Scaling Virtual Classrooms: Overcoming Barriers to Learning Analytics in VR

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Abstract

This paper explores the challenges and solutions for scaling virtual reality (VR) classrooms, with a focus on implementing effective learning analytics (LA). Using a narrative literature review, the study identifies key barriers, including technical challenges, cost implications, and usability concerns. Technical obstacles such as data integration issues and hardware limitations are addressed through innovations like semantic web tools and cloud offloading. Cost-related barriers are mitigated through low-cost VR solutions and institutional collaboration, while usability challenges are tackled with learning analytics-enhanced VR platforms that provide real-time feedback and user-centered designs. The findings emphasize the need for interdisciplinary collaboration and sustainable strategies to ensure scalable, inclusive, and impactful VR classrooms for diverse educational contexts.

Keywords

virtual reality, virtual classrooms, scalability, learning analytics

1. Introduction

Efforts to make education accessible across distances date back to the mid-19th century, when Sir Isaac Pitman, an English educator, introduced a novel approach: correspondence courses delivered by mail [1]. This allowed students, regardless of their location, to receive structured instruction, a groundbreaking concept at the time. Pitman's system of learning exchange and feedback through written correspondence opened the door to distance learning and made education available beyond the traditional classroom setting. Since Pitman's pioneering courses, remote education has continued to evolve, from radio broadcasts to online platforms, ultimately laying the foundation for today's immersive VR learning environments.

The emergence of virtual classrooms in VR represents a significant advancement in distance education, which offers students a level of interaction and engagement that was previously unattainable in traditional online formats [2]. Unlike video conferencing, which can feel detached, VR classrooms provide an immersive sense of presence that allows students to feel as if they are actively participating in a shared physical space [3]. This setting enables hands-on experiential learning activities that were once limited to physical classrooms. This enriches the educational experience and bridges the gap between remote and in-person learning [4]. Platforms like VirtualClassroom illustrate how VR can support dynamic real-time interactions between students and educators, which in turn enhance engagement and depth in the learning process [5].

Virtual classrooms in VR settings have great potential to create more personalized and flexible learning experiences [6]. These environments allow students to progress at their own pace, adapt their learning paths to meet individual goals, and modify their educational journey to suit their needs. This adaptability can create a more inclusive learning environment by accommodating different learning styles and needs, while also encouraging collaborative learning [6]. Students can participate in group projects, discussions, and resource sharing within a virtual space, collaborating with peers across geographical

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boundaries [7]. Such capabilities position VR classrooms as a powerful tool for expanding access to quality education, especially in contexts where traditional physical classrooms may be impractical or inaccessible [6].

Despite the clear advantages of VR classrooms, achieving scalability remains a significant challenge [8]. Scaling these environments requires more than simply expanding VR access; it involves addressing a range of complex barriers that impact the practical implementation of VR on a larger scale. One of the primary requirements for scaling VR classrooms is the development of effective learning analytics systems that can track and evaluate student progress in immersive settings [9]. However, the current state of learning analytics within VR faces various technical and practical challenges, including processing the extensive data generated by VR applications, which requires substantial computational power and can push existing hardware to its limits [10]. These technical demands can lead to accessibility issues, especially for institutions with limited resources, such as smaller schools or those in underfunded regions.

Furthermore, scaling VR classrooms requires user-friendly interfaces that serve diverse user groups, allowing educators and students to navigate these systems easily [11]. Effective interfaces are essential to improve usability and ensure that VR classrooms are accessible to all participants, regardless of their technological background. However, solutions such as TeachInVR and V-Classroom, while advancing VR-based education, also reveal the challenges of integrating comprehensive and scalable analytics tools into immersive platforms [12, 5]. These issues show the need for solutions that address not only technical requirements, but also pedagogical considerations to ensure that VR classrooms can support a wide range of learning styles and environments [13].

The purpose of this study is to explore the technical and practical challenges involved in scaling VR classrooms. Through a narrative literature review, this paper examines key technical barriers, including high bandwidth needs, cost implications, and infrastructure requirements, which impact the scalability and accessibility of VR-based education. In addition, it analyzes specific challenges associated with VR learning analytics, such as data collection and integration, and pedagogical and usability concerns. By identifying and evaluating strategies to address these barriers, this study aims to provide actionable information and propose paths to more scalable, inclusive, and effective VR classrooms that can support data-driven information to enhance learning outcomes.

This paper contributes to the learning analytics community by addressing the challenges created by immersive VR environments and proposing innovative solutions that advance the integration of analytics into emerging educational technologies. Its findings are crucial for shaping scalable practices that support learning analytics to optimize engagement, accessibility, and outcomes in VR classrooms and offer valuable guidance to researchers, educators, and policymakers.

2. Methodology

This narrative literature review aims to examine the challenges and potential solutions associated with scaling virtual classrooms in VR environments, with a focus on implementing effective learning analytics. A narrative approach was selected for its flexibility in synthesizing a wide range of studies and identifying emerging patterns or themes. This methodology facilitates the inclusion of diverse perspectives, allowing for a comprehensive exploration of complex issues like the scalability of VR in education, where multiple factors and solutions intersect.

To gather relevant literature, an exploratory search was conducted using Google Scholar with keywords such as ”scaling education,” ”learning analytics in VR,” and ”VR classrooms.” Articles were screened by reviewing abstracts to ensure alignment with the review’s focus on scalability and the application of learning analytics. Additionally, the quality of the studies was assessed to confirm they met basic publication standards [14].

To ensure a broad and inclusive review, the snowball technique was employed. References cited in selected studies were examined to identify further relevant literature, helping to capture studies that might not have been identified in the initial search. This iterative process enriched the review by uncovering additional insights and perspectives. Studies were ultimately selected based on their relevance to the challenges and solutions highlighted in the literature, particularly those offering concrete strategies for overcoming barriers and scaling VR classrooms effectively.

After selecting the relevant studies, the articles were organized into three primary themes:

1. Technical barriers to scaling virtual classrooms in VR: This theme addresses the core technical obstacles that impact the scalability of VR classrooms. It includes an exploration of high bandwidth requirements and the need for efficient data transmission strategies.
2. Cost implications and infrastructure investment: This theme addresses the financial challenges of scaling VR classrooms, including high initial costs for hardware, software, and infrastructure, as well as ongoing maintenance and training expenses. It highlights strategies to help institutions manage these costs, making VR adoption more practical and sustainable in education.
3. Challenges in scaling learning analytics in VR: This theme examines the challenges of integrating learning analytics within VR environments, which are essential to monitor and improve educational outcomes. Key issues include data collection, integration within VR systems, and the development of user-friendly and pedagogically meaningful interfaces.

The findings were synthesized within these themes to identify common barriers and evaluate the proposed solutions in the literature. This thematic organization offers a comprehensive view of the multifaceted challenges involved in scaling VR classrooms and highlights potential paths to improve accessibility, scalability, and the effectiveness of VR-based education. By organizing the analysis thematically, the paper ensures a structured approach that enables a clearer understanding of how specific challenges and solutions are interrelated [15].

3. Analyzing the themes

3.1. Technical barriers to scaling virtual classrooms in VR

Incorporating VR technology into various educational settings presents an opportunity for changes that can create highly immersive and interactive learning experiences. However, the practical implementation and widespread adoption of virtual reality classrooms face significant limitations that restrict their scalability. This section provides an examination of the technical barriers to scaling VR classrooms. We will also provide solutions that have the potential to mitigate these significant challenges and support the scalable deployment of VR classrooms in educational environments.

3.1.1. High bandwidth needs

VR applications are inherently data intensive, requiring substantial bandwidth to support the transmission of high-resolution content in real time [16]. For example, VR applications using 360-degree video can require bandwidths ranging from 15 to 400 Mbps depending on the quality and resolution [16, 17]. Wireless transmission of frames from Graphics Processing Units (GPUs) to VR headsets requires dedicated high-bandwidth connections to ensure flawless performance and minimize latency-induced disturbances [18]. Additionally, the continuous streaming of high-definition visuals, coupled with interactive elements essential to the VR experience, places significant pressure on network infrastructure [19]. This demand for bandwidth not only impacts the design of VR systems, but also requires advancements in networking technologies, such as 5G and Wi-Fi 6, to effectively meet these requirements [20].

Another important factor increasing bandwidth demands is viewport dependency. In VR environments, users typically view only a small portion of the entire panorama at any given moment. However, to maintain a seamless experience, the system must continuously stream the entire 360-degree view, regardless of which segment the user is currently focusing on [17]. This necessity results in increased data transmission, as the network must handle the full panorama to anticipate user movements and ensure that adjacent areas are ready for immediate display as the user shifts their view [17].

In educational settings where multiple VR headsets are used simultaneously, these bandwidth demands multiply, which means that more reliable and higher-capacity network capabilities are needed. The simultaneous operation of several high-bandwidth VR sessions can pressure existing network infrastructures and lead to potential performance bottlenecks and reduced user experiences [21].

3.1.2. Overcoming bandwidth challenges in scalable VR

Addressing scalability challenges for high bandwidth requirements in the VR classroom involves implementing innovative technological solutions that optimize data transmission and support advanced computational resources. One promising approach is tiled streaming technology, which according to research, significantly reduces bandwidth consumption by focusing data transmission on the specific segments of the VR panorama that users are actively viewing [17]. Instead of streaming the entire 360 degree environment, tiled streaming dynamically adjusts to stream only visible tiles, thereby lowering overall data requirements while maintaining high video quality [17]. This targeted method not only enhances bandwidth efficiency but also allows educational institutions to support a larger number of simultaneous VR users without overburdening their network infrastructure.

In addition to tiled streaming, cloud offloading offers another effective strategy by supporting cloud computing resources to handle intensive processing tasks that would otherwise burden local devices [22]. By offloading computationally demanding tasks, such as rendering high-resolution graphics and managing real-time interactions, educational institutions can reduce the processing and battery constraints on individual VR headsets [22]. This approach optimizes network performance by distributing the processing load and ensures that VR experiences remain smooth and responsive, even as the number of concurrent users increases [21]. Cloud offloading thus enhances the scalability of VR applications and enables educational environments to expand their VR-based learning offerings without necessitating extensive local hardware upgrades.

Wireless VR systems face additional challenges in maintaining high bandwidth, as conventional wireless connections often struggle to meet the demands of VR streaming. Solutions like FoVR have been developed to address these challenges by supporting gaze tracking to prioritize content delivery, effectively reducing bandwidth costs by up to 88.9% [20]. By focusing on the user's gaze direction, FoVR delivers high-quality content only where it is needed, minimizing data transfer for areas outside the user's focus. This solution enables VR systems to operate more efficiently within existing bandwidth limitations and supports larger-scale deployment in educational settings.

These solutions offer a scalable path for VR education that allows institutions to accommodate high-bandwidth VR applications while preparing for future demands in immersive learning experiences.

3.2. Cost implications and infrastructure investment

Implementing VR technology in educational settings requires financial investments beyond the initial acquisition of hardware and software. These costs consist of the establishment of specialized facilities, network upgrades, staff training, and ongoing maintenance. Understanding these financial barriers is crucial for educational institutions that want to scale VR classrooms effectively.

3.2.1. High initial costs

Integrating VR technology into educational settings presents significant financial challenges, mainly due to the substantial upfront investments required for specialized infrastructure [23]. Research highlights considerable variability in costs associated with different aspects of VR systems [24]. The financial investment needed for VR technology can vary widely, depending on factors such as hardware sophistication, software quality, and the specific educational application [25]. Entry-level systems, which offer basic functionalities at a lower price point, make VR more accessible for casual users and educational institutions with limited budgets. For example, research shows that a basic VR setup with two sensors and six degrees of freedom can be assembled for less than $4,000, providing smaller institutions with an affordable option for immersive experiences [26]. These cost-effective systems play

Table 1
Barrier-Solution Matrix for High Bandwidth Needs

Barrier	Description	Impact	Solution
High bandwidth requirements	VR applications require 15-400 Mbps for real-time, high-resolution content transmission [16].	Limits simultaneous users and strains network infrastructure.	Implementing 5G/Wi-Fi 6, optimize data transmission [20].
Viewport dependency	Continuous streaming of full panorama to anticipate user movements [17].	Increases data transmission needs.	Using tiled streaming to focus on visible segments [17].
Multiple users in education	Multiple VR headsets operating simultaneously multiply bandwidth demands [21].	Strains existing network infrastructures.	Deploying cloud offloading to distribute processing load [22].
Wireless VR systems	Conventional wireless connections struggle to meet VR streaming demands [20].	Limits bandwidth efficiency and increases costs.	Using FoVR to support gaze tracking for prioritized content delivery to reduce bandwidth by up to 88.9% [20].

a vital role in expanding access to VR in education and helping more institutions explore and adopt this technology.

In contrast, high-end VR setups require significant financial investment and are generally reserved for specialized professional environments such as gaming studios, architectural firms, and medical training facilities [27]. These advanced systems, which feature immersive graphics, precise tracking, and specialized equipment, require a higher upfront cost. Moreover, the establishment of dedicated VR laboratories, complete with motion tracking systems and safety measures, is essential to create secure and effective learning environments, but requires a much larger financial commitment [28]. For example, the University of Sydney invested in a VR lab equipped with 26 Oculus Rift units and additional equipment that illustrates the scale and expense required for a fully immersive VR setup [28]. Although exact costs were not specified, this example shows the financial challenges that high-quality VR education creates, particularly for smaller institutions with constrained budgets.

3.2.2. Ongoing maintenance and operational costs

Beyond the initial setup, maintaining VR infrastructure sustains continuous costs that can significantly affect institutional budgets. Regular maintenance of VR equipment is essential to ensure longevity and functionality, which includes repairs, software updates, and replacements of outdated hardware [29]. For example, maintenance costs include software updates to keep VR systems current, hardware repairs to address wear and tear, and component replacement to maintain optimal performance [28]. In addition, operational expenses such as electricity, software licensing fees, and technical support services further add to the financial burden. A notable example of these ongoing costs is the calculation of AU$19.50 per student visit in a VR lab, which highlights the continuous operational expenses required to sustain VR programs [28]. These recurring costs make it challenging for educational institutions to maintain VR programs over the long term without financial support, and limits the sustainability and scalability of VR-based learning initiatives.

3.2.3. Training and implementation costs

Training educators and staff to effectively use VR technology is crucial for the successful implementation of VR programs in educational settings. For example, Danielson et al. [29] estimated that the implementation preparation costs for VR training programs in schools amount to approximately $1,427 per school, with additional non-labor costs of $100 per trainee. This financial investment is crucial to ensure that educators are not only proficient in the technical aspects of VR, but also adept at integrating VR into the curriculum to enhance educational outcomes.

The need for comprehensive teacher training and ongoing support is also a recurring theme in the literature. For example, in the context of the adoption of VR in Indian schools, Swargiary et al. [30] emphasized that effective training programs are vital to maximize the educational benefits of VR technology. Without adequate training and support, the integration of VR into curricula may not meet its intended impact, which demonstrates the importance of allocating sufficient resources to comprehensive training programs [31]. Proper training transforms VR from a novel tool into a valuable component of the educational experience and allows educators to use its full potential.

3.2.4. Strategies to overcome financial constraints

According to research, educational institutions have employed various effective strategies to mitigate these financial constraints that focus on supporting cost-effective solutions, using existing resources, and promoting collaborations to enhance scalability.

One primary strategy involves using low-cost VR solutions. Research showed that institutions have adopted mobile VR headsets that use smartphones as the primary computing device, significantly reducing costs compared to traditional VR headsets [32]. Furthermore, the use of affordable VR viewers like Google Cardboard has been highlighted as a practical method to provide immersive experiences without substantial financial investment [33]. Several schools have integrated Google Cardboard into their classrooms, which offers VR experiences at a fraction of the cost of high-end VR systems, allowing greater access to immersive learning and supporting the scalability of VR programs [32].

Another effective approach is the development of Open Educational Resources (OER). According to research, creating and sharing VR content freely reduces the need for expensive established software. For example, the University of Nottingham Ningbo China successfully implemented this strategy by developing a virtual field trip as an OER [34]. This initiative allowed the university to provide immersive learning experiences to a larger number of students without incurring additional software licensing costs, thus enhancing the scalability and sustainability of their VR programs [34].

The bounded adoption strategy is also an essential strategy in scaling VR classrooms. This strategy focuses financial resources on content development rather than hardware acquisition, which in turn maximizes the impact of limited budgets [35]. For instance, some institutions have invested in developing VR curricula and educational modules that can be accessed using existing hardware. This allows them to extend the reach of their VR initiatives without requiring extensive hardware purchases [35]. This targeted allocation of resources ensures that VR programs can scale effectively across various educational platforms.

Collaboration and resource sharing offer another viable solution to overcome financial barriers. According to research, collaborations between institutions, libraries and other educational entities make it easier to share resources, thus reducing individual costs [36]. Academic libraries, for example, have been helpful in providing access to VR technologies and resources, making it more feasible for smaller or less funded schools to implement VR programs [36]. By combining resources, institutions can share the costs associated with purchasing and maintaining VR equipment, thus supporting the scalability of VR classrooms across different educational settings.

Furthermore, integrating existing technologies is a cost-effective strategy that improves scalability [37]. Institutions have integrated virtual reality into existing technology education labs, using software and hardware already available for other educational purposes, such as computer-assisted design programs. According to Tiala et al. [37], a university engineering department could use existing high performance computers and software licenses to support both drafting programs and VR simulations, thus maximizing the utility of their current infrastructure. This approach minimizes additional costs and facilitates the expansion of VR programs without the need for significant new investments.

Table 2
Barrier-Solution Matrix for Cost Implications and Infrastructure Investment

Barrier	Description	Impact	Solution
High initial costs	Significant upfront investments for specialized infrastructure, including high-resolution displays, GPUs, and VR laboratories, making VR adoption costly for institutions with limited budgets [28].	Limits adoption of VR in education.	Using low-cost VR solutions, such as mobile VR headsets and affordable viewers like Google Cardboard, to reduce hardware expenses and enable broader access to VR [32, 33].
Ongoing maintenance and operational costs	Continuous costs for maintaining VR equipment, software updates, and operational expenses like electricity and technical support, which strain institutional budgets [17].	Creates sustainability challenges.	Establishing a dedicated budget for regular maintenance and integrating VR with existing technologies, such as shared labs or high-performance computers, to optimize resource use [28, 37].
Training and implementation costs	Financial investment needed for training educators and staff to effectively use and integrate VR technology into the curriculum, ensuring educational benefits [29].	Limits effective implementation.	Providing comprehensive training programs and adopting Open Educational Resources (OER) to create accessible VR content without significant licensing costs [29, 34].
Financial constraints and limited budgets	Budget constraints limit the ability to invest in high-end VR systems and sustain ongoing costs, impeding widespread adoption and scalability [30].	Restricts scalability.	Implementing collaborative resource-sharing initiatives that focus on content development with bounded adoption strategies, and integrating existing technologies to minimize additional costs [35, 36, 37].

3.3. Challenges in scaling learning analytics in VR

The integration of learning analytics into VR classrooms is essential to understand and improve student participation, providing educators with actionable insights to improve the learning experience [38]. However, implementing scalable approaches to data collection and integration in VR presents significant challenges. These challenges come from the limitations in collecting and managing complex data generated within immersive environments, as well as pedagogical and usability concerns that affect the design and adoption of analytics systems [4]. This section examines the barriers to implementing effective learning analytics in VR classrooms and explores innovative solutions that can address these challenges.

3.3.1. Technological limitations in scaling learning analytics

Scaling VR classrooms requires strong approaches to address the technical barriers that block the effective integration of learning analytics into immersive environments. A key challenge is the limitation of data collection and integration within VR platforms. Unlike traditional web-based systems, VR environments inherently restrict the opportunities to capture and integrate comprehensive learning data, which is critical for meaningful analytics [39]. The immersive nature of VR, while improving student engagement, complicates systematic tracking of user interactions and behaviors, as conventional methods are not suitable to handle the rich multidimensional data generated in these settings [39].

Another major problem is the complexity of the VR systems themselves. Developing VR applications that incorporate learning analytics requires extensive programming knowledge and technical expertise. This complexity can act as a significant barrier for educators and developers, particularly those without the necessary skills or resources to design and implement advanced VR-based systems [40]. Without user-friendly development frameworks or accessible tools, the widespread adoption of scalable VR classrooms remains constrained.

Hardware and software limitations further worsen these challenges. Users often face issues with VR hardware, such as headsets, controllers, and sensors, which can impact the accuracy and reliability of data collection [41]. Additionally, software interactions within VR can be bulky, with design limitations often blocking seamless data capture. These limitations not only affect the quality of the analytics data, but also reduce the overall usability and effectiveness of VR systems for educational purposes [41].

Finally, the fragmented landscape of VR platforms adds to the difficulty of scaling VR classrooms. The diversity of VR applications and systems leads to inconsistencies in data standards and formats, making it challenging to build cohesive learning analytics frameworks. As Elmoazen et al. [42] highlights, this lack of standardization delays the integration of data across platforms and limits the ability of educators and researchers to generate actionable insights or scale solutions effectively. Addressing these technical barriers is essential to unlock the full potential of VR classrooms and ensure their scalability for diverse educational contexts.

3.3.2. Strategies to overcome technical learning analytics challenges

To address the technical challenges of data collection and integration in VR classrooms, semantic web tools and ontologies provide a strong solution to improve scalability [38]. Semantic Web technologies enable interoperability by creating structured frameworks to organize and link data across various VR platforms. According to Abad-Troya and Cadme-Samaniego [38], ontologies can represent course structures, such as those used in MOOCs, allowing data from various VR applications and learning management systems to be seamlessly integrated. This standardization is critical to overcome the fragmented landscape of VR platforms, which enables educators and researchers to access and analyze data consistently. In doing so, they can monitor, assess, and improve student learning experiences on a larger scale.

Moreover, semantic web tools ease the transformation of unstructured VR data—such as user interactions and spatial movements—into structured formats that are easier to process and analyze [38]. This interoperability reduces barriers created by inconsistent data formats and fragmented systems, making it feasible to aggregate and use data from multiple platforms. The ability to load these data into RDF (Resource Description Framework) repositories further enhances accessibility and allows educational institutions to create centralized knowledge bases that support advanced querying and visualization. Such tools enable instructors to provide timely feedback and adapt their teaching strategies to meet the needs of growing and diverse VR classroom populations [38]. By addressing both data complexity and platform fragmentation, semantic web tools and ontologies offer a scalable foundation for effective learning analytics in VR classrooms.

3.3.3. Pedagogical and usability challenges

Scaling learning analytics in VR classrooms demands environments that are both pedagogically effective and user-friendly, as the success of VR training depends on delivering meaningful, engaging learning experiences. The design of VR activities plays a crucial role in meeting educational objectives. As Santamaría-Bonfil et al. [43] highlight, creating meaningful VR activities requires a deep understanding of the subject matter and VR technology. Achieving a balance between immersive engagement and structured educational content is critical to support learning analytics in accurately assessing student progress [43]. However, achieving this equilibrium is complex and requires maintaining learner engagement while meeting educational outcomes.

A key challenge is providing timely and relevant feedback in VR environments. Learning analytics must interpret complex interactions, such as gestures, spatial movements, and collaboration, and translate these into actionable insights for students and educators. Wang et al. [44] emphasize that effective feedback is essential for reinforcing learning, but as Heinemann and Schroeder [40] note, designing systems to deliver intuitive and pedagogically meaningful feedback remains a challenge.

Usability and user experience are also crucial. For VR-based learning analytics to scale effectively, platforms must be accessible to users with varying levels of digital literacy. Usability issues—such as unintuitive navigation and complex interfaces—can hinder engagement and limit the impact of learning analytics [41]. Addressing these issues requires prioritizing accessible design to ensure VR tools are intuitive and effective for diverse learners [43].

Finally, scaling VR classrooms necessitates strong support structures for both teachers and students. Teachers need training to interpret learning analytics data, adapt teaching strategies, and utilize dashboards effectively [45]. Students, likewise, need guidance to use feedback data and navigate VR environments. As Heinemann and Schroeder [40] suggest, scaling VR classrooms requires new pedagogical approaches and dependable support systems to ensure learning analytics enhance rather than complicate education. Without these foundations, the potential for scalable VR classrooms remains limited.

3.3.4. Strategies to overcome pedagocial and usability challenges

A promising solution to these pedagogical and usability challenges is the use of learning analytics-enhanced VR content creation platforms, such as LAVR [44]. These platforms enable students to engage in creative, analytics-supported learning experiences by developing VR stories or simulations and receiving real-time feedback on their progress and content quality [44]. This feedback reinforces learning and allows instructors to monitor engagement and adapt their teaching strategies effectively. LAVR also simplifies classroom management with features for structuring activities, assignments, and assessments, making it easier for educators to provide targeted feedback and support individual learning paths. By combining creativity, structure, and real-time analytics, these platforms address key pedagogical concerns while enhancing student engagement. In addition, the intuitive and user-centered design of this tool overcomes usability barriers, allowing students to explore and create without technological challenges. By aligning learning analytics with accessible content creation, platforms like LAVR foster inclusive and scalable VR classrooms that enhance both engagement and educational outcomes [44].

4. Results and conclusion

The purpose of this study was to explore the technical and practical challenges involved in scaling VR classrooms, with a particular focus on the implementation of effective learning analytics. Through a narrative review of the literature, the study identified and analyzed key barriers under three main themes: technical challenges, costs and infrastructure investments, and challenges in scaling learning analytics in VR.

The findings revealed several critical barriers. Technical challenges, including high bandwidth demands, fragmented VR platforms, and hardware limitations, highlight the need for advanced technological solutions such as tiled streaming, cloud offloading, and semantic web tools. These innovations offer potential pathways to address data transmission inefficiencies and improve the integration of various VR systems.

Cost implications and infrastructure investments emerged as another significant obstacle, including high initial setup costs, ongoing maintenance, and the need for educators. training. Strategies such as adopting low-cost VR solutions, adopting open educational resources (OER), and creating collaborations among institutions were identified as effective ways to mitigate financial barriers and support scalable VR implementations.

Table 3
Barrier-Solution Matrix for Scaling Learning Analytics in VR

Barrier	Description	Impact	Solution
Data collection and integration	VR environments limit comprehensive data capture and integration [39].	Block meaningful analytics insights and progress monitoring.	Semantic web tools to standardize data and enable integration across platforms [38].
Complexity of VR systems	High technical expertise is required to develop VR analytics systems [40].	Restricts adoption by educators and developers with limited resources.	Accessible development tools and frameworks [40].
Feedback mechanisms	Providing real-time, relevant feedback in VR is complex [44].	Reduces students' ability to improve and adapt.	Learning analytics platforms to deliver actionable feedback [44].
Usability challenges	Difficult navigation and interfaces reduce engagement [41].	Prevents effective use of analytics insights.	User-centered VR platforms with intuitive design [44].

Finally, challenges in scaling learning analytics in VR were linked to limitations in data collection, pedagogical design, and usability concerns. Solutions such as learning analytics-enhanced VR platforms, like LAVR, demonstrate the potential to improve data capture, provide meaningful feedback, and create user-centered design to enhance the scalability and inclusivity of VR classrooms.

In conclusion, this paper shows the need for interdisciplinary collaboration between educators, technologists, and policy makers to effectively address these barriers. Using innovative technologies and sustainable strategies, VR classrooms can become more scalable, inclusive and impactful, ensuring equitable access to high-quality education in immersive settings. Future research should focus on the practical implementation of these solutions, evaluating their effectiveness in real-world educational contexts to further advance the potential of VR in education.

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