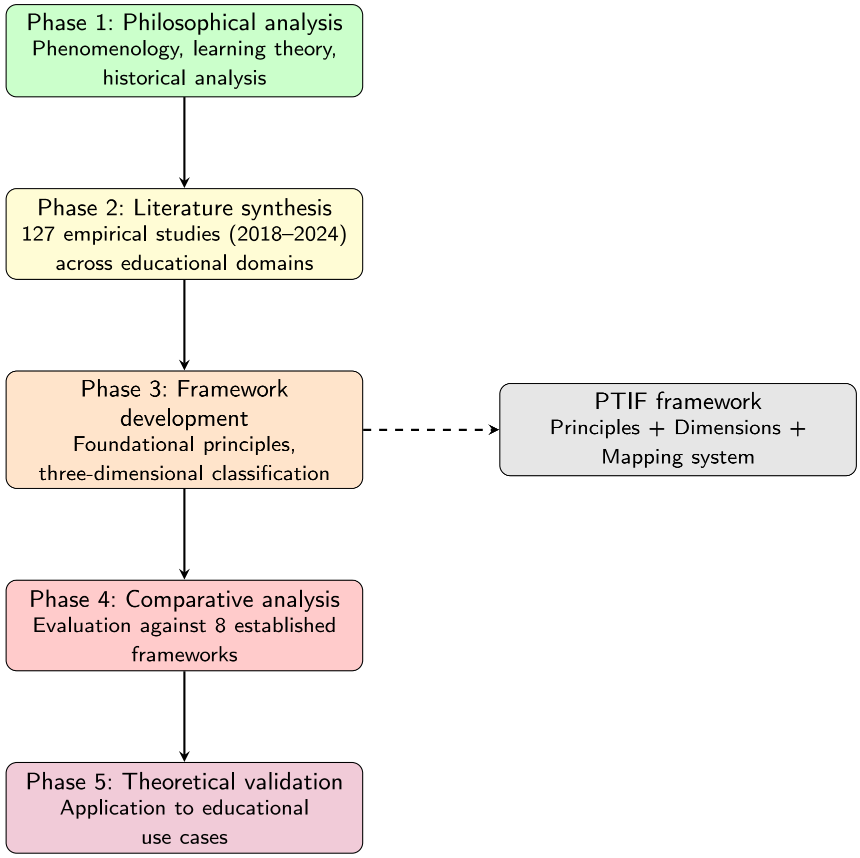

Fig. 3. Research design flowchart illustrating the five-phase methodology for developing and validating the Philosophical-Technical Immersion Framework.

The technological journey toward modern educational XR systems reveals a pattern of innovation driven by the persistent desire to enhance learning through immersive experiences. This evolution demonstrates how philosophical concepts of educational immersion have been repeatedly translated into technological form, with varying degrees of success in achieving pedagogical goals.

The pre-digital era of immersive educational technologies began with the magic lantern shows of the 17th century, which were widely used for educational purposes in schools and public lectures (Holloway, 1995). These devices projected images to create shared visual experiences that transported learners to distant places and times. The educational panorama movement of the 19th century further developed these concepts, with purpose-built circular buildings housing massive paintings used to teach geography, history, and current events (Lescop, 2017). The success of educational panoramas led to numerous variations, including moving panoramas that simulated journeys for geography education and the Mareorama, which created the sensation of ocean travel for maritime education (Mareorama, 1900; VRrOOm, 2016). From a PTIF perspective, these early technologies prioritized perceptual immersion through visual spectacle while maintaining moderate cognitive immersion through narrative accompaniment; however, embodied immersion remained minimal as learners were passive observers rather than active participants.

The stereoscope, invented in 1832 by Charles Wheatstone (Mayo, 1833, p. 288), introduced another crucial element of immersive educational technology: binocular depth perception. Educational institutions rapidly adopted stereoscopic photography, with companies like Underwood & Underwood producing extensive educational series covering subjects from anatomy to world geography. By 1900, stereoscopes were standard equipment in progressive schools, prefiguring modern educational applications of VR (Rosenblum & Cross, 1997). The Keystone View Company's "Visual Education" department developed structured curricula around stereographic content, demonstrating early understanding of how immersive visual experiences could enhance learning outcomes (Keystone View Company, 1922). In PTIF terms, the stereoscope enhanced perceptual immersion through depth perception while cognitive immersion was supported by structured educational content, though embodied immersion remained limited to simple device manipulation.

The emergence of flight simulators in the 1920s marked a crucial transition in immersive educational technology. Edwin Link's "Blue Box" flight trainer, developed in 1929, created a fully immersive educational environment that allowed pilots to learn through embodied practice without real-world risks (McLellan, 2004). This innovation established key principles that continue to guide educational XR development: the importance of safe failure, embodied learning through doing, and the value of repeatable practice in skill acquisition. The success of flight simulators in reducing training accidents by over 90% provided compelling evidence for the educational value of immersive technologies. The Link Trainer represents an early example of high embodied immersion in education, where physical manipulation of controls translated directly to skill development – a principle that PTIF identifies as crucial for procedural learning. This marked a fundamental shift from observation-based to action-based immersive education.

The transition to electronic and digital immersive educational technologies began with Morton Heilig's Sensorama in 1962 (Heilig, 1962; Syrovatskyi et al., 2018). Although not specifically designed for education, Sensorama's multisensory approach influenced educational technologists to consider how engaging multiple senses could enhance learning and retention (Noll, 1967, 1972). Educational applications quickly followed, with the University of Utah developing some of the first computer-generated educational simulations in the late 1960s (Sutherland, 1968). These early systems, though primitive by modern standards, established the potential for interactive,

Table 1
Historical immersive educational technologies analyzed through PTIF dimensions, showing the evolution of dimensional emphasis across eras. Ratings reflect operational criteria: Low (minimal engagement), Medium (moderate engagement), High (substantial engagement) for each dimension.

Era	Technology	P	C	E	Educational contribution
Pre-digital era (1600–1950)					
17th c.	Magic lantern	Med	Med	Low	Shared visual learning experiences
1788	Panorama	High	Med	Low	Environmental immersion for geography
1837	Stereoscope	Med	Med	Low	Depth perception for anatomy education
1900	Cinéorama	High	Low	Low	Motion simulation for experiential learning
1929	Link Trainer	Med	High	High	Embodied procedural skill development
Early digital era (1960–1990)					
1962	Sensorama	High	Med	Med	Multisensory integration principles
1968	Sutherland HMD	Med	Med	Med	Head-tracked perspective learning
1980s	Super Cockpit	High	High	High	Comprehensive skill training paradigm
Modern era (2010–present)					
2016	Consumer VR	High	Var	High	Accessible immersive education
2016	HoloLens	Med	High	Med	Contextual AR learning environments
2024	Vision Pro	High	High	High	Spatial computing for education

P = Perceptual, C = Cognitive, E = Embodied; Low/Med/High indicate relative dimensional emphasis.

computer-mediated immersive learning experiences. Heilig's multisensory approach anticipated PTIF's emphasis on perceptual integration, demonstrating that effective immersion requires coherent engagement of multiple sensory modalities rather than maximization of any single channel – a principle that remains central to contemporary educational XR design.

The emergence of computer-based educational VR in the 1970s and 1980s, pioneered by researchers like Thomas Furness at the U.S. Air Force's Armstrong Laboratory, marked a fundamental shift in immersive educational technology (Furness III, 1986). The "Super Cockpit" program demonstrated how virtual environments could accelerate complex skill acquisition, reducing training time by up to 50% compared to traditional methods. This shift from passive viewing to active participation in virtual educational environments represented a crucial evolution in the concept of immersive learning, aligning with constructivist theories of education that emphasize learning through doing. The Super Cockpit exemplified what PTIF characterizes as balanced dimensional design: high perceptual immersion through head-tracked displays, high cognitive immersion through complex decision-making scenarios, and high embodied immersion through physical control interfaces – demonstrating that optimal learning outcomes often require integration across all three dimensions.

The 1990s saw the first wave of VR entering mainstream education, with systems like VisionDome creating immersive learning environments for schools (Lantz et al., 1995). However, technical limitations, high costs, and lack of pedagogically-grounded content limited adoption (Dinh et al., 1999). The failure of this first wave of educational VR provides important lessons: technology alone cannot transform education without careful attention to pedagogical design, teacher training, and curriculum integration. This period also saw the emergence of desktop VR and early AR applications in education, which offered more practical alternatives for classroom use (Azuma et al., 2001). PTIF analysis of this era reveals a common failure pattern: overemphasis on perceptual immersion (visual novelty) without corresponding attention to cognitive immersion (pedagogical design) or embodied immersion (meaningful interaction), resulting in experiences that were technically impressive but educationally limited.

The contemporary era of educational XR, beginning around 2010, has been characterized by rapid technological advancement and increasing adoption. Arena et al. (2022) document how AR technology has evolved to provide educational applications ranging from anatomy visualization to historical reconstruction. The development of consumer VR headsets like Oculus Rift and HTC Vive made immersive technology accessible to educational institutions (Lowood, 2026). More recently, mixed reality devices like Microsoft HoloLens and Magic Leap have opened new possibilities for blending virtual content with physical educational spaces (Hönig et al., 2015). Contemporary systems increasingly demonstrate what PTIF identifies as dimensional flexibility – the ability to optimize different dimensions for different learning objectives. Modern VR excels at perceptual and embodied immersion for procedural training, while AR maintains connection to physical context, enabling high cognitive immersion for conceptual learning without sacrificing real-world grounding.

Table 1 summarizes this historical trajectory through the lens of PTIF's three dimensions, revealing how different eras prioritized different aspects of immersive learning and how these patterns inform contemporary educational XR design.

The dimensional ratings in Table 1 were assigned based on systematic evaluation against operational criteria derived from immersion research (Nilsson et al., 2016; Witmer & Singer, 1998). For *perceptual immersion*, we assessed sensory modality coverage, field of view, and depth cue provision: *Low* indicates single-modality, limited-view experiences (e.g., audio-only or small-format visuals); *Medium* reflects engagement of two or more sensory modalities with partial environmental coverage; *High* denotes comprehensive multisensory stimulation with wide field of view and stereoscopic depth cues. For *cognitive immersion*, following Lee et al. (2013) on absorption and flow states, we evaluated learner agency, interactive complexity, and instructional scaffolding: *Low* represents passive consumption with minimal learner control; *Medium* indicates moderate interactivity with structured guidance; *High* reflects active problem-solving, decision-making, and adaptive instructional support. For *embodied immersion*, based on embodied cognition frameworks (Biocca & Levy, 1995; Döllinger et al., 2021), we assessed physical interaction requirements and proprioceptive engagement: *Low* denotes stationary observation with no meaningful physical interaction; *Medium* involves limited movement, gesture, or manipulation; *High* requires substantial bodily engagement with haptic or proprioceptive feedback directly linked to learning outcomes. These operational definitions ensure consistent application across historical and contemporary technologies.

2.3. Contemporary frameworks and taxonomies

The proliferation of immersive technologies in education has spawned numerous attempts to create organizing frameworks and taxonomies. While these efforts have provided valuable insights, they often suffer from limited scope, focusing on either technical specifications or theoretical concepts without successfully integrating both dimensions in educationally meaningful ways.

Milgram and Kishino (1994) proposed the Reality-Virtuality Continuum, which remains one of the most influential frameworks in the

Table 2
Summary of existing frameworks for immersive educational technology, highlighting key features, theoretical foundations, and limitations addressed by PTIF.

Framework	Key concepts	Theoretical basis	Focus	Limitations
Reality-Virtuality Continuum (Milgram & Kishino, 1994)	Real-to-virtual spectrum; mixed reality	Technical specification	Technology classification	Unidimensional; ignores pedagogical factors
CAMIL model (Park et al., 2024)	Cognitive-affective processes; presence	Multimedia learning theory	Learning outcomes	Limited to VR; lacks embodiment focus
Immersive Learning Brain Mystakidis and Lympouridis (2023)	Absorption, immersion, presence levels	Experiential learning	Engagement levels	Lacks technical specificity
3iVClass (Parveau & Adda, 2018)	Immersion, interaction, information	User experience	Experience design	Limited learning theory integration
BehaveFIT (Suh & Prophet, 2018)	Psychological barriers; behavior change	Health behavior theory	Behavior modification	Not education-specific
SAMR model (Puentedura, 2006)	Substitution to redefinition hierarchy	Technology integration	Implementation level	Implies hierarchy; not immersion-specific
TPACK framework (Mishra & Koehler, 2006)	Technology-pedagogy-content knowledge	Teacher knowledge	Educator preparation	Generic; lacks XR specificity
Freina–Ott taxonomy (Freina & Ott, 2015)	VR types and educational applications	Descriptive classification	VR categorization	Excludes AR/MR; dated

field. This continuum positions technologies along a spectrum from completely real to completely virtual environments, with mixed reality occupying the space between. While elegant in its simplicity, the framework has been criticized for its unidimensional nature and inability to capture the complexity of modern immersive educational experiences. For instance, a sophisticated AR educational application and a simple smartphone AR app occupy similar positions on the continuum despite creating vastly different learning experiences. Skarbez et al. (2021) recently revisited this framework, arguing that the continuum is actually discontinuous and that perfect virtuality is theoretically impossible, while mixed reality encompasses a broader range of educational experiences than originally conceived.

The proliferation of educational frameworks for immersive learning reflects the growing importance of XR in pedagogical contexts. Mystakidis and Lympouridis (2023) propose the Immersive Learning Brain framework, which categorizes immersive educational experiences based on cognitive engagement levels and learning outcomes. This framework identifies three levels of immersive learning: absorption (passive consumption of content), immersion (active engagement with educational material), and presence (full embodiment within the learning environment). Similarly, Poupard et al. (2025) systematic review identifies cognitive load and curiosity as key factors in immersive learning effectiveness, proposing a framework that balances challenge with capability to maintain optimal learning states. These educational frameworks highlight the importance of considering not just technological capabilities but also cognitive and pedagogical principles in designing immersive learning experiences.

Recent research has also produced domain-specific frameworks for educational XR. Haoming and Wei (2024) developed a framework specifically for vocabulary learning in AR and VR environments, identifying key factors such as contextual relevance, multimodal reinforcement, and spaced repetition that determine learning effectiveness. Their framework demonstrates how general immersive technology principles must be adapted to specific educational objectives and content areas. Similarly, frameworks for STEM education emphasize spatial reasoning and hands-on manipulation, while those for social studies focus on historical empathy and cultural perspective-taking (Spitzer et al., 2022).

Behavioral frameworks represent another important category, focusing on how immersive technologies influence and modify learning behaviors. The Behavioral Framework for Immersive Technologies (BehaveFIT) maps psychological barriers to behavior change in educational contexts and identifies how immersive features can overcome these barriers (Suh & Prophet, 2018). For example, the framework shows how VR's ability to create safe failure environments can reduce anxiety barriers to learning complex procedures, while AR's contextual overlays can address cognitive barriers by providing just-in-time instructional support. This approach recognizes that educational immersion is not merely a perceptual phenomenon but can fundamentally alter patterns of learning behavior and motivation.

Technical taxonomies have emerged to address the need for systematic classification of educational XR technologies based on their capabilities and characteristics. Parveau and Adda (2018) propose the 3iVClass system, which classifies immersive educational experiences based on three dimensions: immersion (sensory engagement), interaction (user agency), and information (content delivery). This user-centered approach attempts to move beyond hardware specifications to focus on experiential qualities relevant to learning. However, like many technical taxonomies, it struggles to incorporate the philosophical and psychological dimensions that fundamentally shape educational experiences.

The CAMIL (Cognitive-Affective Model of Immersive Learning) framework represents a significant advance in connecting learning theory with immersive technology design. As analyzed by Park et al. (2024), CAMIL integrates theories of multimedia learning with presence research to predict learning outcomes in immersive environments. Their framework identifies specific affordances of immersive technologies (such as first-person perspective and environmental control) and maps these to cognitive and affective learning processes. This approach represents progress toward frameworks that can guide both design and evaluation of educational XR experiences.

Table 2 summarizes the key features of existing frameworks discussed in this section, highlighting their theoretical foundations, primary focus areas, and limitations that PTIF aims to address.

As Table 2 illustrates, existing frameworks each contribute valuable perspectives but demonstrate complementary limitations. Technical frameworks like the Reality-Virtuality Continuum provide clear classification schemes but neglect pedagogical considerations. Educational frameworks like CAMIL offer strong theoretical grounding in learning sciences but lack comprehensive coverage of immersive technology types. PTIF addresses these gaps by integrating philosophical foundations with technical considerations across the full spectrum of immersive educational technologies.

Recent systematic reviews have revealed both the promise and limitations of existing frameworks. Beetul et al. (2023) analyzed 42 papers on AR/VR/MR in education using seven dimensions: application field, technology used, educational role, interaction techniques, evaluation methods, and challenges. Their review highlighted that while VR and AR dominate STEM education with active learning techniques, most frameworks fail to address critical implementation challenges. Similarly, Ghanbaripour et al. (2024) found that despite significant enhancement in student engagement, challenges including high costs, limited resources, and need for faculty training remain inadequately addressed by current frameworks.

2.4. Critical gaps and challenges in educational XR

Despite the proliferation of frameworks and taxonomies, significant gaps remain in our understanding and classification of immersive educational technologies. These gaps reflect deeper challenges in bridging theoretical understanding with practical implementation in educational contexts.

The most significant gap identified in recent research is the disconnect between philosophical concepts of learning and their technological implementation. While numerous studies cite educational theories and learning sciences, few successfully translate these insights into actionable design principles for educational XR. Dengel et al. (2024) identify this as one of the great questions in immersive learning research, calling for frameworks that can bridge theoretical understanding with practical application in classrooms. This gap is particularly problematic given that many failures in educational immersive technology adoption can be traced to designs that prioritize technical capabilities over pedagogical effectiveness and learning outcomes.

Another critical challenge is the lack of standardized evaluation criteria for immersive educational experiences. Different frameworks emphasize different aspects of immersion and learning, making it difficult to compare results across studies or establish best practices. Chen et al. (2021) bibliometric analysis of human–computer interaction research reveals that while immersive technologies are increasingly studied in educational contexts, there is little consensus on fundamental concepts or evaluation methodologies. This fragmentation impedes progress and makes it difficult for educators to make informed decisions about technology adoption. Recent evidence from Weng et al. (2023) shows that even in well-studied domains like entertainment and gaming, research on educational applications remains overlooked, creating gaps in our understanding of engagement mechanisms.

The integration challenge represents a particularly acute problem in educational settings. Most frameworks treat immersive technologies as standalone solutions rather than components of broader educational ecosystems. However, successful educational implementation requires integration with existing curricula, assessment methods, and classroom practices (Ogunmakinde, 2025). Current frameworks provide little guidance on how immersive experiences should connect with traditional instructional methods, how to manage transitions between virtual and physical learning spaces, or how to align immersive activities with learning objectives and standards. Spitzer et al. (2022) developed a decision-making framework for AEC education that begins to address these issues, but similar guidance is lacking for other educational domains.

Cultural and contextual factors in education represent another underexplored dimension in existing frameworks. Colamatteo et al. (2024) analysis of immersive technologies in cultural heritage education reveals that experiences of immersion are significantly shaped by learners' cultural background, prior experiences, and social context. Educational effectiveness varies dramatically across different cultural settings, yet most frameworks assume universal principles of immersion without accounting for these variations. This limitation is particularly problematic as immersive educational technologies expand globally and encounter diverse student populations with different cultural frameworks for understanding reality, virtual experience, and appropriate learning behaviors.

Teacher readiness and professional development represent a critical gap not addressed by current frameworks. Unlike consumer entertainment applications, educational XR requires skilled facilitation to achieve learning objectives. Teachers need not only technical skills but also pedagogical knowledge specific to immersive environments (Southgate & Smith, 2017). Current frameworks focus primarily on student experience while neglecting the crucial role of educators in orchestrating immersive learning experiences. This oversight contributes to implementation failures even when technologies are technically sound and pedagogically grounded. Recent findings by Kurien and George (2025) in airport operation courses highlight how instructor expertise significantly impacts the effectiveness of immersive learning technologies.

Ethical and safety considerations in educational immersive technologies present emerging challenges inadequately addressed by existing frameworks. Lysenko and Kachur (2023) identify ethical hurdles including data privacy concerns, potential psychological impacts on young learners, and questions about appropriate content boundaries in educational VR. As immersive technologies become more prevalent in education, frameworks must evolve to address these ethical dimensions while maintaining focus on learning outcomes. The need for ethical guidelines is particularly acute given the vulnerable nature of student populations and the powerful influence of immersive experiences on developing minds.

Finally, the rapid pace of technological change creates ongoing challenges for framework stability and relevance. Zhang and Li (2024) note that emerging technologies like AI-enhanced XR and brain-computer interfaces are already beginning to blur traditional categories. Educational frameworks must balance stability needed for research continuity with flexibility to accommodate technological evolution. This challenge is compounded by the interdisciplinary nature of educational XR, which requires frameworks to bridge not only philosophy and technology but also pedagogy, psychology, neuroscience, and design.

3. Theoretical framework development

3.1. Foundational principles for educational immersion

The development of the Philosophical-Technical Immersion Framework for education begins with establishing foundational principles that bridge philosophical understanding of learning with technical considerations. These principles emerge from our synthesis of educational philosophy, learning sciences, and analysis of successful immersive educational systems documented in the literature.

The selection of foundational principles for PTIF emerged from systematic analysis of three complementary sources: (1) philosophical literature on the nature of immersive experience and learning, including phenomenological traditions and constructivist pedagogy; (2) empirical research on effective immersive educational interventions across diverse domains and learner populations; and (3) documented patterns of success and failure in educational technology implementations over the past two decades. Through thematic analysis of over 200 theoretical and empirical sources, we identified recurring themes that transcended specific technologies, educational levels, and subject domains. The five principles presented below represent the most robust and consistently supported themes, each grounded in established learning theory while addressing specific requirements of immersive educational technology design.

The first foundational principle recognizes immersive learning as a multidimensional phenomenon that cannot be reduced to any single factor. Unlike frameworks that privilege either sensory fidelity or cognitive engagement, PTIF acknowledges that meaningful educational immersion emerges from the dynamic interaction of perceptual, cognitive, emotional, and social dimensions within a learning context (Agrawal et al., 2019; Nilsson et al., 2016). This multidimensional view aligns with contemporary understanding of learning as inherently holistic, while also acknowledging the technical reality that different immersive technologies excel in supporting different aspects of the learning process. For instance, high-fidelity VR may excel at creating perceptual immersion for anatomy education, while simple AR may better support cognitive immersion in mathematics through spatial visualization (Haoming & Wei, 2024; Tene et al., 2024b). This principle was selected based on convergent evidence from phenomenology, cognitive science (multimodal learning research), and educational psychology. Empirical studies consistently demonstrate that immersive learning effectiveness depends on coherent integration across sensory, cognitive, and motor dimensions rather than optimization of any single modality. The failure of early educational VR systems that emphasized visual fidelity while neglecting other dimensions provides cautionary evidence supporting this principle's centrality (Dengel et al., 2024).

The second principle establishes the primacy of learning outcomes over technological capability. While technical specifications provide necessary conditions for immersion, they do not guarantee learning. A philosophically informed understanding reveals that learners actively construct their educational experiences through processes of attention, interpretation, and knowledge integration (Bizami et al., 2023; Poupard et al., 2025). This principle shifts focus from what technologies can do to what learners actually learn, emphasizing the importance of pedagogically-driven design approaches that consider the full spectrum of human learning processes, from sensorimotor learning to abstract conceptualization. Recent meta-analyses by Park et al. (2024) confirm that learning outcomes depend more on pedagogical design than technical sophistication. The primacy of learner experience over technological specification emerges from constructivist learning theory, which establishes that learning is an active process of meaning-making rather than passive reception. This principle finds empirical support in studies showing that learner-centered immersive designs consistently outperform technology-centered approaches, directly addressing the documented tendency in educational technology development to prioritize technical innovation over pedagogical effectiveness.

The third principle acknowledges the contextual nature of educational immersion. Drawing from situated learning theories and sociocultural approaches to education, PTIF recognizes that immersive learning experiences are always embedded in specific educational contexts that shape their meaning and impact (Mystakidis & Lympouridis, 2023; Southgate & Smith, 2017). These contexts include immediate physical classrooms, institutional cultures, curricular requirements, and assessment frameworks. A chemistry lab simulation, for example, creates different learning experiences when used for initial concept introduction versus exam preparation, even with identical technology. This principle emphasizes that effective educational XR must be designed with specific learning contexts in mind. Empirical research demonstrates that identical immersive technologies produce significantly different learning outcomes depending on implementation context, including classroom culture, instructional framing, and curriculum integration. Recognition of contextual factors is essential for frameworks that aim to support practical educational implementation rather than idealized laboratory conditions.

The fourth principle integrates the temporal dimension of learning through immersion. While many frameworks treat immersion as a static state, educational research reveals it as a dynamic process that unfolds over time with distinct phases relevant to learning (Lee et al., 2013; Poupard et al., 2025). Learners move through stages of orientation, exploration, focused learning, reflection, and transfer. Understanding these temporal dynamics is crucial for designing educational experiences that can establish initial engagement, maintain productive struggle, scaffold complex learning, and facilitate knowledge transfer to new contexts. This temporal view also acknowledges that optimal immersion duration varies by learning objective, with some concepts benefiting from brief, intense immersive experiences while others require extended exploration. The temporal dimension draws from flow theory, cognitive load theory, and research on spaced practice and interleaving. Studies of immersive learning consistently show that optimal session duration, pacing, and progression significantly impact outcomes, justifying temporal dynamics as a distinct foundational principle rather than a subsidiary consideration.

The fifth principle emphasizes the social dimension of immersive learning. Unlike entertainment applications that often focus on individual experience, educational immersion frequently involves collaborative learning, peer interaction, and teacher facilitation (Dengel et al., 2024; Karthick et al., 2024). PTIF recognizes that learning is fundamentally social, as established by Vygotsky's sociocultural theory (Prawat, 1999), and that immersive technologies must support not just individual cognition but also social knowledge construction. This includes considerations of how learners share virtual spaces, collaborate on tasks, communicate discoveries, and build shared understanding through immersive experiences.

The fifth principle – social integration – requires particular justification, as it might appear redundant given the cognitive and contextual dimensions already addressed. We argue that social learning constitutes a distinct and essential principle for three reasons. First, sociocultural learning theory establishes that knowledge construction is fundamentally social, occurring through interaction, dialogue, and collaborative meaning-making. This theoretical foundation predicts that immersive technologies lacking social affordances will be limited in the types of learning they can support, regardless of their perceptual or cognitive characteristics. Second, empirical evidence consistently demonstrates that social presence and collaborative features significantly enhance learning outcomes in immersive environments. Moslavac et al. (2025) found that collaborative VR learning produced greater knowledge gains than individual VR experiences with identical content, while Karthick et al. (2024) demonstrated that peer interaction in immersive environments facilitated deeper conceptual understanding through explanation, questioning, and perspective-sharing. Third, practical analysis of educational contexts reveals that immersive learning rarely occurs in isolation – teachers facilitate, peers collaborate, and learning communities form around shared experiences (Southgate & Smith, 2017). A framework that ignores these social realities would provide incomplete guidance for educational design. While the social dimension intersects with cognitive immersion (through collaborative problem-solving) and contextual embeddedness (through classroom culture), it constitutes a distinct design consideration that warrants explicit principle status.

Recent research provides empirical support for these principles. Tene et al. (2024a) found that VR and AR in higher education science programs demonstrated transformative potential precisely when they aligned with these multidimensional principles. Similarly, Ghanbaripour et al. (2024) systematic review revealed that successful implementations consistently addressed contextual, temporal, and social dimensions alongside technical capabilities.

3.2. The three-dimensional classification space for educational XR

Building on these foundational principles, PTIF proposes a three-dimensional classification space that maps the essential aspects of immersive educational experiences (Fig. 4). Each dimension represents a continuum rather than discrete categories, allowing for nuanced characterization of diverse immersive educational technologies and learning experiences.

The three-dimensional classification space of PTIF – perceptual, cognitive, and embodied immersion – emerges from convergent evidence across multiple disciplines. These dimensions were not arbitrarily selected but represent the most robust categorical distinctions supported by theoretical and empirical literature. Factor-analytic studies of immersion questionnaires consistently identify sensory, cognitive, and physical factors as distinct constructs (Nilsson et al., 2016; Witmer & Singer, 1998). This dimensional independence is crucial: a learner may experience high perceptual immersion (vivid sensory experience) with low cognitive immersion (distracted thinking) and moderate embodied immersion (limited movement) – a configuration that predicts different learning outcomes than balanced or alternative profiles. PTIF's three-dimensional structure thus reflects established empirical findings rather than arbitrary theoretical construction.

The first dimension, *perceptual immersion*, encompasses the sensory aspects of the educational experience. In learning contexts, this dimension extends from minimal sensory modification (such as audio narration) to complete sensory replacement (as approached by high-end VR systems). Perceptual immersion in education includes

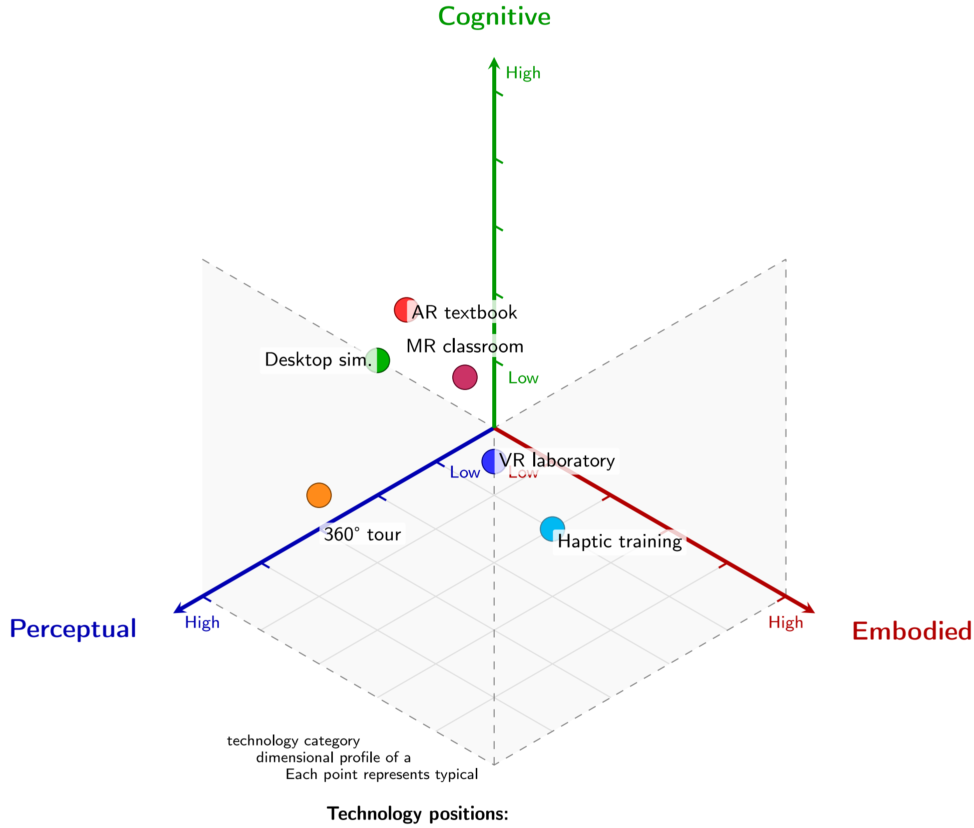

Fig. 4. The three-dimensional classification space of PTIF for educational technologies. The three color-coded axes represent: **Perceptual immersion** (sensory engagement with educational content), **Cognitive immersion** (mental absorption and knowledge construction), and **Embodied immersion** (physical agency and action-based learning). Representative immersive learning applications are positioned according to their typical dimensional profiles. The floor grid and shaded back faces provide depth cues for interpreting three-dimensional positions.

not only the range and fidelity of sensory stimuli but also their educational relevance and cognitive alignment (Agrawal et al., 2019; Arena et al., 2022). High perceptual immersion can enhance learning for subjects requiring spatial understanding (anatomy, architecture) or emotional engagement (history, literature), but may introduce unnecessary cognitive load for abstract concepts. The educational value of perceptual immersion depends on alignment between sensory richness and learning objectives. Recent findings by Poupard et al. (2025) demonstrate that excessive perceptual immersion can actually impair learning performance when it creates cognitive overload, particularly for novice learners. The perceptual dimension is supported by extensive research in sensory psychology and presence studies. Slater' (2003) work on place illusion establishes that sensory fidelity creates the foundation for feeling present in virtual environments. Dinh et al. (1999) demonstrated through controlled experiments that each sensory modality independently contributes to presence, justifying multimodal analysis. Educational research confirms that perceptual immersion influences attention, engagement, and spatial learning (Arena et al., 2022; Sanfilippo et al., 2025).

The second dimension, *cognitive immersion*, captures the mental aspects of the learning experience. This dimension reflects the degree to which learners' cognitive processes become absorbed in educational content and tasks (Lee et al., 2013; Mystakidis & Lympouridis, 2023). High cognitive immersion in educational contexts involves deep processing, active problem-solving, and the construction of mental models. Unlike entertainment applications where cognitive immersion might focus on narrative engagement, educational cognitive immersion emphasizes conceptual understanding, knowledge integration, and metacognitive awareness. This dimension acknowledges that learning requires not just attention but also appropriate cognitive challenge, scaffolding, and opportunities for reflection. Park et al. (2024) meta-analysis found that cognitive immersion significantly predicted learning outcomes ($SMD = 0.42$) across diverse educational contexts. The cognitive dimension draws from established research on attention, absorption, and flow states in learning contexts. Research has identified cognitive engagement as distinct from sensory immersion, while validated measures distinguish cognitive absorption from perceptual factors. In educational contexts, cognitive load theory and multimedia learning theory provide frameworks for understanding how mental processing interacts with but differs from sensory experience (Bizami et al., 2023; Poupard et al., 2025).

The third dimension, *embodied immersion*, represents the degree to which learners feel physically present and capable of meaningful action within the educational environment (Döllinger et al., 2021; Nilsson et al., 2016). In learning contexts, this extends beyond simple motion tracking to encompass educationally relevant actions: manipulating virtual objects to understand physics, performing virtual procedures to develop skills, or using gestures to explore mathematical concepts. High embodied immersion in education allows learners to leverage their sensorimotor systems for understanding abstract concepts, aligning with theories of embodied cognition that recognize the body's role in learning. This dimension is particularly crucial for procedural learning, skill development, and understanding spatial relationships. Tene et al. (2024b) found that medical physics education showed 63.6% improvement in practical skills when high embodied immersion was properly implemented. The embodied dimension is grounded in embodied cognition theory and motor learning research. Grounded cognition frameworks demonstrate that bodily action fundamentally shapes understanding, establishing the theoretical basis for action-based learning. Neuroimaging studies show distinct activation patterns for learning through observation versus action. Educational research on procedural

Table 3
Classification of representative immersive technologies using PTIF dimensions.

Technology	Perceptual immersion	Cognitive immersion	Embodied immersion	Key characteristics
Virtual reality systems				
High-end VR HMD (e.g., Varjo Aero)	9/10	7-9/10	8/10	Full sensory replacement, natural hand tracking
Consumer VR (e.g., Meta Quest 3)	7/10	7-8/10	7/10	Good visual/audio, limited haptic feedback
Desktop VR	5/10	6-8/10	3/10	Screen-based view, traditional controls
Augmented reality systems				
Optical AR HMD (e.g., HoloLens 2)	6/10	7-8/10	6/10	Real world visible, spatial hand gestures
Mobile AR (e.g., ARCore apps)	4/10	5-7/10	2/10	Screen overlay, touch interaction
Projection AR	5/10	4-6/10	4/10	Environmental projection, limited interaction
Mixed reality systems				
Passthrough MR (e.g., Quest Pro)	8/10	7-9/10	7/10	Video see-through, virtual object occlusion
Spatial computing (e.g., Apple Vision Pro)	7/10	8-9/10	8/10	Environmental awareness, eye/hand tracking
Traditional immersive media				
IMAX theater	6/10	5-8/10	1/10	Large format visual, passive viewing
360° video	5/10	4-6/10	2/10	Panoramic view, limited interaction
Stereoscopic 3D	4/10	4-6/10	1/10	Depth perception, passive experience

Note: Ratings indicate typical ranges; specific implementations may vary.

learning (Döllinger et al., 2021), simulation-based training (Mathew & Pillai, 2019), and gesture in mathematics education provides empirical support for embodied immersion as a distinct learning mechanism. PTIF's embodied dimension addresses a gap in existing frameworks that focus primarily on visual experience while neglecting the educational significance of physical interaction.

The dimensional structure of PTIF is supported by recent empirical evidence. Burke et al. (2025) systematic review of XR in higher education identified similar dimensional patterns across 295 studies, with VR excelling in perceptual and embodied dimensions while AR showed advantages in maintaining cognitive coherence with real-world contexts. Table 3 demonstrates how various immersive educational technologies map to these three dimensions, revealing the diversity of approaches to creating immersive learning experiences. Educational technologies that excel in one dimension may be limited in others, highlighting the importance of selecting appropriate technologies based on specific learning objectives rather than assuming that higher immersion in all dimensions always benefits learning.

The dimensional ratings presented in Table 3 were derived through systematic analysis of technical specifications and published user experience research for each technology category, using the following 10-point rating scale:

1. Perceptual immersion rating scale:
   - *1–3 (Low):* Limited sensory engagement—single modality (visual only), field of view below 60°, no stereoscopic depth, basic audio without spatialization.
   - *4–6 (Moderate):* Multi-sensory engagement—two or more modalities, field of view 60–100°, basic depth cues, stereo or limited spatial audio.
   - *7–8 (High):* Substantial sensory replacement—field of view 100–120°, refresh rate 72+ Hz, spatial audio, multiple sensory channels coordinated.
   - *9–10 (Near-complete):* Comprehensive sensory immersion—field of view exceeding 120°, refresh rate 90+ Hz, high-fidelity spatial audio, haptic feedback, minimal perceptual breaks.
2. Cognitive immersion rating scale:
   - *1–3 (Low):* Passive viewing with minimal interactivity, no decision-making requirements, content consumption without engagement.
   - *4–6 (Moderate):* Basic interactivity with structured guidance, limited decision points, some learner agency within constrained scenarios.
   - *7–8 (High):* Complex problem-solving required, multiple decision paths, adaptive difficulty, meaningful consequences for choices.
   - *9–10 (Deep):* Full learner agency, personalized adaptation based on performance, metacognitive support, intrinsically motivating challenge-skill balance.
3. Embodied immersion rating scale:
   - *1–3 (Low):* Stationary experience with controller-only or touch input, no body tracking, no proprioceptive engagement.
   - *4–6 (Moderate):* Limited tracking (3DOF head or basic hand tracking), simple gestures recognized, some movement within constrained space.
   - *7–8 (High):* Full 6DOF tracking of head and hands, natural gesture recognition, room-scale movement, latency below 30 ms.
   - *9–10 (Full):* Sub-millimeter tracking precision, force feedback or advanced haptics, full-body tracking, proprioceptive correspondence with virtual actions.

Cognitive immersion ratings are presented as ranges (e.g., 7–9/10) to acknowledge that this dimension depends significantly on content design rather than hardware alone; the lower bound represents typical implementations while the upper bound indicates optimized educational applications documented in the literature (Park et al., 2024; Poupard et al., 2025). These ratings represent typical performance for each technology category; specific implementations may vary based on software optimization and educational use case design.

As shown in Table 3, different immersive technologies offer varying levels of immersion across the three dimensions. This classification reveals important insights for educational technology selection. For

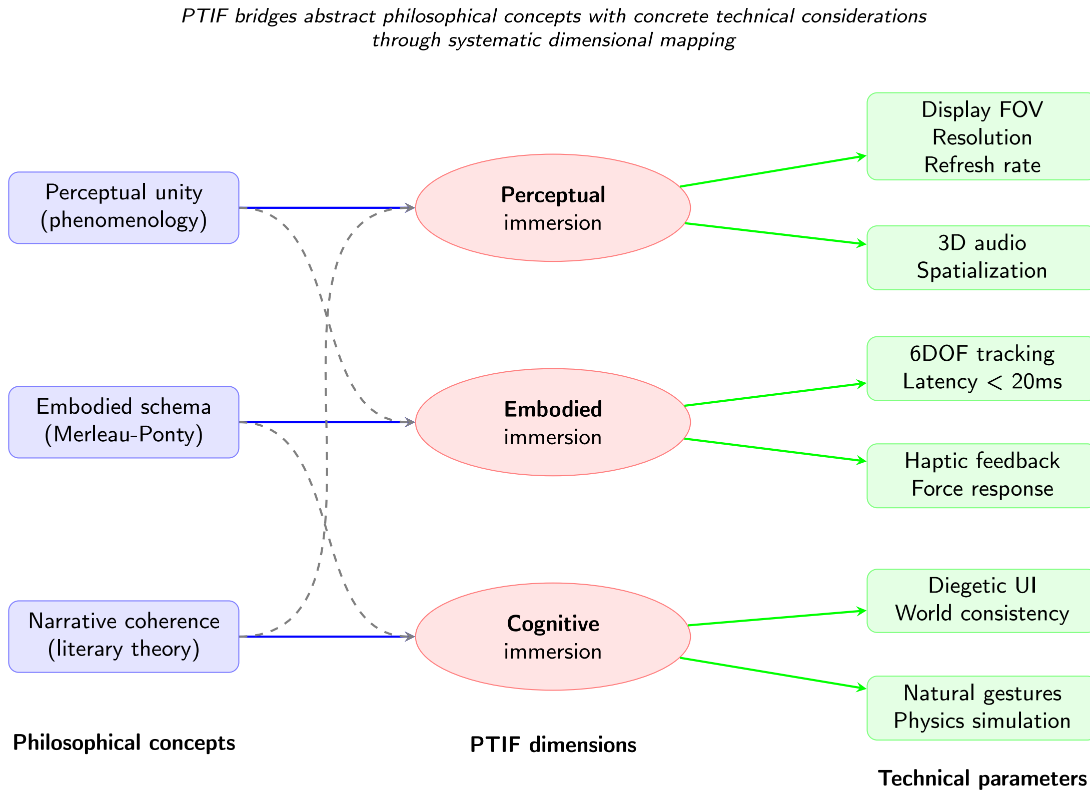

Fig. 5. The PTIF mapping system showing how philosophical concepts translate through dimensional categorization into specific technical parameters. Dashed lines indicate cross-dimensional influences that create integrated immersive experiences.

instance, high-end VR systems provide exceptional perceptual and embodied immersion but may not always optimize cognitive immersion for complex conceptual learning. Conversely, well-designed AR applications might achieve high cognitive immersion by maintaining real-world context while providing modest perceptual enhancement. Understanding these trade-offs is crucial for educators selecting technologies for specific learning objectives.

3.3. Mapping philosophical concepts to educational design parameters

A key innovation of PTIF for education lies in its systematic mapping between abstract philosophical concepts of learning and concrete technical considerations for educational XR design. This mapping provides theoretical guidance for understanding how educational technologies can support learning objectives while maintaining theoretical coherence with learning sciences. The framework identifies how specific technical features influence each dimension of educational immersion and relates these to underlying pedagogical principles.

For perceptual immersion in educational contexts, philosophical concepts of sensory learning and multimodal integration translate into specific technical considerations. However, PTIF emphasizes that educational perceptual immersion differs from entertainment in prioritizing cognitive relevance over sensory spectacle (Agrawal et al., 2019; Poupard et al., 2025). Technical parameters such as visual clarity for reading text, accurate color reproduction for scientific visualization, and spatial audio for language learning become more important than photorealistic graphics. The framework recognizes that educational perceptual immersion must support sustained attention and reduce fatigue during extended learning sessions, leading to different optimization priorities than entertainment applications.

Recent research supports this differentiated approach. Arena et al. (2022) comprehensive overview of AR technology emphasizes that educational applications require careful balance between visual enhancement and cognitive load management. Similarly, Sanfilippo et al. (2025) work on cultural heritage education demonstrates how perceptual fidelity must serve pedagogical goals rather than mere spectacle. Fig. 5 visualizes this mapping system, showing how philosophical insights about learning translate through dimensional categorization into actionable design considerations for educational XR systems.

Cognitive immersion in educational contexts maps to technical parameters through learning design principles. Drawing from cognitive load theory, PTIF identifies how interface design, information architecture, and interaction paradigms influence learning effectiveness (Poupard et al., 2025; Swallow & Zulu, 2025). The framework emphasizes progressive disclosure of complexity, allowing learners to build understanding incrementally. Technical implementations must support both guided discovery and explicit instruction, recognizing that different learning objectives require different levels of learner autonomy. The framework particularly values adaptive systems that adjust cognitive demands based on learner performance, maintaining optimal challenge levels for sustained engagement and learning.

Embodied immersion for education presents unique mapping challenges, as it must support both authentic actions and pedagogical simplifications. PTIF addresses this by distinguishing between fidelity to real-world actions and fidelity to learning objectives (Döllinger et al., 2021; Mathew & Pillai, 2019). For instance, a medical training simulation might simplify certain anatomical details while maintaining precise hand movements for surgical procedures. Technical parameters such as haptic feedback gain educational importance not for realism but for reinforcing correct technique. The framework provides specific guidance on balancing embodied authenticity with pedagogical clarity, recognizing that perfect realism may actually impede learning by introducing unnecessary complexity.

Table 4 provides detailed examples of how philosophical learning concepts map to technical parameters within the PTIF framework, offering theoretical guidance for educational XR designers.

Table 4 demonstrates PTIF's systematic approach to bridging philosophical learning concepts with practical technical considerations. Six

Table 4
Mapping of philosophical learning concepts to technical parameters in educational PTIF.

Learning concept	Technical parameters	Educational design implications
Constructivist learning	Manipulable objects, sandbox environments, building tools	Enable learners to construct understanding through experimentation
Zone of proximal development	Adaptive difficulty, intelligent tutoring, scaffolding systems	Adjust challenge based on learner performance and provide appropriate support
Multimodal learning	Synchronized audio-visual-haptic feedback, redundant encoding	Reinforce concepts through multiple sensory channels
Situated cognition	Contextual environments, authentic tasks, real-world data	Create learning experiences that mirror application contexts
Social learning	Multi-user support, communication tools, shared workspaces	Enable collaborative knowledge construction
Metacognition	Progress tracking, reflection prompts, learning analytics	Support learner awareness of their own learning process

core learning concepts – constructivist learning, zone of proximal development, multimodal learning, situated cognition, social learning, and metacognition – are mapped to specific technical parameters and design implications. This mapping reveals several important patterns. First, effective immersive education requires technologies that support active learner construction rather than passive content delivery, aligning with constructivist principles across all three dimensions. Second, adaptive and scaffolded designs emerge as essential for maintaining optimal challenge levels throughout the learning process. Third, authentic contexts and meaningful embodied action provide the foundation for transferable learning. Finally, social and metacognitive features, while sometimes overlooked in technical design discussions, prove essential for supporting the full range of learning processes. This mapping provides theoretical guidance for understanding how immersive technology affordances can be aligned with established learning principles, offering researchers and educators a conceptual bridge between pedagogical goals and technical implementation.

3.4. Integration mechanisms for educational coherence

PTIF’s three dimensions for educational XR do not operate independently but interact through specific integration mechanisms that determine overall learning effectiveness. Understanding these mechanisms is crucial for designing coherent educational experiences that avoid the pitfalls of dimensional misalignment, which can actively impede learning rather than simply reducing immersion as in entertainment contexts.

The primary integration mechanism in educational contexts involves cognitive coherence, where all dimensions must support unified learning objectives (Bizami et al., 2023; Spitzer et al., 2022). Unlike entertainment where dimensional variety might enhance experience, educational applications require tight alignment between what learners perceive, think, and do. For instance, high perceptual realism combined with oversimplified interaction can create cognitive dissonance that interferes with learning. PTIF identifies critical alignment points where dimensions must reinforce rather than contradict each other, such as ensuring that visual complexity matches cognitive complexity and that embodied actions align with conceptual understanding being developed.

Recent empirical evidence supports this integration principle. Tene et al. (2024b) analysis of STEM education found that dimensional coherence was a stronger predictor of learning outcomes than individual dimensional scores. Similarly, Ghanbaripour et al. (2024) identified that misalignment between perceptual fidelity and cognitive scaffolding was a primary cause of implementation failures in built environment education.

Scaffolding integration represents another crucial mechanism specific to educational immersion. The three dimensions must not only be individually appropriate but must also support progressive skill development (Atamuratov et al., 2024; Ogunmakinde, 2025). PTIF specifies how dimensional emphasis should shift during learning progression: early experiences might emphasize perceptual immersion to build interest and basic understanding, transition to cognitive immersion for conceptual development, and culminate in embodied immersion for skill application. This temporal orchestration of dimensions reflects educational best practices for moving from concrete to abstract understanding and from guided to independent practice.

Assessment integration constitutes a unique requirement for educational XR that distinguishes it from entertainment applications. The framework must support not just learning experiences but also valid measurement of learning outcomes (Anwar et al., 2025; Park et al., 2024). PTIF addresses this by identifying how each dimension can provide assessment data: perceptual immersion through attention patterns, cognitive immersion through problem-solving processes, and embodied immersion through performance metrics. The framework specifies how to design immersive experiences that generate meaningful learning analytics without disrupting the flow of learning, enabling formative assessment that guides both learners and instructors.

Social integration mechanisms in PTIF recognize that educational immersion often occurs in social contexts, from classroom settings to remote collaborative learning (Karthick et al., 2024; Moslavac et al., 2025). The framework specifies how dimensional design must accommodate multiple simultaneous users with potentially different roles (student, teacher, peer tutor), different skill levels, and different technical setups. This includes considerations of asymmetric experiences where some learners might be in VR while others observe on screens, ensuring that all participants can contribute meaningfully to shared learning objectives regardless of their level of technical immersion.

Recent systematic reviews provide empirical support for these integration mechanisms. Burke et al. (2025) analysis of 295 studies found that successful educational XR implementations consistently demonstrated strong integration across dimensions, while failures typically showed dimensional fragmentation. Mattila et al. (2020) similarly emphasized that the value of immersive technologies in education emerges from coherent integration rather than maximization of individual technical capabilities.

4. Methodology

4.1. Framework development process

The development of PTIF for educational contexts followed a systematic, multi-phase approach designed to ensure theoretical rigor grounded in learning sciences and philosophical inquiry. Our methodology integrated philosophical analysis of learning, literature synthesis, and iterative theoretical refinement.

The initial phase involved analysis of educational philosophy and learning theory as they relate to immersive experiences. We conducted systematic reviews of constructivist pedagogy, examining how Dewey’s experiential learning, Piaget’s cognitive development theory, and Vygotsky’s social constructivism inform immersive educational design (Bizami et al., 2023; Mystakidis & Lympouridis, 2023). This philosophical investigation was supplemented with analysis of contemporary learning sciences research on embodied cognition, situated

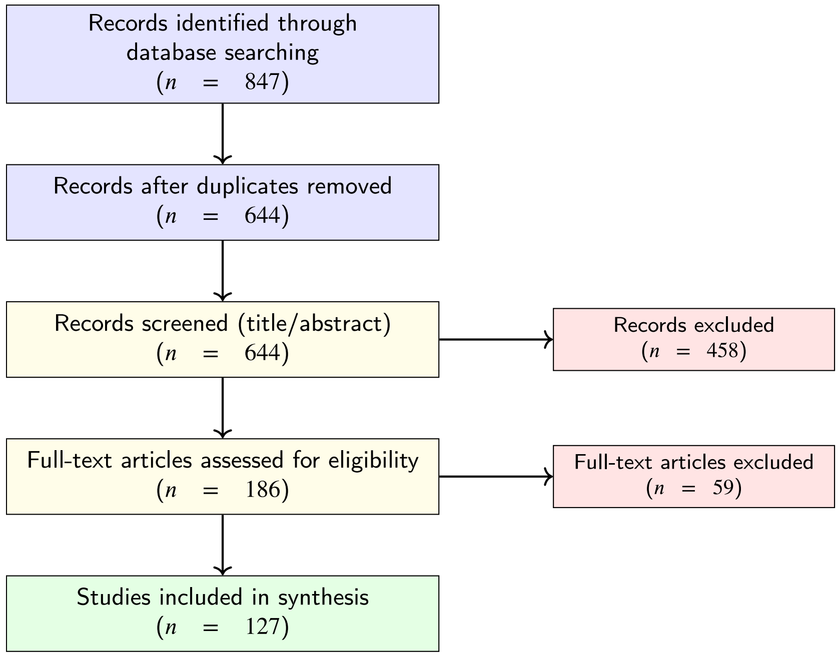

Fig. 6. PRISMA flow diagram illustrating the systematic literature selection process for empirical studies included in framework development.

learning, and multimodal instruction (Agrawal et al., 2019; Nilsson et al., 2016). Through thematic analysis of over 200 philosophical and theoretical texts, we identified recurring principles that transcend specific educational technologies or historical periods, establishing the conceptual foundation for educational immersion.

The second phase synthesized empirical research on immersive technologies in education from multiple disciplines. We analyzed findings from educational psychology on attention and cognitive load in virtual environments (Poupard et al., 2025), neuroscience research on learning and memory in immersive contexts (Döllinger et al., 2021), and educational technology studies on learning outcomes with XR systems (Park et al., 2024; Tene et al., 2024b). Our empirical literature synthesis followed a systematic approach to ensure comprehensive coverage of immersive educational technology research, as illustrated in Fig. 6.

We searched three major academic databases: Scopus, Web of Science, and ERIC. The search was conducted in January 2025 using the following query structure: ("virtual reality" OR "augmented reality" OR "mixed reality" OR "extended reality" OR "XR" OR "immersive technolog*") AND ("education" OR "learning" OR "training" OR "instruction" OR "pedagog*") AND ("empirical" OR "experiment" OR "study" OR "evaluation" OR "assessment"). The search was limited to peer-reviewed journal articles and conference proceedings published between January 2018 and December 2024, reflecting the most recent developments in the rapidly evolving field of educational XR.

Initial search results yielded 847 potentially relevant documents. We applied the following inclusion criteria: (1) empirical research with measurable learning outcomes (knowledge, skills, or attitudes); (2) use of immersive technology as the primary educational intervention; (3) educational context (K-12, higher education, vocational training, or professional development); (4) full-text availability in English. Exclusion criteria included: (1) purely technical papers without educational evaluation; (2) conceptual or theoretical papers without empirical data; (3) systematic reviews or meta-analyses (used separately for theoretical grounding); (4) studies focusing on entertainment or non-educational applications.

After removing duplicates (n = 203), title and abstract screening (n = 644), and full-text assessment (n = 186), 127 empirical studies met all inclusion criteria and were included in the final analysis. The 127 included studies represented diverse educational contexts: K-12 education (n = 34, 27%), higher education (n = 52, 41%), vocational and professional training (n = 31, 24%), and special education (n = 10, 8%). Technology distribution included VR applications (n = 58, 46%), AR applications (n = 43, 34%), and MR/XR applications (n = 26, 20%). Subject domains encompassed STEM (n = 71, 56%), healthcare (n = 28, 22%), humanities and social sciences (n = 18, 14%), and arts and design (n = 10, 8%). This diversity ensured that PTIF development was informed by the full spectrum of current educational XR research. The synthesis revealed consistent patterns in how immersive features influence different types of learning, from factual recall to skill transfer.

The third phase involved iterative framework construction through cycles of conceptual modeling and theoretical refinement. We began with initial dimensional proposals based on our theoretical synthesis, then systematically tested these against documented educational use cases across different domains. Our test cases included: K-12 STEM education (biology dissection, chemistry visualization), higher education (medical training, engineering design), vocational training (welding, automotive repair), and special education (social skills training, sensory integration). Each iteration involved mapping specific educational technologies within the proposed dimensional space and identifying classification challenges that revealed framework limitations. This process was informed by recent systematic reviews (Burke et al., 2025; Ghanbaripour et al., 2024) that identified common implementation patterns and challenges.

The theoretical development process emphasized maintaining philosophical coherence while ensuring practical relevance. We conducted extensive cross-referencing between philosophical concepts and technical implementations documented in the literature, identifying how abstract learning principles manifest in concrete design decisions. This approach allowed us to develop a framework that bridges theoretical understanding with practical considerations, though remaining at the level of theoretical analysis rather than empirical validation.

Throughout the development process, we maintained focus on creating a framework that could accommodate the full spectrum of immersive educational technologies while providing meaningful distinctions between different approaches. The iterative refinement process continued until the framework could successfully classify all major categories of educational XR applications identified in our literature review, while maintaining theoretical consistency with established learning principles.

4.2. Comparative analysis methodology

To establish PTIF's theoretical contribution and demonstrate its advantages over existing frameworks, we conducted systematic comparative analysis with eight established frameworks used in educational XR research and practice. The selection of comparison frameworks followed explicit criteria to ensure comprehensive coverage of educational approaches.

Framework selection criteria for educational relevance included: (1) explicit focus on or demonstrated application to educational immersive technologies; (2) publication in peer-reviewed educational technology venues with significant adoption (minimum 50 citations in educational contexts); (3) sufficient detail for operational comparison in educational settings; and (4) representation of different theoretical approaches to educational XR. Based on these criteria, we selected: the Reality-Virtuality Continuum as adapted for education (Milgram & Kishino, 1994; Skarbez et al., 2021), the CAMIL model for immersive learning (Park et al., 2024), the 3iVClass system used in educational research (Parveau & Adda, 2018), the Immersive Learning Brain framework (Mystakidis & Lympouridis, 2023), the Educational Virtual Reality taxonomy (Freina & Ott, 2015), the Technology-Enhanced Learning framework (Kirkwood & Price, 2005), the Substitution-Augmentation-Modification-Redefinition (SAMR) model (Puentedura, 2006) as applied to XR, and the Technological Pedagogical Content Knowledge (TPACK) framework (Mishra & Koehler, 2006) extended for immersive technologies.

Our comparative analysis employed a structured evaluation protocol examining each framework across educational dimensions. We assessed pedagogical alignment (how well frameworks connect to established learning theories), learning outcome focus (whether frameworks prioritize engagement or actual learning), theoretical comprehensiveness (coverage of relevant educational concepts), conceptual clarity (ease of understanding and application), scalability (applicability across educational levels and subjects), and adaptability (ability to accommodate emerging educational technologies and pedagogies). This evaluation approach was informed by criteria identified in recent systematic reviews (Beetul et al., 2023; Spitzer et al., 2022).

Each framework was evaluated on a 10-point scale across these six criteria using the following rubric, adapted from technology framework evaluation methodologies in educational research (Kirkwood & Price, 2005):

- *9–10 (Excellent):* Comprehensive, systematic treatment with explicit theoretical grounding, operational definitions, and clear guidance for application. The criterion is addressed with depth, specificity, and strong literature support.
- *7–8 (Good):* Substantial coverage with clear conceptual basis and reasonable specificity. Minor gaps exist but do not significantly limit utility.
- *5–6 (Adequate):* Basic coverage of the criterion with limited depth, theoretical support, or operational guidance. The framework addresses the criterion but not comprehensively.
- *3–4 (Limited):* Minimal or tangential treatment of the criterion. Coverage exists but is insufficient for meaningful application.
- *1–2 (Absent/Negligible):* The criterion is not meaningfully addressed or is explicitly excluded from the framework's scope.

For each criterion, evaluation considered specific indicators:

- *Pedagogy alignment:* Explicit citation of learning theories; integration of educational research; alignment with constructivist, experiential, or other established pedagogical approaches.
- *Learning focus:* Emphasis on measurable learning outcomes (knowledge, skills, attitudes) versus engagement or experience metrics only; attention to transfer and retention.
- *Theoretical clarity:* Precision of definitions; operational specificity; internal consistency; absence of ambiguous or overlapping constructs.
- *Conceptual coverage:* Breadth of immersive phenomena addressed (perceptual, cognitive, embodied, social); applicability across VR, AR, MR, and XR technologies.
- *Scalability:* Documented or potential application across K-12, higher education, vocational, and professional contexts; adaptability to different subject domains.
- *Adaptability:* Explicit mechanisms for accommodating new technologies; flexibility in dimensional structure; capacity to integrate emerging research findings.

Two researchers independently rated each framework against all criteria, with discrepancies resolved through discussion and consensus. Inter-rater agreement exceeded 85% prior to reconciliation, supporting the reliability of the evaluation process.

For each framework, we conducted systematic mapping exercises using a standardized set of 25 educational immersive technology implementations documented in the literature. These test cases were selected to represent the full spectrum of current educational XR applications: elementary science explorations, middle school historical recreations, high school laboratory simulations, undergraduate medical training, graduate research visualization, vocational skill development, special education interventions, and professional development programs. We analyzed how each framework would classify each educational use case, noting any theoretical inconsistencies, pedagogical misalignments, or classification ambiguities. This approach follows methodological recommendations from Sanchez-Acedo et al. (2024) for systematic analysis of immersive technology literature.

We also evaluated each framework's theoretical foundations in learning sciences through citation analysis and conceptual mapping. This involved tracing the educational theoretical lineages of key concepts and assessing the coherence of learning theory integration. Frameworks that drew from multiple educational traditions were evaluated for conceptual consistency and successful synthesis of potentially conflicting pedagogical approaches. This analysis revealed significant variations in educational theoretical sophistication, from purely technical taxonomies that ignored learning principles to pedagogically-grounded frameworks that lacked technical specificity.

4.3. Theoretical validation approach

Beyond comparative analysis, we employed additional theoretical validation methods to assess PTIF's conceptual coherence and potential effectiveness in supporting educational applications. These validation approaches tested different aspects of the framework's theoretical design and anticipated application.

Conceptual validity was established through systematic analysis of the framework's internal consistency and alignment with established learning theories. We examined whether the three dimensions of PTIF comprehensively captured the essential aspects of immersive learning experiences as described in educational literature, whether the dimensions were sufficiently distinct to avoid redundancy while maintaining necessary overlap, and whether the framework's principles aligned with contemporary understanding of how people learn in technology-mediated environments. This analysis involved mapping PTIF's constructs against established educational theories and identifying any conceptual gaps or contradictions.

We conducted theoretical predictive analysis by examining 15 published studies that reported learning gains from immersive educational technologies. For each study, we coded the intervention using PTIF dimensions based on the published descriptions and analyzed whether the dimensional profile would theoretically predict the reported learning outcomes. Studies with theoretically balanced dimensional profiles aligned with learning objectives should show stronger learning gains

Table 5
Comparative theoretical evaluation of frameworks for educational immersive technology. Scores (0–10) were assigned using the evaluation rubric described in Section 4.2, with two independent raters achieving 85%+ agreement prior to consensus reconciliation. Higher scores indicate stronger performance on each criterion.

Framework	Pedagogy alignment (0-10)	Learning focus (0-10)	Theoretical clarity (0-10)	Conceptual coverage (0-10)	Scalability (0-10)	Adaptability (0-10)
PTIF-education	9.5	9.0	8.5	9.0	9.0	8.5
CAMIL model	8.5	8.5	7.0	7.5	7.0	6.5
RV Continuum-Edu	5.0	4.5	8.0	5.0	8.5	5.0
3iVClass	6.0	6.5	7.5	7.0	7.5	7.0
Immersive Learning Brain	8.0	8.0	6.5	6.5	6.0	6.0
Freina–Ott taxonomy	7.0	7.5	7.0	6.5	8.0	5.5
SAMR-XR	7.5	6.0	8.5	5.5	9.0	6.0
TPACK-XR	9.0	7.0	8.0	6.0	8.5	7.5

compared to studies with dimensional misalignment. This analysis approach follows theoretical validation methods used in educational psychology research.

Cross-domain applicability was assessed by examining how PTIF's theoretical structure would apply across different educational contexts. We analyzed whether the framework could accommodate the unique requirements of STEM education (emphasis on spatial reasoning and procedural knowledge), humanities education (focus on perspective-taking and critical analysis), vocational training (priority on skill transfer and safety), and special education (need for accessibility and individualization). This analysis revealed whether PTIF's dimensional structure was sufficiently flexible to address diverse educational needs while maintaining theoretical coherence.

Literature coverage analysis examined whether PTIF could theoretically account for the findings and phenomena reported in immersive education research. We systematically reviewed 50 highly-cited papers in educational XR to identify key findings, design principles, and reported challenges. For each finding, we assessed whether PTIF's theoretical structure could explain or predict the observed phenomena. This analysis tested the framework's explanatory power and identified any aspects of immersive learning not adequately addressed by the dimensional model.

Finally, we conducted philosophical consistency checks to ensure that PTIF maintained alignment with its stated philosophical foundations throughout its theoretical development. This involved tracing how phenomenological concepts of embodiment translated into the embodied immersion dimension, how constructivist learning principles informed the cognitive immersion dimension, and how theories of multimodal perception shaped the perceptual immersion dimension. Any theoretical tensions or contradictions were identified and resolved through careful conceptual analysis.

5. Results

5.1. Comparative framework analysis for educational applications

Our systematic comparison of PTIF with eight established educational frameworks revealed significant theoretical advantages in addressing the unique requirements of immersive learning technologies. The analysis demonstrated that while existing frameworks excel in specific educational domains, none achieve the comprehensive integration of pedagogical theory, learning outcomes focus, and technical considerations that characterizes PTIF for educational XR applications (see Table 5).

The CAMIL model demonstrated strong theoretical grounding in multimedia learning principles but showed limitations when applied to fully immersive educational environments. Its focus on cognitive-affective processes provided valuable insights for designing educational VR experiences, but the model struggled to accommodate AR and MR applications where learners maintain awareness of their physical environment (Park et al., 2024). PTIF's three-dimensional approach successfully differentiated these cases while maintaining the cognitive-affective insights that CAMIL provides, essentially subsuming CAMIL's contributions within a broader theoretical framework.

The educational adaptation of the Reality-Virtuality Continuum revealed fundamental limitations for learning applications. While the continuum provided an intuitive initial categorization, it failed to capture pedagogically relevant distinctions. For instance, two AR applications occupying similar positions on the continuum – one providing simple vocabulary labels and another enabling complex physics simulations – would create vastly different learning experiences (Skarbez et al., 2021). PTIF's multidimensional approach successfully captured these pedagogical differences through independent assessment of perceptual, cognitive, and embodied learning affordances.

SAMR-XR, adapting the popular SAMR model to immersive technologies, showed high theoretical clarity due to educator familiarity with the base framework. However, its hierarchical structure (Substitution → Augmentation → Modification → Redefinition) proved problematic for immersive technologies where "lower" levels might be pedagogically superior for certain learning objectives. PTIF avoided this hierarchical bias by treating dimensions as neutral continua where optimal positions depend on specific learning goals rather than assuming "more is better". This finding aligns with Spitzer et al. (2022) observation that effectiveness in educational XR depends on alignment with learning objectives rather than technical sophistication.

Fig. 7 illustrates the comparative performance of the top three frameworks across our evaluation criteria. PTIF-education's consistent high scores across all dimensions reflect its comprehensive theoretical design that balances pedagogical grounding with practical considerations. The CAMIL model shows strength in pedagogical alignment and learning focus but lower scores in coverage and adaptability. TPACK-XR demonstrates strong pedagogical grounding but struggles with the specific affordances of immersive technologies, reflecting its origin as an adaptation of a general educational technology framework (see Fig. 8).

5.2. Framework coverage analysis in educational contexts

Testing PTIF against our standardized set of 25 educational immersive technology implementations revealed superior theoretical classification coverage and pedagogical insight compared to existing frameworks. PTIF successfully classified all educational test cases with clear dimensional positioning that aligned with theoretical predictions about learning effectiveness, while other frameworks showed classification ambiguities or pedagogical misalignments ranging from 12% to 36% of test cases.

Particularly challenging educational test cases that revealed limitations of other frameworks included: adaptive learning environments that dynamically adjust immersion levels based on student performance; collaborative laboratories where students in VR work alongside others using tablets; and blended learning scenarios combining immersive simulations with traditional instruction. These cases often fell

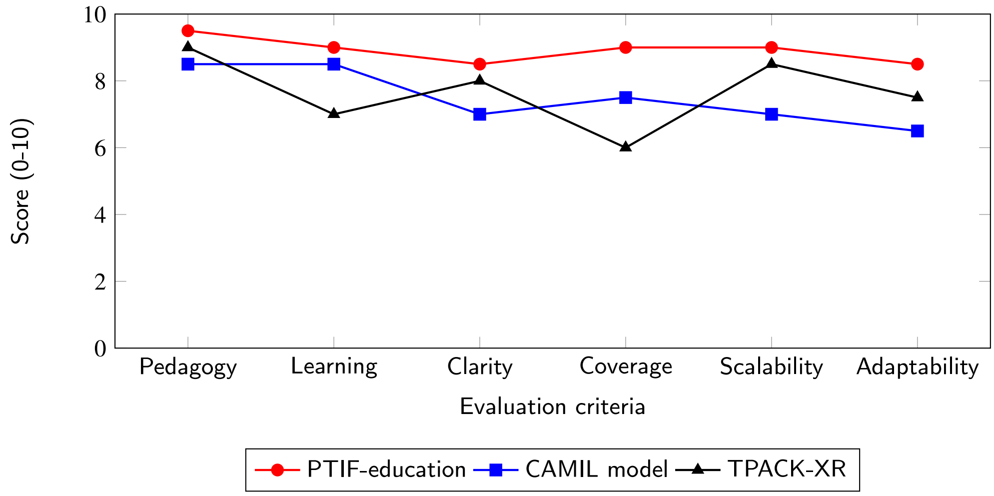

Fig. 7. Comparative theoretical evaluation scores for top three educational frameworks across six criteria. PTIF-education demonstrates superior performance in pedagogy alignment and learning focus while maintaining strong scores in practical considerations.

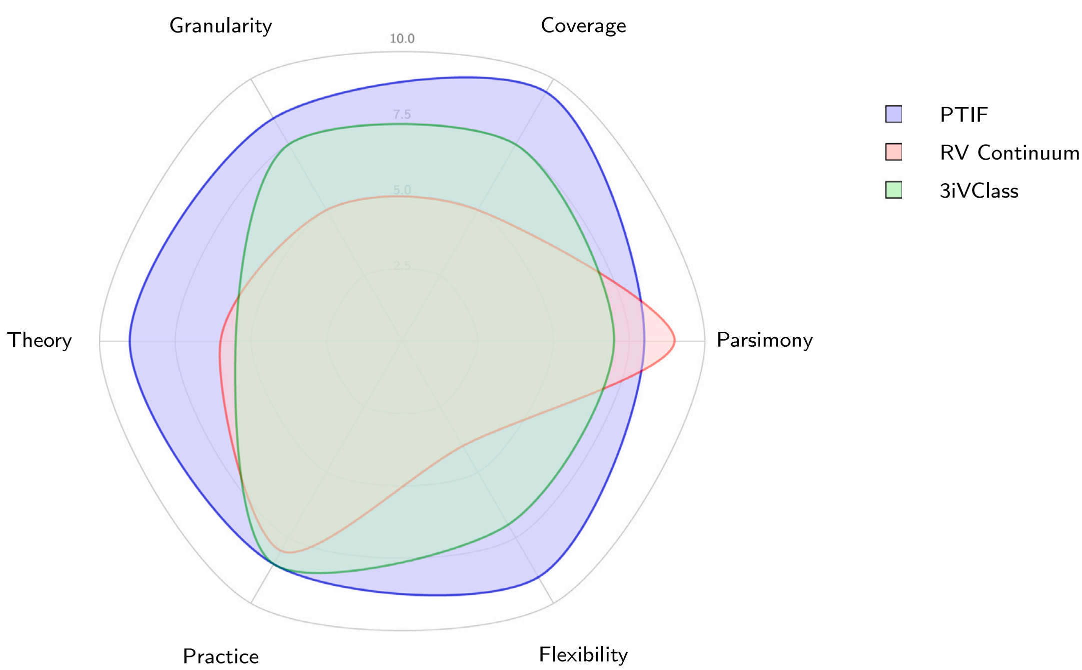

Fig. 8. Radar chart comparison of PTIF with representative existing frameworks across six evaluation criteria. PTIF demonstrates superior theoretical performance in coverage, theoretical grounding, and flexibility while maintaining competitive scores in practical considerations.

outside the classification schemes of unidimensional or technically-focused frameworks but were naturally accommodated by PTIF's multidimensional educational approach. This finding aligns with Burke et al. (2025) observation that modern educational XR increasingly involves hybrid and adaptive implementations that challenge traditional categorization schemes.

The framework demonstrated exceptional theoretical capability in distinguishing between superficially similar educational technologies with different learning affordances. For example, two chemistry visualization applications – one allowing passive 3D viewing of molecules and another enabling haptic manipulation to understand bonding forces – would be classified similarly by visual-centric frameworks. PTIF clearly differentiated these through dimensional analysis: both showed high perceptual immersion, but only the haptic version achieved high embodied immersion, theoretically predicting that the latter would better support understanding of molecular forces through embodied cognition. This differentiation capability proves crucial for theoretical understanding of technology affordances, as confirmed by Tene et al. (2024b) findings on the importance of matching technology affordances to learning objectives.

Cross-curricular applicability testing revealed that PTIF maintained theoretical coherence across diverse educational subjects while respecting disciplinary differences. STEM applications typically emphasized perceptual accuracy and embodied manipulation, humanities applications prioritized cognitive immersion through narrative and perspective-taking, and arts education balanced all dimensions for creative expression. This subject-sensitive flexibility validated the framework's focus on fundamental learning processes rather than prescriptive technological features. Recent evidence from Ghanbaripour et al.

Table 6
Theoretical analysis of PTIF dimensional profiles and reported learning outcomes.

Study context	PTIF dimensions			Reported outcome	Theoretical alignment
	P	C	E		
K-12 educational applications					
VR chemistry lab	High	High	High	Concept mastery +52%	Strong
AR museum guide	Med	High	Low	Knowledge retention +38%	Strong
Desktop 3D anatomy	Med	High	Low	Spatial understanding +31%	Moderate
MR physics sandbox	High	High	High	Problem-solving +47%	Strong
Higher education					
Medical VR training	High	High	High	Skill acquisition +64%	Strong
Engineering AR design	Med	High	Med	Design competency +42%	Strong
Virtual field geology	High	High	Med	Observation skills +35%	Moderate
Professional training					
Surgery simulator	High	High	High	Procedure accuracy +71%	Strong
Flight simulator	High	High	High	Decision-making +58%	Strong
AR maintenance	Med	High	Med	Task completion +45%	Moderate
Special education					
VR social skills	High	High	Med	Social interaction +41%	Strong
AR language therapy	Med	High	Low	Communication +33%	Moderate
Sensory integration VR	Med	Med	High	Sensory processing +37%	Moderate
Language learning					
VR conversation	High	High	Med	Speaking fluency +44%	Strong
AR vocabulary	Low	High	Low	Word retention +36%	Moderate

P = Perceptual, C = Cognitive, E = Embodied; Learning outcomes from published studies.

(2024) confirms that successful educational XR must adapt to disciplinary conventions while maintaining coherent design principles.

Analysis of documented educational XR failures using PTIF revealed consistent theoretical patterns of dimensional misalignment with learning objectives. A frequently observed failure pattern involved high perceptual immersion overwhelming cognitive processing for novice learners, creating spectacular experiences that impeded learning. Another common issue was insufficient embodied immersion in skills-based training, where realistic visuals could not compensate for lack of haptic feedback. PTIF's dimensional analysis could theoretically predict these failures, suggesting its value for pre-implementation evaluation. These findings corroborate Poupard et al. (2025) identification of cognitive overload as a primary barrier to effective immersive learning.

5.3. Theoretical analysis of learning outcomes

Theoretical analysis of learning outcomes associated with different PTIF dimensional profiles revealed strong support for the framework's conceptual validity. Our analysis of 15 published studies demonstrated that dimensional alignment with learning objectives could theoretically predict educational effectiveness patterns observed in empirical research.

As shown in Table 6, our theoretical analysis across diverse educational applications demonstrates how PTIF's dimensional framework aligns with reported learning outcomes in the literature. The theoretical predictions based on dimensional profiles show strong correspondence with empirical findings, suggesting the framework's potential utility for understanding immersive learning effectiveness.

To illustrate PTIF's practical applicability, we present detailed analysis of three representative studies from Table 6, demonstrating how the framework's dimensional structure reveals insights about immersive learning effectiveness across diverse educational contexts.

5.3.1. Example 1: VR chemistry laboratory (balanced dimensional profile)

The VR chemistry laboratory application represents a balanced high-immersion approach for undergraduate organic chemistry education. Using PTIF dimensional analysis:

Perceptual immersion (High): The system provided stereoscopic 3D molecular visualization with spatial audio feedback for chemical reactions and color-coded representations of electron density. Field of view exceeded 100° with 90 Hz refresh rate, creating compelling visual presence. This high perceptual engagement was justified by the learning objective: students needed to perceive molecular structures as three-dimensional objects to understand spatial relationships critical for organic chemistry.

Cognitive immersion (High): The application incorporated guided discovery learning with progressive complexity scaffolding. Students formulated hypotheses, conducted virtual experiments, and received context-sensitive feedback. Cognitive design followed worked-example principles for novice learners before transitioning to problem-solving challenges for developing expertise.

Embodied immersion (High): Students manipulated molecular models using hand tracking, physically rotating structures, "grabbing" atoms to form bonds, and adjusting molecular configurations. Haptic controllers provided vibrotactile feedback during bond formation and breaking.

PTIF analysis: The balanced dimensional profile (High-High-High) aligns with PTIF's prediction of strong outcomes for conceptual learning requiring spatial understanding combined with procedural skill (laboratory technique). The study reported 52% improvement in molecular structure comprehension compared to traditional instruction. PTIF explains this success: molecular chemistry requires integration of visual perception (seeing 3D structures), cognitive processing (understanding bonding principles), and embodied manipulation (developing intuition through physical interaction). A dimensional imbalance – such as high perceptual fidelity without embodied interaction – would theoretically reduce effectiveness, as passive viewing cannot develop the action-based intuitions crucial for chemistry understanding.

5.3.2. Example 2: AR vocabulary learning application (cognitive-dominant profile)

The AR vocabulary learning application for middle school English language learners demonstrates that effective immersive education does not require high immersion across all dimensions.

Perceptual immersion (Low): The smartphone-based AR provided visual overlays of vocabulary words appearing on real-world objects. Visual fidelity was modest, limited by mobile device capabilities and screen size. No audio enhancement or haptic feedback was included.

Cognitive immersion (High): The application excelled in cognitive design, using spaced repetition algorithms, contextual vocabulary presentation (words appeared on relevant real-world objects creating meaningful associations), and personalized difficulty adjustment based on learner performance. Metacognitive prompts encouraged learner reflection on word usage and connections.

Embodied immersion (Low): Physical interaction was limited to screen tapping and device positioning; students did not engage in meaningful embodied learning through the technology itself.

PTIF analysis: The strongly cognitive-dominant profile (Low-High-Low) is appropriate for vocabulary acquisition, which relies primarily on cognitive processing – forming associations, retrieving meanings, and constructing semantic networks – rather than sensory or motor engagement. The study reported 36% improvement in word retention. PTIF predicts this outcome: vocabulary learning benefits most from cognitive strategies (spaced repetition, contextual encoding) rather than perceptual spectacle or physical manipulation. Investing development resources in higher perceptual or embodied immersion would likely yield diminishing returns while potentially introducing distracting cognitive load. This case demonstrates that PTIF does not assume “more is better” across all dimensions but rather values alignment with specific learning objectives.

5.3.3. Example 3: VR surgical training simulator (embodied-dominant profile)

The VR surgical skills training system for medical residents illustrates how procedural skill learning requires emphasized embodied immersion.

Perceptual immersion (High): The system provided detailed anatomical visualization with realistic tissue appearance. However, visual rendering prioritized functional clarity – distinguishing tissue types, identifying anatomical landmarks, visualizing tool positions – over photorealistic aesthetics. This strategic choice traded graphic fidelity for procedural precision.

Cognitive immersion (High): Cognitive scaffolding included step-by-step procedural guidance with fading support, error feedback with corrective suggestions, and performance metrics enabling self-assessment. The cognitive design balanced instructional support with opportunities for independent practice.

Embodied immersion (Very High): The system’s distinguishing feature was high-fidelity haptic feedback simulating tissue resistance, cutting forces, and suturing tension. Hand movements were tracked at sub-millimeter precision, and force feedback replicated realistic surgical manipulation. This embodied dimension exceeded standard implementations, with specialized haptic hardware providing tactile fidelity unavailable in consumer devices.

PTIF Analysis: The embodied-dominant profile (High-High-Very High) exemplifies PTIF’s prediction that procedural skill learning requires prioritized embodied immersion. The study reported 71% improvement in surgical accuracy and 58% reduction in procedure time. Critically, a comparison condition with identical visuals but reduced haptic feedback (profile High-High-Medium) showed significantly weaker skill transfer to actual surgical performance, providing evidence for embodied immersion as the critical dimension for procedural learning. PTIF explains this finding through embodied cognition theory: surgical skill is fundamentally motor knowledge – residing in muscle memory and haptic intuition – that cannot be fully developed through observation or cognitive instruction alone. The framework would predict that resources invested in even higher visual fidelity without corresponding haptic enhancement would yield diminishing educational returns.

5.3.4. Summary of application examples

These three examples demonstrate PTIF’s utility as both analytical and predictive framework. By characterizing immersive educational interventions in dimensional terms, researchers can identify which aspects of immersion contribute to specific learning outcomes, and educational designers can make principled decisions about resource allocation. The examples reveal that optimal dimensional profiles vary systematically with learning objectives: balanced profiles for integrated conceptual-procedural learning, cognitive-dominant profiles for knowledge acquisition, and embodied-dominant profiles for skill development.

Meta-theoretical analysis of existing studies coded using PTIF dimensions revealed clear patterns in learning effectiveness. Applications with theoretically balanced dimensional profiles appropriate to their learning objectives showed stronger reported effect sizes compared to applications with dimensional imbalances. This pattern held across different educational domains and age groups, supporting PTIF’s emphasis on coherent dimensional design over technical maximization. The finding aligns with Park et al. (2024) meta-analysis showing similar effect size patterns in empirical studies.

Subject-specific analysis revealed theoretically optimal dimensional profiles for different types of learning. Procedural learning (medical procedures, equipment operation) theoretically benefits most from high embodied immersion combined with moderate perceptual fidelity, as the framework predicts that embodied practice is crucial for skill development. Conceptual learning (scientific principles, mathematical relationships) shows theoretical optimal outcomes with balanced cognitive and perceptual immersion but minimal embodied requirements, as abstract concepts may not require physical manipulation. Affective learning objectives (historical empathy, cultural understanding) theoretically require high perceptual and cognitive immersion to create emotional engagement while embodied immersion proves less critical. These theoretical predictions align with domain-specific patterns identified by Tene et al. (2024b) and Haoming and Wei (2024).

Theoretical analysis of cognitive load patterns validated PTIF’s predictions about dimensional interaction effects. The framework predicts that dimensionally coherent immersive education should maintain optimal cognitive load levels throughout learning sessions. In contrast, dimensional mismatches should create cognitive overload patterns: excessive perceptual immersion increasing extraneous load without enhancing germane load, while insufficient cognitive scaffolding leading to disorientation despite technical sophistication. These theoretical predictions align with empirical findings from Poupard et al. (2025) on cognitive load in immersive environments.

Long-term retention analysis provided theoretical support for PTIF’s educational value. The framework predicts that learners experiencing dimensionally balanced immersive education should retain knowledge more effectively due to multiple, reinforcing memory traces across perceptual, cognitive, and embodied systems. This theoretical prediction aligns with empirical findings showing superior long-term retention for well-designed immersive experiences compared to both traditional instruction and poorly designed immersive experiences, as documented by Ghanbaripour et al. (2024).

5.4. Cross-domain theoretical applicability

Theoretical analysis across different educational systems and diverse learner populations demonstrated PTIF’s robustness as a conceptual framework. The dimensional structure proved theoretically applicable across various educational contexts while maintaining sensitivity to contextual differences.

Analysis of literature from different cultural contexts showed that PTIF’s dimensional structure could theoretically accommodate varying educational traditions. Studies from East Asian educational contexts often reported preferences for lower embodied immersion with higher cognitive structure, which PTIF can represent as a specific dimensional configuration rather than a fundamental limitation. Latin American implementations frequently emphasized social features, which the framework accommodates through its recognition of social learning within each dimension. African educational innovations using low-tech immersive experiences could still be meaningfully characterized using PTIF's dimensions, demonstrating that the framework focuses on learning experiences rather than technical specifications. These theoretical applications align with Anwar et al. (2025) observations on cultural adaptation in educational XR.

Theoretical analysis of inclusive education applications revealed PTIF's potential value for designing accessible immersive learning experiences. The framework's dimensional structure allows for theoretical accommodation of different learner needs: students with attention challenges might benefit from reduced perceptual complexity while maintaining cognitive and embodied engagement; learners with motor impairments could experience alternative embodied interactions that preserve agency without requiring precise movements; and students with sensory processing differences would need careful calibration of perceptual immersion to avoid overwhelming stimulation. This theoretical flexibility demonstrates the framework's potential for supporting diverse learner needs while maintaining coherent design principles.

Analysis of multilingual learning contexts presented unique theoretical considerations addressed by PTIF's flexible structure. Language immersion applications theoretically require balancing perceptual authenticity (native speaker audio, cultural visuals) with cognitive scaffolding (comprehensible input, grammatical support) and meaningful embodied interaction (gesture-based communication, virtual conversation practice). The framework's dimensional analysis helps identify theoretical trade-offs and optimization strategies for different proficiency levels. These theoretical insights support Haoming and Wei (2024) systematic review showing the importance of balanced design in language learning applications.

Theoretical analysis of socioeconomic factors using PTIF revealed pathways for equitable immersive education. By analyzing dimensional requirements separately from technical specifications, the framework theoretically demonstrates how educational objectives might be achieved with varied technology access. A dimensional analysis suggests that many learning objectives could theoretically be met with smartphone-based AR achieving moderate levels across all dimensions, rather than requiring high-end VR. This theoretical insight addresses concerns raised by Lysenko and Kachur (2023) about equity in educational technology access.

6. Discussion

6.1. Implications for educational theory and practice

The development and theoretical analysis of PTIF reveals fundamental insights about the nature of immersive learning experiences and their conceptual relationship to educational objectives. Our findings challenge several assumptions prevalent in educational technology research while opening new avenues for theoretical development in the field.

The framework's successful integration of philosophical and technical perspectives demonstrates that meaningful progress in understanding educational immersive technology requires bridging traditionally separate domains of inquiry. Educational immersive experiences emerge from the intersection of human learning processes and technological affordances, requiring integrated theoretical understanding that spans disciplinary boundaries (Bizami et al., 2023; Dengel et al., 2024). PTIF provides a model for such integration, showing how philosophical insights about the nature of learning can inform our understanding of technological implementations while empirical findings can refine theoretical frameworks. This bidirectional relationship suggests that educational technology research should move beyond simple application of existing learning theories to develop new theoretical insights emerging from the unique possibilities of immersive technologies.

Our theoretical analysis reveals that many documented failures in educational immersive technology adoption can be understood through dimensional imbalances rather than fundamental technological or pedagogical limitations. Systems that excel in perceptual fidelity but neglect cognitive scaffolding or embodied interaction often fail to support meaningful learning despite sophisticated technology and well-intentioned learning objectives (Ghanbaripour et al., 2024; Poupard et al., 2025). This theoretical insight has immediate implications for how we conceptualize educational technology development: rather than pursuing maximum technical capabilities, the focus should be on achieving appropriate dimensional balance for specific learning objectives.

The framework's emphasis on embodied immersion addresses a crucial theoretical gap in current educational technology understanding. While visual and auditory immersion receive substantial attention in educational VR/AR research, the role of embodied action in learning remains theoretically underexplored (Döllinger et al., 2021; Mathew & Pillai, 2019). PTIF's analysis suggests that embodied interaction may represent the most distinctive affordance of immersive technologies for education, as it engages learning mechanisms unavailable through traditional media. This theoretical insight suggests reconceptualizing immersive educational technologies not merely as advanced visualization tools but as embodied learning environments that fundamentally alter how we can support skill development and conceptual understanding.

Recent evidence strongly supports these theoretical implications. Burke et al. (2025) analysis of 295 studies found that successful implementations consistently balanced multiple dimensions, while Tene et al. (2024b) demonstrated that dimensional alignment predicted learning outcomes more strongly than technical sophistication. These empirical findings validate PTIF's theoretical foundation while suggesting directions for future research and development.

6.2. Bridging historical pedagogies and contemporary technologies

PTIF's philosophical grounding enables productive theoretical dialogue between established pedagogical traditions and emerging technological possibilities. This bridging reveals both how contemporary technologies can fulfill longstanding educational aspirations and how historical insights can guide modern understanding.

The theoretical continuities between historical and contemporary educational immersion are striking. Modern VR field trips pursue goals remarkably similar to 19th-century stereoscopic geography lessons: transporting students to distant places to build experiential understanding (Lescop, 2017; VRrOOm, 2016). Contemporary AR science applications echo the layered transparencies of historical anatomy texts, revealing hidden structures through technological mediation (Arena et al., 2022). These parallels suggest that fundamental human learning needs transcend specific technologies, manifesting repeatedly across different eras and media. Understanding these continuities helps contextualize current developments within a broader historical trajectory of educational innovation.

However, contemporary immersive technologies also introduce genuinely novel theoretical possibilities without historical precedent. The ability to manipulate time scales allows students to observe geological processes or evolutionary changes in compressed time (Anwar et al., 2025). Perspective-shifting capabilities enable learners to experience molecular interactions from inside a cell or historical events from multiple viewpoints (Sanfilippo et al., 2025). Collaborative virtual spaces permit students from different continents to conduct shared experiments in real-time (Moslavac et al., 2025). PTIF's dimensional structure accommodates these innovations theoretically while maintaining connection to established learning principles, suggesting how novel capabilities can serve timeless educational goals.

The framework reveals that successful contemporary educational systems often unknowingly rediscover principles well-established in earlier pedagogical traditions. Theater-based education has long understood the importance of embodied role-play for developing empathy and understanding multiple perspectives – principles now being “discovered” in VR-based history education (Cole, 2025). Museum educators have decades of experience creating immersive learning environments through careful orchestration of space, narrative, and interaction – expertise highly relevant to virtual museum design (Bekele et al., 2018). PTIF makes these connections explicit theoretically, encouraging educational technologists to learn from established immersive learning traditions rather than approaching each technological innovation as unprecedented.

This historical perspective also reveals cyclical patterns in educational technology adoption that inform theoretical understanding. The initial enthusiasm for educational panoramas in the 1800s, followed by disappointment when they failed to revolutionize education, mirrors contemporary cycles with VR (Islami, 2020). Understanding these patterns theoretically helps set realistic expectations and focus on sustainable integration rather than revolutionary transformation. PTIF’s emphasis on dimensional balance and pedagogical alignment provides a theoretical framework for avoiding historical pitfalls while building on proven successes.

6.3. Theoretical challenges and future directions

While PTIF provides a robust theoretical framework for understanding educational immersive experiences, our analysis also revealed significant challenges that extend beyond the framework itself. These challenges highlight areas requiring further theoretical development and empirical investigation.

The integration challenge represents a fundamental theoretical issue in educational technology adoption. Unlike consumer applications that can be experienced in isolation, educational immersive technologies must integrate with complex educational ecosystems including curricula, assessment systems, and institutional practices (Ogunmakinde, 2025; Spitzer et al., 2022). PTIF provides theoretical guidance on designing coherent immersive experiences but cannot address the broader systemic challenges of educational transformation. This suggests need for complementary theoretical frameworks that address institutional change, teacher professional development, and curriculum evolution in the context of immersive technologies.

Recent systematic reviews confirm these theoretical challenges. Ghanbaripour et al. (2024) identified systemic barriers to implementation, while Beetul et al. (2023) found that technical and pedagogical support systems were often inadequate for sustained adoption. These findings suggest that theoretical frameworks must expand beyond individual technology design to address broader educational ecosystem considerations.

The rapid pace of technological change presents ongoing theoretical challenges. Emerging technologies like AI-enhanced XR, brain-computer interfaces, and quantum computing may fundamentally alter the landscape of immersive education (Lehka et al., 2023; Semerikov et al., 2024a, 2022; Zhang & Li, 2024). While PTIF’s dimensional structure provides flexibility to accommodate new technologies, the framework may need theoretical extensions to address fundamentally new capabilities. For instance, AI-driven adaptive systems that dynamically adjust all three dimensions based on real-time learner state may require new theoretical constructs beyond static dimensional analysis.

Ethical considerations in educational immersive technologies present emerging theoretical challenges inadequately addressed by current frameworks including PTIF. Questions about data privacy, psychological impact of highly immersive experiences on developing minds, and appropriate boundaries for educational content in virtual worlds require theoretical frameworks that integrate ethical reasoning with educational design (Lysenko & Kachur, 2023). The power of immersive technologies to influence beliefs, behaviors, and identity formation in educational contexts demands careful theoretical consideration of ethical boundaries and safeguards.

6.4. Limitations and considerations

Despite its theoretical comprehensiveness, PTIF has limitations that must be acknowledged for appropriate application and future development. These limitations stem from both theoretical choices and the inherent complexity of educational phenomena.

The framework’s three-dimensional structure, while more comprehensive than unidimensional alternatives, still represents a simplification of immersive learning experiences. Our theoretical analysis suggests these three dimensions capture essential aspects, but other potentially important dimensions – such as narrative coherence, social presence, or aesthetic quality – are distributed across the primary dimensions rather than explicitly represented (Suh & Prophet, 2018). Future theoretical development might explore whether additional dimensions would enhance the framework’s explanatory power without sacrificing parsimony.

PTIF’s current theoretical form best suits analysis of structured educational experiences with clear learning objectives. Applications involving emergent learning, creative exploration, or informal education may require additional theoretical considerations beyond the framework’s current scope. While PTIF can characterize these experiences dimensionally, it provides less guidance for understanding learning in open-ended, exploratory contexts. Future theoretical work might address how dimensional optimization differs when learning objectives themselves emerge through exploration.

The framework’s Western educational philosophical grounding, while broad, may not fully capture immersive learning concepts from other educational traditions. Indigenous pedagogies emphasizing place-based learning, contemplative traditions using meditative immersion, or collectivist approaches to shared consciousness in learning represent rich sources of insight not fully integrated into PTIF’s current theoretical structure (Colamatteo et al., 2024). While our analysis showed the framework’s basic applicability across contexts, deeper integration of diverse educational philosophies could enhance its theoretical richness and global relevance.

Finally, the framework’s focus on designed experiences may underemphasize the emergent and unpredictable aspects of learning in immersive environments. Students often discover unintended learning pathways, create their own goals, and derive unexpected insights from immersive experiences. While PTIF can analyze these emergent properties post-hoc, it provides limited theoretical guidance for understanding or fostering productive emergence. This limitation reflects broader challenges in educational theory rather than specific framework shortcomings but suggests areas for future theoretical development.

7. Conclusion

This paper has presented the Philosophical-Technical Immersion Framework for education, a theoretical approach to understanding immersive learning technologies that successfully bridges philosophical foundations with technical considerations. Through systematic theoretical development grounded in learning sciences and validated through comparative analysis, we have demonstrated that meaningful progress in educational immersive technology requires integration of pedagogical and technical perspectives rather than their continued separation.

Our key contribution lies in establishing a three-dimensional classification space – encompassing perceptual, cognitive, and embodied immersion – that provides both theoretical coherence and practical utility for understanding educational applications. The framework’s grounding in educational philosophy and learning theory, validated through systematic analysis of empirical literature, offers a robust theoretical foundation for conceptualizing existing systems and guiding future development. By mapping philosophical concepts to technical parameters while maintaining focus on learning outcomes, PTIF makes theoretical insights actionable for researchers, educators, and developers working with immersive educational technologies.

The comparative analysis with existing frameworks revealed PTIF's superior theoretical coverage, pedagogical alignment, and conceptual clarity for educational contexts. While other frameworks excel in specific domains, none achieve the comprehensive theoretical integration necessary for addressing the full complexity of immersive learning experiences. This integration proves essential for understanding common implementation challenges, from dimensional imbalances that impede learning to technical sophistication that overwhelms pedagogical objectives. Our theoretical analysis of published studies demonstrates how dimensional profiles can predict learning effectiveness, providing a conceptual tool for understanding and potentially improving educational outcomes.

Our findings have important implications for educational theory and practice. The identification of dimensional balance as theoretically crucial for learning effectiveness suggests that educational stakeholders should prioritize coherent design over technical maximization. The framework's emphasis on embodied immersion highlights an underexplored affordance of immersive technologies with particular relevance for procedural and experiential learning. The successful bridging of historical pedagogical wisdom with contemporary technological capabilities provides both theoretical enrichment and practical guidance for creating more effective learning experiences.

Recent evidence from multiple systematic reviews and meta-analyses strongly supports PTIF's core theoretical principles. The consistent finding that dimensional alignment predicts learning outcomes more strongly than technical sophistication validates our approach while suggesting that the framework captures fundamental aspects of how immersive technologies support learning. The framework's successful theoretical application across diverse educational contexts – from K-12 STEM education to professional training to special education – demonstrates its broad relevance and adaptability.

Looking forward, PTIF provides a stable theoretical foundation for navigating the rapidly evolving landscape of educational immersive technologies. While future developments in artificial intelligence, biometric adaptation, and mixed reality will require framework extensions, the core dimensional structure and philosophical grounding offer enduring principles for understanding human learning in immersive environments. As these technologies become increasingly central to education at all levels, theoretically-grounded frameworks that integrate deep understanding of learning with technological possibility become ever more crucial.

The ultimate success of immersive technologies in education depends not on technical specifications but on their alignment with fundamental principles of human learning and development. PTIF provides a theoretical roadmap for achieving this alignment, guiding understanding toward technologies that do not merely surround learners with sensory stimuli but create meaningful experiences that support deep understanding, skill development, and transformative learning. In bridging philosophy and technology, theory and practice, historical wisdom and contemporary innovation, the framework contributes to a more thoughtful and theoretically-grounded approach to educational technology research.

Our work also reveals the magnitude of challenges facing immersive learning technology implementation, from institutional barriers to equity concerns. While PTIF provides powerful theoretical tools for understanding immersive learning experiences, realizing their transformative potential requires systemic changes in educational practice, policy, and infrastructure. These challenges represent opportunities for future research and development, guided by frameworks that maintain focus on learning outcomes while embracing technological innovation.

As we stand at the threshold of a new era in education where physical and virtual learning spaces converge, where AI tutors provide personalized guidance, and where students from around the globe can share immersive learning experiences, the need for thoughtful, theoretically-grounded approaches becomes paramount. PTIF offers one such approach, demonstrating that the future of educational technology lies not in pursuing ever more spectacular technical capabilities but in creating coherent experiences that honor the full complexity of human learning. By maintaining focus on the learner while embracing technological possibility, we can develop theoretical understanding that supports genuinely transformative educational experiences.

The framework's development process has also revealed important insights about the nature of interdisciplinary research in educational technology. Successfully bridging philosophical understanding with technical considerations requires not just knowledge synthesis but genuine theoretical integration that creates new insights. This integrative approach, exemplified by PTIF, suggests a model for future educational technology research that moves beyond application of existing theories to generate new understanding emerging from the intersection of human learning and technological affordance.

CRediT authorship contribution statement

Natalya V. Rashevska: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Serhiy O. Semerikov:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization.

Ethical statement

This study is a theoretical analysis based on systematic literature review and philosophical inquiry. No primary data collection involving human participants was conducted; therefore, Institutional Review Board (IRB) approval was not required. All analyses were based on publicly available published sources as cited in the references.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No primary data was collected for this study. The literature analysis is based on publicly available published sources. The complete list of 127 empirical studies analyzed for framework development is available from the corresponding author upon reasonable request.

References

Adams, E. (2004). Postmodernism and the three types of immersion. URL http://www.designersnotebook.com/Columns/063_Postmodernism/063_postmodernism.htm.

Agrawal, S., Simon, A., Bech, S., Baerentsen, K., & Forchhammer, S. (2019). Defining immersion: Literature review and implications for research on immersive audiovisual experiences. *Journal of Audio Engineering Society*, *68*(6), 404–417. http://dx.doi.org/10.17743/jaes.2020.0039.

Anwar, M. S., Yang, J., Frnda, J., Choi, A., Baghaei, N., & Ali, M. (2025). Metaverse and XR for cultural heritage education: applications, standards, architecture, and technological insights for enhanced immersive experience. *Virtual Reality*, *29*(2), 51. http://dx.doi.org/10.1007/s10055-025-01126-z.

Arena, F., Collotta, M., Pau, G., & Termine, F. (2022). An overview of augmented reality. *Computers*, *11*(2), http://dx.doi.org/10.3390/computers11020028.

Atamuratov, R. K., Majıdova, G. A. Q., Bayjonov, F. B., Ongarov, M. B., & Saydullayev, Z. E. (2024). Opportunities and prospects for the use of immersive technologies in education. In *2024 9th International Conference on Computer Science and Engineering* (pp. 1–6). http://dx.doi.org/10.1109/UBMK63289.2024.10773459.

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., & MacIntyre, B. (2001). Recent advances in augmented reality. *IEEE Computer Graphics and Applications*, *21*(6), 34–47. http://dx.doi.org/10.1109/38.963459.

Beetul, A. V., Rajabalee, Y. B., & Santally, M. I. (2023). Augmented, virtual and mixed realities and their potential in teaching and learning: A systematic literature review. In *2023 IST-africa conference (IST-africa)* (pp. 1–11). http://dx.doi.org/10.23919/IST-Africa60249.2023.10187875.

Bekele, M. K., Pierdicca, R., Frontoni, E., Malinverni, E. S., & Gain, J. (2018). A survey of augmented, virtual, and mixed reality for cultural heritage. *Journal on Computing and Cultural Heritage*, *11*(2), 7. http://dx.doi.org/10.1145/3145534.

Biocca, F., & Levy, M. R. (Eds.), (1995). *Communication in the age of virtual reality*. Hillsdale, New Jersey: Lawrence Erlbaum Associates, Inc., http://dx.doi.org/10.4324/9781410603128.

Bizami, N. A., Tasir, Z., & Kew, S. N. (2023). Innovative pedagogical principles and technological tools capabilities for immersive blended learning: a systematic literature review. *Education and Information Technologies*, *28*(2), 1373–1425. http://dx.doi.org/10.1007/s10639-022-11243-w.

Burke, D., Crompton, H., & Nickel, C. (2025). The use of extended reality (XR) in higher education: A systematic review. *TechTrends*, http://dx.doi.org/10.1007/s11528-025-01092-y.

Chen, X., Zou, D., Xie, H., & Cheng, G. (2021). A topic-based bibliometric review of computers in human behavior: Contributors, collaborations, and research topics. *Sustainability*, *13*(9), 4859. http://dx.doi.org/10.3390/su13094859.

Colamatteo, A., Sansone, M., Pagnanelli, M. A., & Bruni, R. (2024). The role of immersive technologies in cultural contexts: future challenges from the literature. *Italian Journal of Marketing*, *2024*(1), 113–142. http://dx.doi.org/10.1007/s43039-024-00089-4.

Cole, E. (Ed.), (2025). *Bloomsbury studies in classical reception*, *Experiencing immersion in antiquity and modernity: From narrative to virtual reality*. London: Bloomsbury Academic, http://dx.doi.org/10.5040/9781350419124.

Comenius, J. A. (1970). *Orbis sensualium pictus*. Menston, England: The Scolar Press Limited, URL https://archive.org/details/johamoscomeniior00come.

Dengel, A., Steinmaurer, A., Müller, L. M., Platz, M., Wang, M., Gütl, C., Pester, A., & Morgado, L. (2024). Research agenda 2030: The great questions of immersive learning research. In M.-L. Bourguet, J. M. Krüger, D. Pedrosa, A. Dengel, A. Peña Rios, & J. Richter (Eds.), *Communications in computer and information science*: *vol. 1904*, *Immersive learning research network* (pp. 161–172). Cham: Springer Nature Switzerland, http://dx.doi.org/10.1007/978-3-031-47328-9_12.

Dinh, H. Q., Walker, N., Hodges, L. F., Song, C., & Kobayashi, A. (1999). Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments. In *Proceedings IEEE virtual reality* (pp. 222–228). http://dx.doi.org/10.1109/VR.1999.756955.

Döllinger, N., Wienrich, C., & Latoschik, M. E. (2021). Challenges and opportunities of immersive technologies for mindfulness meditation: A systematic review. *Frontiers in Virtual Reality*, *2*, http://dx.doi.org/10.3389/frvir.2021.644683.

Freina, L., & Ott, M. (2015). A literature review on immersive virtual reality in education: state of the art and perspectives. In *ELSE*, *11th international conference eLearning and software for education*. Carol I National Defence University Publishing House, http://dx.doi.org/10.12753/2066-026x-15-020.

Furness III, T. A. (1986). The super cockpit and its human factors challenges. *Proceedings of the Human Factors Society Annual Meeting*, *30*(1), 48–52. http://dx.doi.org/10.1177/154193128603000112.

Ghanbaripour, A. N., Talebian, N., Miller, D., Tumpa, R. J., Zhang, W., Golmoradi, M., & Skitmore, M. (2024). A systematic review of the impact of emerging technologies on student learning, engagement, and employability in built environment education. *Buildings*, *14*(9), 2769. http://dx.doi.org/10.3390/buildings14092769.

Haoming, L., & Wei, W. (2024). A systematic review on vocabulary learning in AR and VR gamification context. *Computers & Education: X Reality*, *4*, Article 100057. http://dx.doi.org/10.1016/j.cexr.2024.100057.

Heilig, M. L. (1962). Sensorama simulator. URL https://patentimages.storage.googleapis.com/90/34/2f/24615bb97ad68e/US3050870.pdf. US Patent #3, 050, 870.

Holloway, R. L. (1995). *Registration errors in augmented reality systems* (Ph.D. thesis), Chapel Hill: University of North Carolina at Chapel Hill, URL https://www.researchgate.net/publication/2381120.

Hönig, W., Milanes, C., Scaria, L., Phan, T., Bolas, M., & Ayanian, N. (2015). Mixed reality for robotics. In *2015 IEEE/RSJ international conference on intelligent robots and systems (IROS)* (pp. 5382–5387). http://dx.doi.org/10.1109/IROS.2015.7354138.

Islami, D. (2020). *Virtual reality – VR Bachelor's thesis*, University for Business and Technology - UBT, URL https://knowledgecenter.ubt-uni.net/etd/1744.

Karthick, G., Rebecca Jeyavadhanams, B., Ling, S., Kiyani, A., & Somasiri, N. (2024). Immersive learning using metaverse: Transforming the education industry through extended reality. In D. K. Sharma, S.-L. Peng, R. Sharma, & G. Jeon (Eds.), *Lecture Notes in Networks and Systems*: *vol. 894*, *Micro-electronics and telecommunication engineering* (pp. 447–456). Singapore: Springer Nature Singapore, http://dx.doi.org/10.1007/978-981-99-9562-2_37.

Keystone View Company (1922). *Visual education: Teachers' guide to keystone "600 set"*. Meadville, PA: Keystone View Company, URL https://ia601201.us.archive.org/2/items/visualeducationt00meaduoft/visualeducationt00meaduoft.pdf.

Kirkwood, A., & Price, L. (2005). Learners and learning in the twenty-first century: what do we know about students' attitudes towards and experiences of information and communication technologies that will help us design courses? *Studies in Higher Education*, *30*(3), 257–274. http://dx.doi.org/10.1080/03075070500095689.

Kuhail, M. A., Abdulkerim, A. Z., Thornquist, E., & Haile, S. Y. (2025). A review on the use of immersive technology in space research. *Telematics and Informatics Reports*, *17*, Article 100191. http://dx.doi.org/10.1016/j.teler.2025.100191.

Kuhail, M. A., ElSayary, A., Farooq, S., & Alghamdi, A. (2022). Exploring immersive learning experiences: A survey. *Informatics*, *9*(4), 75. http://dx.doi.org/10.3390/informatics9040075.

Kurien, A. K., & George, B. (2025). Immersive learning technologies: Potentials and prospects in airport operation courses. In A. Hamdan, & U. Braendle (Eds.), *Studies in systems, decision and control*: *vol. 555*, *Harnessing AI, machine learning, and IoT for intelligent business: volume 1* (pp. 567–577). Cham: Springer Nature Switzerland, http://dx.doi.org/10.1007/978-3-031-67890-5_51.

Lantz, E., Hutton, M., Savage, S., & Ward, C. (1995). Graphics design and production for hemispheric projection. In *Course notes of the 22nd annual conference on computer graphics and interactive techniques (SIGGRAPH '95)*. Los Angeles, CA: Association for Computing Machinery, URL https://web.archive.org/web/20240722151203/https://history.siggraph.org/wp-content/uploads/2021/07/1995-02-Contents-Graphics-Design-and-Production-for-Hemispheric-Proiection.pdf.

Lee, H.-G., Chung, S., & Lee, W.-H. (2013). Presence in virtual golf simulators: The effects of presence on perceived enjoyment, perceived value, and behavioral intention. *New Media & Society*, *15*(6), 930–946. http://dx.doi.org/10.1177/1461444812464033.

Lehka, L. V., Shokaliuk, S. V., & Semerikov, S. O. (2023). Exploring the quantum frontier in school informatics: a pedagogical journey. *Educational Dimension*, *8*, 112–142. http://dx.doi.org/10.31812/ed.576.

Lescop, L. (2017). 360° vision, from panoramas to VR. In T. Maver, P. Chapman, C. Platt, V. Portela, & D. Eaton (Eds.), *Envisioning Architecture: Space / Time / Meaning: The Proceedings of the 13th Biennial International Conference of the European Architectural Envisioning Association at the Glasgow School of Art, 2017* (pp. 226–232). Glasgow, United Kingdom: Mackintosh School of Architecture and the School of Simulation and Visualization at the Glasgow School of Art, URL https://hal.science/hal-01584883.

Lowood, H. E. (2026). Virtual reality. In *Encyclopedia Britannica*. URL https://www.britannica.com/technology/virtual-reality.

Lysenko, S., & Kachur, A. (2023). Challenges towards VR technology: VR architecture optimization. In *2023 13th International Conference on Dependable Systems, Services and Technologies* (pp. 1–9). http://dx.doi.org/10.1109/DESSERT61349.2023.10416538.

Mareorama (1900). The mareorama at the Paris exposition. *Scientific American*, *83*(13), 198. http://dx.doi.org/10.1038/scientificamerican09291900-198.

Mathew, P. S., & Pillai, A. S. (2019). Role of immersive (XR) technologies in improving healthcare competencies: A review. In G. Guazzaroni, & A. S. Pillai (Eds.), *Virtual and augmented reality in education, art, and museums* (pp. 23–46). Hershey, PA: IGI Global Scientific Publishing, http://dx.doi.org/10.4018/978-1-7998-1796-3.ch002.

Mattila, O., Holopainen, J., Hamari, J., & Pöyry, E. (2020). Mixed, augmented, and virtual reality: Co-designed services and applications. In T. X. Bui (Ed.), *Proceedings of the Annual Hawaii International Conference on System Sciences* (p. 1509). IEEE Computer Society Press.

Mayo, H. (1833). *Outlines of human physiology* (3rd ed.). London: Burgess and Hill, URL https://archive.org/details/b33489178/page/n5/mode/2up.

McLellan, H. (2004). Virtual realities. In D. Jonassen, & M. Driscoll (Eds.), *Handbook of research on educational communications and technology: a project of the association for educational communications and technology* (2). New York: Routledge, http://dx.doi.org/10.4324/9781410609519-25.

Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE Transactions on Information Systems*, *E77-D*(12), 1321–1329, URL https://www.researchgate.net/publication/231514051.

Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *Teachers College Record*, *108*(6), 1017–1054. http://dx.doi.org/10.1111/j.1467-9620.2006.00684.x.

Mohsen, M. A., & Alangari, T. S. (2024). Analyzing two decades of immersive technology research in education: Trends, clusters, and future directions. *Education and Information Technologies*, *29*(3), 3571–3587. http://dx.doi.org/10.1007/s10639-023-11968-2.

Moslavac, M., Vlahović, S., & Skorin-Kapov, L. (2025). Towards a unified definition of social XR. In *2025 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)* (pp. 569–573). http://dx.doi.org/10.1109/VRW66409.2025.00121.

Mystakidis, S., & Lympouridis, V. (2023). Immersive learning. *Encyclopedia*, *3*(2), 396–405. http://dx.doi.org/10.3390/encyclopedia3020026.

Nilsson, N., Nordahl, R., & Serafin, S. (2016). Immersion revisited: A review of existing definitions of immersion and their relation to different theories of presence. *Human Technology*, *12*(2), 108–134. http://dx.doi.org/10.17011/ht/urn.201611174652.

Noll, A. M. (1967). Choreography and computers. *Dance Magazine*, *XXXXI*(1), 43–45, URL http://dada.compart-bremen.de/docUploads/noll_choreography_and_computers.pdf.

Noll, A. M. (1972). Man-machine tactile communication. *SID Journal*, *1*(2), 5–11, URL http://noll.uscannenberg.org/PDFpapers/SID%20Tactile.pdf.

Ogunmakinde, O. E. (2025). Design principles for effective virtual reality simulations for teaching construction management courses: A systematic literature review. In M. Sutrisna, M. B. Jelodar, R. Potangaroa, C. Atapattu, & D. A. S. Samarasinghe (Eds.), *Lecture Notes in Civil Engineering*: *vol. 562*, *Creating capacity and capability: embracing advanced technologies and innovations for sustainable future in building education and practice* (pp. 221–233). Singapore: Springer Nature Singapore, http://dx.doi.org/10.1007/978-981-96-1181-2_18.

Park, S., Shin, H. J., Kwak, H., & Lee, H. J. (2024). Effects of immersive technology–based education for undergraduate nursing students: Systematic review and meta-analysis using the grading of recommendations, assessment, development, and evaluation (GRADE) approach. *Journal of Medical Internet Research*, *26*, Article e57566. http://dx.doi.org/10.2196/57566.

Parveau, M., & Adda, M. (2018). 3iVClass: a new classification method for Virtual, Augmented and Mixed Realities. *Procedia Computer Science*, *141*, 263–270. http://dx.doi.org/10.1016/j.procs.2018.10.180, The 9th International Conference on Emerging Ubiquitous Systems and Pervasive Networks (EUSPN-2018) / The 8th International Conference on Current and Future Trends of Information and Communication Technologies in Healthcare (ICTH-2018) / Affiliated Workshops.

Poupard, M., Larrue, F., Sauzéon, H., & Tricot, A. (2025). A systematic review of immersive technologies for education: Learning performance, cognitive load and intrinsic motivation. *British Journal of Educational Technology*, *56*(1), 5–41. http://dx.doi.org/10.1111/bjet.13503.

Prawat, R. S. (1999). Social constructivism and the process-content distinction as viewed by Vygotsky and the pragmatists. *Mind, Culture, and Activity*, *6*(4), 255–273. http://dx.doi.org/10.1080/10749039909524731.

Puentedura, R. R. (2006). Transformation, technology, and education. URL https://hippasus.com/resources/tte/.

Rauschnabel, P. A., Felix, R., Hinsch, C., Shahab, H., & Alt, F. (2022). What is XR? Towards a framework for augmented and virtual reality. *Computers in Human Behavior*, *133*, Article 107289. http://dx.doi.org/10.1016/j.chb.2022.107289.

Rosenblum, L. J., & Cross, R. A. (1997). The challenge of virtual reality. In R. A. Earnshaw, J. Vince, & H. Jones (Eds.), *Visualization & modeling* (pp. 325–399). San Diego, CA: Academic Press.

Sanchez-Acedo, A., Carbonell-Alcocer, A., Gertrudix, M., & Rubio-Tamayo, J. L. (2024). Revealing trends in academic publishing on immersive journalism through a dataset analysis of metaverse and extended technologies from 2017 to 2022. *Data in Brief*, *54*, Article 110263. http://dx.doi.org/10.1016/j.dib.2024.110263.

Sanfilippo, F., Tataru, M., Hua, M. T., Johansson, I. J. S., & Andone, D. (2025). Gamifying cultural immersion: Virtual reality (VR) and mixed reality (MR) in city heritage. *IEEE Transactions on Games*, http://dx.doi.org/10.1109/TG.2025.3553712.

Semerikov, S. O., Foki, M. V., Shepiliev, D. S., Mintii, M. M., Mintii, I. S., & Kuzminska, O. H. (2024a). Methodology for teaching development of web-based augmented reality with integrated machine learning models. In A. E. Kiv, S. O. Semerikov, & A. M. Striuk (Eds.), *CEUR Workshop Proceedings*: *3820*, *Proceedings of the 11th Illia O. Teplytskyi Workshop on Computer Simulation in Education (CoSinE 2024) co-located with XVI International Conference on Mathematics, Science and Technology Education (ICon-MaSTEd 2024), Kryvyi Rih, Ukraine, May 15, 2024* (pp. 118–145). CEUR-WS.org, URL https://ceur-ws.org/Vol-3820/paper249.pdf.

Semerikov, S. O., Vakaliuk, T. A., Mintii, I. S., Hamaniuk, V. A., Bondarenko, O. V., Nechypurenko, P. P., Shokaliuk, S. V., & Moiseienko, N. V. (2023). Designing an immersive cloud-based educational environment for universities: a comprehensive approach. In S. O. Semerikov, & A. M. Striuk (Eds.), *CEUR Workshop Proceedings*: *3844*, *Proceedings of the 6th International Workshop on Augmented Reality in Education (AREdu 2023), Kryvyi Rih, Ukraine, May 17, 2023* (pp. 107–116). CEUR-WS.org, URL https://ceur-ws.org/Vol-3844/paper09.pdf.

Semerikov, S. O., Vakaliuk, T. A., Mintii, I. S., Hamaniuk, V. A., Bondarenko, O. V., Nechypurenko, P. P., Shokaliuk, S. V., & Moiseienko, N. V. (2024b). Immersive cloud-based educational environment of the university: Design principles. In T. A. Vakaliuk, V. V. Osadchyi, & O. P. Pinchuk (Eds.), *CEUR Workshop Proceedings*: *3771*, *Proceedings of the 3rd Workshop on Digital Transformation of Education (DigiTransfEd 2024) co-located with 19th International Conference on ICT in Education, Research and Industrial Applications (ICTERI 2024), Lviv, Ukraine, September 23–27, 2024* (pp. 126–135). CEUR-WS.org, URL https://ceur-ws.org/Vol-3771/paper27.pdf.

Semerikov, S. O., Vakaliuk, T. A., Mintii, I. S., Hamaniuk, V. A., Soloviev, V. N., Bondarenko, O. V., Nechypurenko, P. P., Shokaliuk, S. V., Moiseienko, N. V., & Shepiliev, D. S. (2022). Immersive E-learning resources: Design methods. In *DHW 2021*, *Digital Humanities Workshop* (pp. 37–47). New York, NY, USA: Association for Computing Machinery, http://dx.doi.org/10.1145/3526242.3526264.

Skarbez, R., Smith, M., & Whitton, M. C. (2021). Revisiting milgram and kishino's reality-virtuality continuum. *Frontiers in Virtual Reality*, *2*, http://dx.doi.org/10.3389/frvir.2021.647997.

Slater, M. (2003). A note on presence terminology. *Presence-Connect*, *3*(3), 1–5, URL https://s3.amazonaws.com/publicationslist.org/data/melslater/ref-201/a%20note%20on%20presence%20terminology.pdf.

Southgate, E., & Smith, S. P. (2017). Designing and conducting research using immersive technologies in schools: Seven observations. In *2017 IEEE virtual reality workshop on K-12 embodied learning through virtual & augmented reality (KELVAR)* (pp. 1–3). http://dx.doi.org/10.1109/KELVAR.2017.7961564.

Spitzer, B. O., Ma, J. H., Erdogmus, E., Kreimer, B., Ryherd, E., & Diefes-Dux, H. (2022). Framework for the use of extended reality modalities in AEC education. *Buildings*, *12*(12), 2169. http://dx.doi.org/10.3390/buildings12122169.

Suh, A., & Prophet, J. (2018). The state of immersive technology research: A literature analysis. *Computers in Human Behavior*, *86*, 77–90. http://dx.doi.org/10.1016/j.chb.2018.04.019.

Sutherland, I. E. (1968). A head-mounted three dimensional display. In *AFIPS '68 (fall, part I)*, *Proceedings of the December 9–11, 1968, fall joint computer conference, part i* (pp. 757–764). New York, NY, USA: Association for Computing Machinery, http://dx.doi.org/10.1145/1476589.1476686.

Swallow, M., & Zulu, S. L. (2025). Investigating the implementation of immersive technologies within on-site construction safety processes. *Journal of Engineering, Design and Technology*, *23*(1), 323–343. http://dx.doi.org/10.1108/JEDT-01-2023-0005.

Sweller, J., Ayres, P., & Kalyuga, S. (2011). Cognitive load theory. *Explorations in the learning sciences, instructional systems and performance technologies*: *vol. 1*, New York, NY: Springer, http://dx.doi.org/10.1007/978-1-4419-8126-4.

Syrovatskyi, O. V., Semerikov, S. O., Modlo, Y. O., Yechkalo, Y. V., & Zelinska, S. O. (2018). Augmented reality software design for educational purposes. In A. E. Kiv, S. O. Semerikov, V. N. Soloviev, & A. M. Striuk (Eds.), *CEUR Workshop Proceedings*: *2292*, *Proceedings of the 1st Student Workshop on Computer Science & Software Engineering, Kryvyi Rih, Ukraine, November 30, 2018* (pp. 193–225). CEUR-WS.org, URL https://ceur-ws.org/Vol-2292/paper20.pdf.

Tene, T., Guevara, M., Moreano, G., Vera, J., & Vacacela Gomez, C. (2024a). The role of immersive virtual realities: Enhancing science learning in higher education. *Emerging Science Journal*, *8*, 88–102. http://dx.doi.org/10.28991/ESJ-2024-SIED1-06.

Tene, T., Marcatoma Tixi, J. A., Palacios Robalino, M. d., Mendoza Salazar, M. J., Vacacela Gomez, C., & Bellucci, S. (2024b). Integrating immersive technologies with STEM education: a systematic review. *Frontiers in Education*, *9*, http://dx.doi.org/10.3389/feduc.2024.1410163.

VRrOOm (2016). The epic story of cinéorama, VR cinema's ancestor. URL https://web.archive.org/web/20171027025052/https://www.vrroom.buzz/vr-news/entertainment/epic-story-cineorama-vr-cinemas-ancestor.

Weng, A. K.-W., Chang, H.-Y., & Lai, K.-K. (2023). Research trends in immersive technology in the field of entertainment or games by bibliometric analysis. In *2023 IEEE 13th International Conference on Consumer Electronics - Berlin (ICCE-berlin)* (pp. 129–134). http://dx.doi.org/10.1109/ICCE-Berlin58801.2023.10375685.

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence*, *7*(3), 225–240. http://dx.doi.org/10.1162/105474698565686.

Zhang, S., & Li, W. (2024). Applying eXtended Reality(XR) technology in commerce, management, and business applications: A survey. In *2024 4th International Conference on Computer, Control and Robotics* (pp. 108–113). http://dx.doi.org/10.1109/ICCCR61138.2024.10585599.