Editorial on the Special Issue on Extended Realities 2025: The Long Road to Unlocking Alluring Treasures

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Abstract: Virtual Reality (VR) and Augmented Reality (AR) technologies are increasingly integrated into education across diverse contexts, from primary schools to higher education and vocational training. The collection associated with this editorial provides insights from eleven recent studies on VR/AR-enhanced learning, including systematic reviews, experimental designs, and case studies in resource-constrained environments. The articles in the collection have been organized into three key clusters of research: (1) reviews and taxonomies that attempt to structure the rapidly evolving field, (2) empirical studies in higher education testing immersive and collaborative platforms, and (3) practice-oriented case studies that apply AR in trades and indigenous communities. While the findings of the articles highlight significant potential for motivation, collaboration, and inclusivity, issues such as methodological fragmentation, small sample sizes, and cost barriers remain persistent challenges in conducting VR/AR experiments. We argue that future work must move beyond isolated case studies toward integrated curricula, inclusive frameworks, and cost-effective solutions to ensure that VR and AR become sustainable, reliable tools in education.

Keywords: Virtual reality, Augmented reality, Education, Computational thinking, Indigenous communities, Higher education, Systematic review, Inclusive learning

1. Introduction

Johnson-Glenberg (2018) emphasizes that extended realities (XR), such as augmented reality (AR) or virtual reality (VR), add didactic value when the two core affordances are used: presence (feeling "there") and embodied interaction (gestures/manipulation in 3D). A similar observation has been made in the Cognitive Affective Model of Immersive Learning (CAMIL, Makransky & Petersen, 2021) by stating that the perceived feeling of presence and agency are the key affordances of immersive learning. Affordances (Gibson, 2014) of learning technologies are educationally meaningful options for action and perception that digital media open up for learners and teachers. They result from the interaction of technology, learning context, and user skills (Kirschner, 2002). Subsequently, the design of XR learning scenarios along the unique affordances of VR is being called for (Froehlich, Plass and Homer, 2025). Examples of affordances in the medical field—one of the frontrunners for the educational use of XR—include authentic 3D simulations of critical situations, automated feedback, high interactivity, emotional involvement, automated feedback, objective performance evaluation, immersive presence, risk-free training without danger to anyone involved, and multiple repetitions of complex situations (Jiang *et al.*, 2022; Wu *et al.*, 2022; Neher *et al.*, 2025). One example of how affordances can be exploited is that XR is particularly strong when it comes to spatial-procedural learning objectives. Reviews consistently find that XR is particularly suitable for training (Xie *et al.*, 2021), spatial understanding (Gittinger and Wiesche, 2024; Yang *et al.*, 2025), abstract or invisible phenomena (e.g., molecules, fields) (Alnagrat *et al.*, 2022; Emma, 2026), and contexts that are difficult to access, dangerous or expensive in real life (Alnagrat *et al.*, 2022; Gil Parga *et al.*, 2024; Malungana and Chimbo, 2024)

For guiding the meaningful design of XR learning tools, models of learning with XR have been established, which then also result in design guidelines that are organized in so-called frameworks. Not to be forgotten is the extension of the Cognitive Theory of Multimedia Learning (CTML), which has been supplemented by the Immersion Principle (Mayer, 2024). Other models and frameworks include Meaningful Immersive VR Learning (M-iVR-L) (Mulders, Buchner and Kerres, 2020), the XR-Ed Framework (Yang, Zhou and Radu, 2020), and the Immersive Virtual Reality Pedagogical Model (iVRPM) (Bicalho, Piedade and Matos, 2025). With particular reference to the pivotal role of affordances, one of the most influential models of immersive VR learning, the

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CAMIL (Makransky and Petersen, 2021), focuses on presence and agency as core affordances and interest, motivation, self-efficacy, embodiment, cognitive load, and self-regulation as factors influencing learning processes in immersive VR.

The considerations outlined above indicate XR is a particularly instruction-design-intensive medium. A prominent trend is the transfer of proven multimedia instructional principles to XR (Çeken and Taşkın, 2022), including segmentation (Wyssenbach, Kaufmann and Schwaninger, 2025), signaling (Albus, Vogt and Seufert, 2021), cues (Weerasinghe *et al.*, 2022), pre-training (Huang, 2018; Buchner, Buntins and Kerres, 2022; Nurjanah and Retnowati, 2024), or guided tasks (Herbert *et al.*, 2022; Liao *et al.*, 2024). An example is a framework that combines CTML (Cognitive Theory of Multimedia Learning) principles with immersive VR specifics and derives concrete guidelines from them (Mulders, Buchner and Kerres, 2020). More recent syntheses explicitly collect evidence-based design and didactic principles for educational VR, including signaling, guidance, interaction design, and assessment (Radianti *et al.*, 2020; Won *et al.*, 2023; Steindorff *et al.*, 2024; Zackoff, Klein and Real, 2024; Oje, Hunsu and Fiorella, 2025).

Having seen impressive technical achievements in recent years, this Special Issue now enumerates insights that have been gained in XR-related teaching/learning research since 2018. The articles have been organized into three key clusters of research: (1) reviews and taxonomies that attempt to structure the rapidly evolving field, (2) empirical studies in higher education testing immersive and collaborative platforms, and (3) practice-oriented case studies that apply AR in trades and indigenous communities.

2. Cluster 1: Reviews and Taxonomies

Reviews and taxonomies help to structure the (still) fragmented field of VR and AR research. Recent reviews have looked more closely at specific target groups (e.g., special education) and derived requirements for adaptability, accessibility, overload avoidance, and supportive forms of interaction. In the review by (Wehrmann and Zender, 2024), a framework for inclusive VR learning applications has been developed based on the Universal Design for Learning framework. It emphasizes the need to design VR environments that accommodate diverse student populations in K–12 education. (Bisswang *et al.*, 2023) provide a taxonomy of VR use cases in higher education. Their classification offers both researchers and practitioners a systematic foundation for further design and evaluation. Reviewing 25 empirical studies, (Fadillah *et al.*, 2025) compare AR and VR in fostering computational thinking skills. It highlights AR's greater prevalence and VR's strong immersive qualities, while also pointing to high costs and device limitations as obstacles. (Walstra, Cronje and Vandeyar, 2023), again, analyzed 100 articles across twelve countries, to capture teachers' perceptions of VR in primary schools. Teachers acknowledge the motivational potential of VR but also note practical barriers such as infrastructure and training gaps.

3. Cluster 2: Empirical Studies in Higher Education

Given this continuous development of theoretical and technical foundations and the rapidly growing number of studies in recent years (Jiang *et al.*, 2022; Tudor Car *et al.*, 2022; Wu *et al.*, 2022), this Special Issue focuses on empirical studies related to virtual platforms that enable collaborative learning, which is an effective strategy zur Förderung von u.a. tiefem Verständnis, Motivation, sozialer Kompetenz und Lernleistung (Makransky and Petersen, 2023; Khan, 2024; Montag *et al.*, 2025). The mixed-method study in this Special Issue by (Wong *et al.*, 2024) explores the Classlet metaverse platform with students in Hong Kong and Thailand. Results suggest positive effects on learners' intention to use immersive environments, though technological hurdles persist. Comparing Gather.town-based discussions with face-to-face learning, the quasi-experimental study by (Rayyan *et al.*, 2024) finds comparable or even improved outcomes in language learning. It demonstrates the potential of virtual discussion platforms in foreign language teaching. Through a case study, the work of (Foster, Barth and Chaudhry, 2024) evaluates platforms such as Topia and WorkAdventure. The study reveals that educators' technological self-efficacy is a decisive factor in adoption and effective use. The study by (Averbeck *et al.*, 2024) compares VR headsets for collaborative activities with 360° video integration for reflection in social work education. Both approaches proved pedagogically valuable, albeit with different strengths. Finally, surveying 321 respondents in Indonesia, (Binowo *et al.*, 2023) apply structural equation modeling to understand continued use of virtual education exhibitions. Findings underline the importance of perceived usefulness and flow experiences for sustained adoption.

4. Cluster 3: Practice-Oriented AR Case Studies

Case studies can pave the way for deriving larger research questions based on particularly unique fields of learning, or bringing insight into areas which have rarely been investigated (yet). In the case study by (Beltrán and Huertas, 2023) mobile AR-based learning environment for carpentry skills among the Wayuu community in Colombia has been designed. Despite the small sample, results show that AR can provide effective vocational training in marginalized settings. Extending their earlier work, the authors implement in another article the AR application in a structured carpentry course with twelve participants, showing that AR can enhance skill acquisition and foster learner engagement (Beltrán Alvarado, 2024).

In summary, this special issue's body of work demonstrates that VR and AR are no longer confined to experimental pilots but are on the brink to mainstream education. From primary schools to indigenous vocational programs, these technologies are diversifying learning environments and expanding pedagogical possibilities. Further, the findings highlight significant potential specifically for motivation, collaboration, and inclusivity. Yet, significant challenges remain. The field is marked by small-scale studies, heterogeneous platforms, cost barriers and inconsistent, fragmented evaluation methods (e.g., (Martella *et al.*, 2026)). Systematic reviews and taxonomies offer structure but cannot substitute for coherent theoretical models. Future research must therefore prioritize – amongst others – inclusivity, scalability, and cost-effectiveness. Developing integrated curricula, fostering digital self-efficacy among educators, and lowering technological barriers will be crucial. Such measures would be crucial for moving VR and AR beyond fragmented niches to become transformative, equitable tools in global education.

5. Concluding Remarks

Finally, the scientifically based design of XR learning tools and their use have made great strides in recent years, as the contributions in this Special Issue notably demonstrate. XR learning tools are capable of being extremely powerful when utilized in accordance with their affordances. However, it must also be noted that there is still much work to be done before XR learning is fully understood. For instance, there is still a need to investigate the extent to which XR learning tools (and other complex learning tools) are subject to the same principles as those established in the Cognitive Theory of Multimedia Learning. Some of these principles have been proven, while others have been contradicted by findings (e.g., the reversal of the modality principle (Albus and Seufert, 2023)). XR also seems to prevail where the high cost of establishing XR learning tools can be offset by a comparative advantage, i.e., where the use of XR learning tools generates the greatest benefit through specific affordances. A comparative advantage is evident, for example, when excursions are made possible virtually through VR environments, resulting in massive cost savings (Spangenberger and Söbke, 2025). But even if the costs of creating and using XR learning tools can be reduced, there is still a comparative advantage, for example in 360°-based desktop VR excursions (Wolf *et al.*, 2023). A comparative advantage is also met where one would be exposed to danger or where it would not be possible to have certain experiences without VR. Given this continuous development of theoretical and technical foundations and the rapidly growing number of studies in recent years (Jiang *et al.*, 2022; Tudor Car *et al.*, 2022; Wu *et al.*, 2022), the potential impact of future technological advances, such as AI, warrants further investigation.

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