An Edu-Metaverse framework to foster knowledge gain and retention

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Abstract

My research investigates the design and effectiveness of Edu-Metaverses, i.e., persistent, multi-user, virtual learning environments leveraging Extended Reality technologies, with the aim of addressing both learners' and educators' perspectives to develop evidence-based guidelines for effective Edu-Metaverses. My first user study, conducted within an Edu-Metaverse I developed, reveals that collaborative learning significantly improves the acquisition and retention of concise cultural heritage knowledge compared to individual exploration. Other achieved results showed how locomotion techniques influence learning outcomes, showing that teleportation-based methods enhance vocabulary learning while minimizing simulator sickness. From a technical standpoint, we optimized path planning algorithms to support scalable navigation in complex virtual environments, laying the groundwork for future integration of autonomous agents and multi-user interactions inside Edu-Metaverses. My research also identified future research areas related to embodiment, adaptive content delivery, and feedback mechanisms for both educators and learners, along with broader possibilities in AI-enhanced pedagogical tools. Building on this, I propose a draft framework to guide educators, developers, and institutions in creating scalable Edu-Metaverses to improve knowledge acquisition, retention, and engagement across diverse educational contexts.

Keywords

Edu-Metaverse, Extended Reality, Virtual Learning Environments, Immersive Learning, Knowledge Gain, Knowledge Retention, Educational Technology, User Interaction in VR, User Studies

1. Introduction

The rapid evolution of Extended Reality (XR) technologies has expanded educational possibilities [1, 2]. By overcoming the limitations of space and time found in traditional learning environments, XR offers tools to engage learners and deliver educational content effectively [1, 3, 4, 2]. More recently, within this broader technological landscape, Edu-Metaverses [5, 6, 7, 8, 9] have emerged as a promising paradigm for improving educational experiences though shared, persistent, and decentralized multi-user virtual environments (VEs) [5, 7, 10, 8, 9, 11].

While XR technologies' effects and their positive impact on learning are well-established in the literature [4, 12, 13, 2], Edu-Metaverses represent an advancement, creating persistent, dynamic, collaborative virtual learning spaces [5, 9, 14, 15]. However, it remains unclear whether the educational benefits and design principles of XR that are well known in the literature transfer directly to Edu-Metaverse contexts [7, 8]. As this paradigm evolves, its effectiveness may differ across various scenarios, populations, and implementations, highlighting the need for user studies to determine its strengths and weaknesses.

My contribution is a structured, dual perspective (learners' and educators') framework that extrapolates lessons learned from user studies to guide effective construction of Edu-Metaverse learning environments that promote improved knowledge acquisition and retention across diverse learning contexts and scenarios. To this purpose, my work seeks to establish evidence-based design principles that leverage the unique possibilities of Edu-Metaverses while acknowledging their distinct characteristics and similarities to XR applications.

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2. Related Work

The Metaverse has gained attention in recent years (see Mystakidis [16]), with a growing interest in the industry, especially after Facebook's 2021 rebranding as Meta [15, 17]. Although the idea first appeared in science fiction (see Neal Stephenson's 1992 book [18]), it has gradually shaped into a more tangible concept. As a result, researchers are looking into the Metaverse as a promising tool in many fields. In education specifically, this has led to the Edu-Metaverse paradigm [5], which technologically consists of persistent, multi-user decentralized digital platforms where the primary objective is learning, and with additional educational capabilities compared to traditional learning like user interaction, community building, and creative collaboration [5, 7, 9, 17, 19, 20].

The Edu-Metaverse is opening up new possibilities for education by taking learning beyond traditional classrooms and linear teaching methods [5, 9, 15, 21]. This paradigm facilitates innovative pedagogical approaches grounded in interactive engagement, immersive learning environments, and collaborative knowledge construction [5, 10, 8, 15, 21].

To realize its potential, researchers have developed multiple frameworks. Wang et al. [5] have proposed a framework to guide the design and growth of Edu-Metaverse platforms, highlighting the need for a broad view that considers technical, educational, and social components. Sin et al. [10] emphasize the importance of grounding Edu-Metaverse design in multiple theoretical foundations, including constructivism (see Sjøberg [22]), immersive learning theory (see Gibson [23]), visual literacy [10], and collaborative learning [8, 10]. Bobko et al. [7] contribute to this foundation by proposing a 3D ecosystem model to foster learner-centered innovation through modular, scalable, and interactive environments. Other recent studies have explored the emerging potential and limitations of Edu-Metaverse platforms. Chen et al. [9] comprehensively analyze the main research trends and collaboration networks in Metaverse-based education. Li et al. [8] focus on the empirical validation of enabling technologies for collaborative learning in Edu-Metaverses, emphasizing technical robustness and user-centered design.

Beyond more theoretical frameworks, recent research has produced concrete Edu-Metaverse applications and domain-specific systems [15, 9]. These range from immersive science labs and language learning platforms to collaborative virtual classrooms and training simulations [6, 9, 14, 15, 19, 24]. While these examples demonstrate the potential of Edu-Metaverse technologies, they also expose possible gaps in instructional coherence, scalability, and educator support [5, 15, 17, 25]. These new challenges, along with opportunities [25], point to factors that extend beyond the well-documented benefits of XR in education [4, 2, 12, 13, 26, 27]. Furthermore, it is necessary to better understand how well-established XR-related psychological and experiential factors (e.g., presence, social presence, cognitive load, usability, and simulator sickness) may affect learning outcomes [28, 29] (both immediate knowledge gain and long-term retention) inside Edu-Metaverses, thus highlighting the need to account for both technological tools and their psychological and pedagogical impacts.

However, existing frameworks acknowledge significant limitations in bridging theory and practice [5, 7, 10] and applications often emerge from technological possibilities rather than educational needs [9, 15]. Peña-Rios and Wu [25] highlight a gap in frameworks connecting technical capabilities with pedagogical needs. In fact, few studies have considered how these immersive environments influence both learner and educator perspectives. My framework addresses this by linking theory to practice and providing concrete design guidelines for effective Edu-Metaverse learning experiences.

3. Proposed Framework

To address the lack of integrated pedagogical and technical models (see Peña-Rios and Wu [25]) in immersive learning, I propose a dual-perspective Edu-Metaverse framework, considering both XR capabilities [1, 3, 2, 27] and foundational educational theories [30], as well as considering core design elements of Edu-Metaverses [5, 7, 10] (see Figure 1).

From the **learners' perspective**, the framework is rooted in constructivist learning theory [22], which emphasizes active, contextualized knowledge construction through social interaction, and incorporates its application within Edu-Metaverse environments [10]. It is further informed by the Cognitive Affective Model of Immersive Learning (CAMIL), which links cognitive aspects influenced by XR technologies with learning outcomes [28]. Among the key potentialities and challenges on this side are the effects of content type (e.g., discursive and concise), VE locomotion, embodiment (of self and others), avatar representation, collaborative learning dynamics, and social learning dynamics. I am addressing this aspect considering their relation with experiential dimensions intrinsic to XR technologies, such as presence, social presence, cognitive load, motivation, and the importance of interaction within the VEs (see Makransky and Petersen [28] and Makransky and Lilleholt [29]). The framework integrates varied content types with gamification and adaptive learning, all supported by feedback systems. To ensure meaningful interaction even in low-population Edu-Metaverse settings, we propose the concept of "bootstrapping the Metaverse" based on AI-driven agents in the same VE as learners to simulate peer interactions and sustain collaborative dynamics.

From the **educators' perspective**, the framework helps instructional innovation through tools such as AI-assisted content creation and AI-based topic modeling [31, 32], enabling faster preparation of immersive lessons while supporting consistency and alignment with curricular goals. It supports learning performance evaluation and instructional control (e.g., pacing and sequencing) to optimize the effectiveness of learning sessions. Although Edu-Metaverses are often conceptualized as primarily learner-centric environments [5, 7], my framework emphasizes the expanded role of educators not only as facilitators, but also as active creators of content and participants within the learning process [7, 20]. The framework, from this perspective, also examines how key elements such as embodiment, presence, and social presence affect teaching effectiveness (considering the CAMIL model [28]). Educators can also leverage direct gamification and adaptive learning, as well as provide contextual feedback and coherent, continuous communication to learners adapted to their educational needs [9]. The framework also supports hybrid learning ecosystems (via the concept of "bootstrapping the Metaverse") by integrating AI agents that simulate teaching assistants or peer collaborators, compensating for the limited human presence inside, yet scarcely populated Edu-Metaverses.

This framework combines established theories on XR, learning science, and educational technologies with practical insights, drawn from our user studies, to support the design of effective Edu-Metaverse experiences, thus avoiding focus on specific hardware implementations and possibly adapting to evolving XR technologies. The goal is to ensure that Edu-Metaverses enhance educational outcomes by improving knowledge gain, retention, and transfer of learning, both formal and informal (see Ainsworth and Eaton [33]), while fostering collaboration, creativity, and critical thinking.

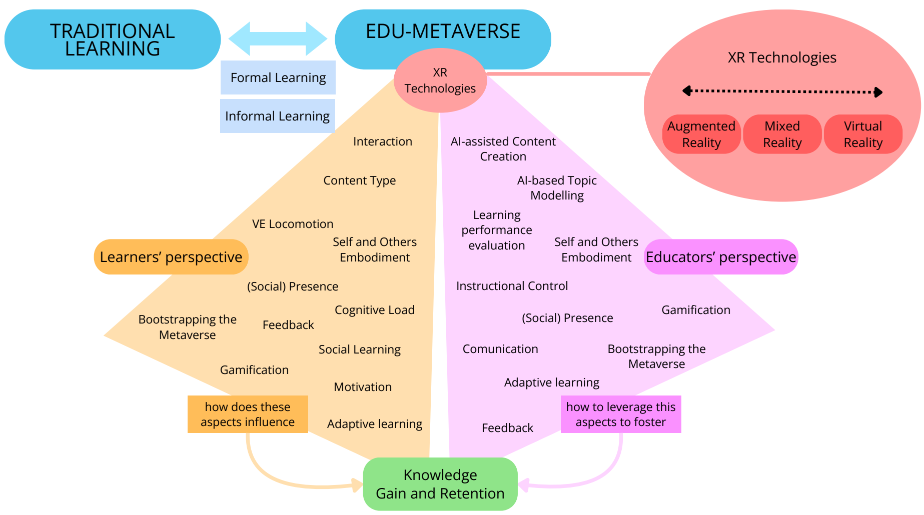

Figure 1: Conceptual scheme of the proposed Edu-Metaverse framework for fostering knowledge gain and retention, illustrating key components, learners' and educators' perspectives, and influencing factors within the research scope.

4. Results so far

My efforts to develop an evidence-based Edu-Metaverse framework began by focusing on a core subset of this broader research agenda. Specifically, I have explored several key components related to the learner experience. Three studies have been completed and are ready for submission.

In my first study I developed an immersive VR Edu-Metaverse reconstructing a North-East Italy rural area to evaluate how collaborative learning impacts cultural heritage knowledge acquisition. I investigated whether collaborative learning boosts content retention compared to individual learning and for which content type. Results show that collaborative learning significantly benefits concise content, where users activated more objects, while discursive content showed no difference. Social presence was higher in collaborative conditions, while no statistically significant difference was found for the sense of presence. These findings indicate that immersive collaboration improves learning when information is concise and easily shareable between peers, highlighting the need to organize knowledge into manageable chunks inside Edu-Metaverses in informal learning scenarios.

The second study examined how locomotion techniques affect cultural heritage learning in immersive VR. Native Italian speakers learned dialect vocabulary about rural objects from the Natisone Valleys in a virtual environment populated with autonomous agents simulating a collaborative experience. Three conditions were tested: teleportation, arm-swing, and "lerport" (teleportation for self with continuous movement visualization for others). Teleportation significantly improved vocabulary retention, reduced simulator sickness compared to arm-swing, and enhanced presence over lerport. No significant differences were found in social presence, satisfaction, or usability, supporting teleportation as an effective technique for cultural learning in immersive VR and potentially inside Edu-Metaverses.

The third study developed a framework for generating VE, extracting navigation meshes, and comparing pathfinding algorithms across 1.5 million instances. Results indicate that Best-First Search is a resource-efficient alternative to A*, while BFS balances path quality and computational speed. These findings could enhance agent navigation (especially on resource-constrained standalone XR devices) in scalable Edu-Metaverses, supporting our proposed concept of "bootstrapping the Metaverse".

5. Ongoing and Future Work

Ongoing research focuses on expanding and refining the proposed Edu-Metaverse framework, which will be validated through user studies across diverse educational contexts.

A key ongoing effort deploys an implementation of Edu-Metaverse based on the proposed framework to compare immersive VR classrooms with traditional lecture in class, using low-cost head-mounted displays in formal education. This comparison assesses Edu-Metaverse's impact on engagement, knowledge retention, and instructional effectiveness. In parallel, I investigate how embodiment (self and others) affects learning, focusing on avatar representation, non-verbal communication, and interactions. Additional work centers on designing and validating AI-assisted tools for educators, enabling content generation, adaptive sequencing, and instructional feedback within immersive VEs.

Future research will propose the concept of "bootstrapping the Metaverse", integrating AI-driven agents with real Edu-Metaverse users to ensure persistent interaction even in scarcely populated Edu-Metaverses or individual learning contexts. Additionally, I aim to develop adaptive learning tools for educators to provide educational content based on behavioral and performance data. I will also conduct user studies to evaluate the effectiveness of traditional learning approaches and different XR technologies (e.g., virtual vs. augmented reality), comparing traditional methods against XR technologies as well as the two XR technologies, one against the other, within Edu-Metaverses.

6. Conclusions

My doctoral research proposes an Edu-Metaverse framework grounded in empirical evidence from multiple user studies. The results so far demonstrate that collaborative learning enhances knowledge acquisition for concise content, that teleportation-based locomotion optimizes vocabulary learning while maintaining user comfort, and that efficient pathfinding algorithms effectively support scalable multi-agent environments.

The proposed framework bridges technical capabilities with pedagogical needs by addressing learner and educator perspectives. It emphasizes that successful Edu-Metaverses require careful orchestration of multiple interdependent elements.

My doctoral thesis will apply a revised version of the proposed framework, grounded in my research results, to define guidelines and design principles for building effective Edu-Metaverses.

Declaration on Generative AI

During the preparation of this work, the author used ChatGPT-4o and Grammarly for grammar and spelling checks, writing style improvements, and paraphrasing and rewording, in line with the GenAI Usage Taxonomy at https://ceur-ws.org/GenAI/Taxonomy.html. After using these tools, the author reviewed and edited the content as needed and takes full responsibility for the publication's content.

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