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(REVIEW ARTICLE)

Impact of virtual reality and augmented reality technologies on biology education: A review

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Abstract

The integration of virtual reality (VR) and augmented reality (AR) technologies into biology education represents a transformative approach to addressing the complexities inherent in biological concepts. This comprehensive review synthesises current research on the efficacy of VR and AR in enhancing student engagement, conceptual understanding, and spatial awareness in biology education. While evidence suggests that these immersive technologies can foster deeper learning and motivation, findings regarding their overall effectiveness compared to traditional teaching methods are mixed. Factors such as cognitive load, individual learner differences, and technical challenges significantly influence outcomes. The review examines applications across various biology subdisciplines, including anatomy, cellular biology, ecology, and genetics, highlighting successes and limitations. Furthermore, it explores the potential of VR and AR to facilitate collaborative and personalised learning experiences while acknowledging the inherent challenges of cost, content development, and integration into existing curricula. Critical analysis revealed that while these technologies offer unique visualisation and interaction opportunities, their educational value is contingent upon thoughtful implementation and alignment with pedagogical objectives. Future research directions emphasise the need for adaptive technologies, innovative assessment methods, and long-term studies to fully leverage the educational benefits of VR and AR in biology education. This review underscores the importance of a balanced approach that considers both the potential and limitations of immersive technologies in enhancing biology education.

Keywords: Augmented reality; Biology education; Educational technology; Pedagogical methods; Student engagement; Virtual reality

1. Introduction

The integration of virtual reality (VR) and augmented reality (AR) technologies into biology education represents a significant shift in pedagogical practices, driven by the need for innovative approaches to enhance learning outcomes. As the complexity of biological concepts increases, traditional teaching methods often fall short in effectively conveying intricate details and fostering student engagement. VR and AR offer immersive experiences that can transform how students interact with biological content, allowing for deeper understanding and retention of knowledge. Research has shown that VR and AR can significantly improve learning efficiency and student engagement in various educational contexts. For instance, a study by Zhou and colleagues [1] highlighted the effectiveness of VR and AR in enhancing the learning experience of biological microscopy, demonstrating that students using these technologies exhibited improved comprehension of complex structures compared to those relying solely on conventional methods.

Additionally, the use of VR in biology education has been linked to increased motivation and interest among students, as it provides interactive and visually stimulating environments that traditional classrooms may lack [2]. The application of VR and AR technologies in biology education is not limited to higher education; K-12 educators are

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increasingly adopting these tools to create engaging lesson plans that facilitate experiential learning. For example, immersive experiences allow students to explore the human body or observe cellular processes in real time, bridging the gap between theoretical knowledge and practical application [3]. This shift towards experiential learning is particularly important in biology, where many concepts are abstract and challenging to visualise without the aid of technology.

Moreover, the potential of VR and AR extends beyond mere visualisation; these technologies can foster collaborative learning environments where students can work together in virtual spaces, enhancing their communication and teamwork skills [2]. The ability to manipulate three-dimensional models and conduct virtual experiments in a safe and controlled environment further enriches the educational experience, making complex biological processes more accessible and understandable [4] [3]. This review examines the current state of VR and AR implementation in biology education by analysing their impacts, benefits, challenges, and future potential.

1.1. Overview of VR and AR Technologies in Education

Virtual reality refers to computer-generated simulations of three-dimensional environments that can be interacted with in seemingly real ways using specialised electronic equipment, such as head-mounted displays. Augmented reality, on the other hand, overlays digital information onto the real world, typically through smartphone or tablet applications. Both technologies have gained significant traction in educational contexts due to their ability to create immersive, interactive learning experiences. In biology education specifically, VR and AR offer unique advantages [1] [3]:

- Visualisation of complex biological structures and processes
- Virtual field trips and laboratory experiences
- Interactive simulations of microscopic and macroscopic phenomena
- Safe exploration of otherwise dangerous or inaccessible environments

2. Impact on Student Learning Outcomes

2.1. Conceptual Understanding

The integration of virtual reality (VR) and augmented reality (AR) technologies into biology education has sparked considerable interest, particularly regarding their impact on students' conceptual understanding of complex biological concepts. While numerous studies suggest that these immersive technologies can enhance learning outcomes, the evidence is not uniformly positive and presents a nuanced landscape of findings [1] [3] [4] [5] [6]. Moro et al. [5] conducted a study comparing the effectiveness of VR and AR in anatomy education to traditional teaching methods. They found that VR and AR were equally effective in improving student learning outcomes. However, a critical examination of their methodology revealed limitations, including a small sample size and a short duration of the intervention, which may undermine the generalizability of their findings. The authors acknowledged that while students reported increased engagement, the actual improvement in conceptual understanding was not as pronounced as anticipated [5].

In contrast, Parong and Mayer [7] examined the use of immersive VR in biology education and found that students who learned using traditional PowerPoint slides outperformed those who utilised VR on immediate posttests. This study raises important questions about the efficacy of VR as a learning tool. While VR may provide an engaging experience, it does not necessarily translate to better conceptual understanding. The authors suggest that the cognitive load associated with VR environments may hinder learning as students struggle to process the immersive content effectively [7].

Further complicating the narrative, [8] reported that high school students using VR to learn about human organs demonstrated improved learning efficiency compared to traditional methods. However, they also noted that prolonged use of VR could lead to discomfort, such as dizziness, which could detract from the learning experience. This finding aligns with the concerns raised by other researchers about the physical limitations of VR technology and its impact on learning outcomes [5] [7]. The mixed results highlight the importance of considering individual differences among students. For instance, some learners may thrive in immersive environments, while others may find traditional methods more effective. Research by Liu et al. [9] emphasised that students with higher spatial abilities tend to benefit more from VR experiences, suggesting that the effectiveness of these technologies may vary based on learners' cognitive profiles.

2.2. Spatial Awareness and Visualisation Skills

The potential of VR and AR to enhance spatial awareness and visualisation skills in biology education is frequently cited as a significant advantage. Paxinou et al. [10] reported improved spatial understanding and visualisation skills among students using a three-dimensional virtual reality biology lab. Their findings suggest that VR can facilitate a deeper comprehension of spatial relationships in biological structures, which is crucial for topics like anatomy and cellular biology.

However, it is essential to note that not all students benefit equally from these technologies. Individual differences in spatial ability and cognitive load can significantly impact the effectiveness of VR and AR in improving spatial awareness. Research by Hegarty [11] indicates that students with lower spatial abilities may experience increased cognitive load in immersive environments, potentially leading to frustration and disengagement. This variability suggests that while VR can enhance learning for some, it may hinder it for others, necessitating a more tailored approach to its implementation in educational settings.

2.3. Engagement and Motivation

Many studies reported increased engagement and motivation when using VR and AR technologies, yet these claims warrant critical examination [6] [9] [10] [11]. The novelty effect, as described by Clark [12], suggests that initial increases in engagement may stem from the newness of the technology rather than its inherent educational value. Long-term studies are essential to determine if the reported increases in engagement and motivation are sustained over time. Makransky et al. [13] found that while students reported higher levels of presence and enjoyment in immersive VR compared to desktop VR, they learned less and experienced a higher cognitive load.

This paradox highlights the need to balance engagement with effective learning design. The authors argue that while immersive experiences can be captivating, they must be carefully designed to avoid overwhelming the students and detracting them from their learning. Moreover, Liu et al. [9] emphasised that engagement does not always correlate with improved learning outcomes. Their findings indicate that while students may find VR experiences enjoyable, this does not guarantee a deeper understanding of the material. This disconnect raises questions about the pedagogical effectiveness of VR and suggests that educators must prioritise learning objectives over mere engagement [9].

2.4. Retention and Transfer of Knowledge

The impact of VR and AR on knowledge retention and transfer remains a contentious study area. While some researchers [14] [15] reported improved knowledge retention compared to traditional teaching methods, others have found no significant difference or negative effects. This inconsistency in results underscores the need for more rigorous, long-term studies to establish the true impact of these technologies on knowledge retention and transfer.

A meta-analysis by Merchant et al. [16] found that the effectiveness of virtual reality-based instruction on learning outcomes has been mixed. Some studies showed positive effects, while others demonstrated no significant difference between VR and traditional methods. This variability suggests that the context in which VR is implemented, including the subject matter and the specific design of the VR experience, plays a crucial role in determining its effectiveness [16].

2.5. Learning Efficiency

Claims of improved learning efficiency through VR and AR technologies should be scrutinised carefully. Zhou et al. [1] reported enhanced learning experiences in biological microscopy using these technologies. However, it is essential to consider the additional time and resources required to implement VR and AR in educational settings. The cost-benefit ratio of these technologies regarding learning efficiency remains controversial. Kassutto et al. [8] also highlighted that while students reported higher satisfaction with VR learning experiences, the actual time spent learning did not significantly decrease compared to traditional methods. This raises concerns about whether the investment in VR technology translates into more efficient learning or merely shifts the nature of the learning experience without enhancing overall efficiency.

2.6. Collaborative Learning

The potential of VR and AR to foster collaborative learning environments is often touted as a significant advantage. However, Bower et al. [17] highlighted that effective collaboration in virtual environments requires careful design and facilitation. Simply providing a virtual space does not guarantee meaningful collaboration; in some cases, technical issues can hinder rather than enhance collaborative learning experiences.

For instance, a study by Liu et al. [9] found that while students appreciated the collaborative aspects of VR, they also encountered challenges related to communication and coordination in virtual spaces. This suggests that while VR has the potential to facilitate collaboration, educators must be mindful of the design and implementation of these environments to ensure that they genuinely support collaborative learning [9] [16].

2.7. Personalised Learning

While the potential for personalised learning experiences through VR and AR is promising, the current state of technology and content development limits the extent of true personalisation. Most VR and AR applications in biology education offer the same content to all users, with limited adaptation to individual learning needs. Developing genuinely adaptive VR and AR systems for biology education remains a significant challenge [17].

Research by Huang et al. [4] indicates that while personalised learning is a key benefit of AR technologies, most existing applications do not adequately address individual differences among learners. This gap highlights the need for further research and development to create adaptive systems that can tailor content to meet the diverse needs of students in biology education.

3. Applications in Biology Education

3.1. Anatomy and Physiology

Anatomy and physiology education has been at the forefront of VR and AR applications in biology. These technologies offer students the opportunity to explore detailed, interactive models of human and animal anatomy, potentially providing insights that are challenging to achieve through traditional methods. The HoloAnatomy software suite, developed by Case Western Reserve University using Microsoft HoloLens AR technology, has been a pioneering effort in this field [18]. Wish-Baratz et al. [18] conducted a study comparing traditional cadaver-based learning with the HoloAnatomy AR application. They found that students using the AR application performed equally well on anatomy examinations compared to those using traditional methods. Moreover, students reported higher satisfaction and engagement levels with the AR approach.

However, contrasting results were reported by Moro et al. [5], who compared VR, AR, and tablet-based applications for anatomy education. While they found no significant differences in learning outcomes between the three modalities, they noted that some students experienced discomfort and motion sickness with VR, potentially hindering learning [5].

A more recent study by Bork et al. [19] explored the use of VR in teaching cardiovascular anatomy and physiology. They found that VR significantly improved students’ understanding of complex anatomical relationships and physiological processes. However, they also noted that the effectiveness of VR was highly dependent on the quality of the software and the instructional design [19].

3.2. Cellular and Molecular Biology

VR and AR technologies offer unique opportunities to visualise and interact with cellular and molecular structures that are typically too small to observe directly. These immersive experiences can potentially help students better understand complex biological processes at the microscopic level [17]. The Cellular Worlds VR application, developed by researchers at the University of Queensland, allows students to explore a virtual cell environment. While initial feedback has been positive, with students reporting an improved understanding of cellular structures and functions, rigorous studies on its effectiveness are still lacking [18].

In contrast, a study by Safadel and White [20] on using AR in teaching protein structure and function showed significant improvements in student understanding and retention of complex molecular concepts. They found that AR allowed students to manipulate 3D protein models, enhancing their spatial understanding of molecular structures. However, Makransky et al. [13] cautioned that while immersive VR can increase motivation and engagement in molecular biology education, it may not always lead to better learning outcomes. They found that students using a desktop version of a molecular biology simulation outperformed those using an immersive VR version on knowledge tests despite reporting lower levels of presence and enjoyment [13].

3.3. Ecology and Environmental Biology

Virtual field trips and simulations enabled by VR and AR technologies allow students to explore diverse ecosystems and observe ecological interactions that may be difficult or impossible to experience in person. Google Expeditions offers a range of AR-based virtual field trips, allowing students to explore various habitats and ecosystems from the classroom [20]. While these experiences can supplement traditional fieldwork, their effectiveness in replacing actual field experiences is debated [19].

A study by Tarng et al. [21] on using AR for ecology education in elementary schools showed positive results, with students demonstrating an improved understanding of ecological concepts and increased motivation. However, they noted that the technology was most effective when combined with hands-on activities rather than as a standalone tool [21].

In contrast, Markowitz et al. [22] found that immersive VR experiences of ocean acidification led to increased knowledge gains and fostered a sense of environmental stewardship among students. They argued that VR's ability to simulate future environmental scenarios could be particularly valuable in teaching about climate change and its ecological impacts [22].

3.4. Genetics and Evolution

VR and AR technologies have the potential to help visualise complex genetic processes and evolutionary concepts. Interactive simulations of genetic inheritance, DNA replication, and evolutionary mechanisms can potentially enhance students' understanding of these abstract concepts [22]. The Genome Explorer VR application allows students to navigate through a virtual DNA molecule, observe its structure and participate in simulations of genetic processes. While such applications show promise, empirical studies on their effectiveness in improving learning outcomes are still limited [23].

A study by Lee et al. [24] on using AR in teaching Mendelian genetics found that students using AR-enhanced materials showed a significantly better understanding of inheritance patterns than those using traditional textbooks. They attributed this improvement to the ability of AR to provide dynamic, interactive visualisations of genetic crosses [24].

However, Southgate et al. [25] cautioned against over-reliance on VR and AR for teaching complex biological concepts like evolution. They argued that while these technologies can provide engaging visualisations, they may oversimplify complex processes and potentially reinforce misconceptions if not carefully designed and implemented [25].

3.5. Challenges and Limitations

While VR and AR technologies offer significant potential benefits for biology education, several challenges and limitations must be addressed to fully realise their potential. This section critically examines these challenges, comparing and contrasting findings from multiple research studies.

3.6. Cost and Accessibility

High-quality VR and AR equipment can be prohibitively expensive, potentially limiting widespread adoption in educational settings. Additionally, not all students may have access to the necessary devices or internet connectivity required for these technologies. Hamilton et al. [26] highlighted that while VR can enhance learning outcomes, the cost of VR headsets and the need for high-performance computers can be a significant barrier to implementation, particularly in underfunded schools.

Similarly, Fernandez [27] noted that the high cost of VR equipment and the lack of access to reliable internet connectivity can exacerbate educational inequalities, as not all students can afford or access these technologies. In contrast, a study by Familoni and Onyebuchi [28] suggests that the cost of VR and AR technologies may decrease over time as the technologies become more widespread and production costs lower. They argue that early adopters in education can benefit from grants and funding opportunities aimed at integrating advanced technologies into classrooms [28].

3.7. Technical Issues and User Experience

Technical difficulties, such as motion sickness in VR environments or tracking issues in AR applications, can detract from the learning experience. Ensuring a smooth and intuitive user experience is crucial for effective implementation. Hamilton et al. [26] found that some students experienced dizziness when using VR glasses for extended periods, suggesting that VR sessions should be limited to 30 minutes to mitigate this issue. Similarly, Fernandez [27] reported that while students generally found VR useful, moderate levels of nausea were a concern, particularly during the initial weeks of use.

In contrast, Zhou et al. [1] reported fewer technical issues in their AR-based biological microscope learning systems study. They found that AR provided a stable and intuitive user experience, which contributed to its effectiveness in enhancing learning outcomes. This suggests that while VR may present more significant technical challenges, AR might offer a more user-friendly alternative for certain applications [1].

3.8. Content Development

Creating high-quality, educationally relevant VR and AR content requires significant time, expertise, and resources. There is a need for more biology-specific content that aligns with curriculum standards and learning objectives. Makransky et al. [13] emphasised the importance of high-quality content development, noting that poorly designed VR experiences can lead to cognitive overload and detract from learning. They argue that effective VR content must be pedagogically sound and aligned with learning objectives to be truly beneficial [13].

However, Safadel and White [20] highlighted the potential benefits of AR in content development. They found that AR applications for teaching protein structure and function were highly effective, suggesting that AR might offer a more accessible and cost-effective content development solution than VR [20].

3.9. Integration with Existing Curricula

Effectively integrating VR and AR technologies into existing biology curricula can be challenging. Educators need support and training to effectively incorporate these tools into their teaching practices. Southgate et al. [25] pointed out that while VR and AR have great potential, their integration into existing curricula requires significant changes in teaching practices and curriculum design. They argue that educators need comprehensive training and support to effectively use these technologies in the classroom [25].

In contrast, Tarng et al. [21] found that AR could be more easily integrated into existing curricula, particularly when used as a supplementary tool rather than replacing traditional methods. They argue that AR can enhance traditional teaching methods without requiring significant changes to the curriculum [21].

3.10. Assessment of Learning Outcomes

Developing appropriate assessment methods for VR and AR-based learning experiences remains a challenge. Traditional assessment techniques may not adequately capture the unique learning outcomes associated with these immersive technologies. Makransky et al. [16] highlighted the difficulty of assessing learning outcomes in VR environments, noting that traditional tests might not fully capture the depth of understanding and skills developed through immersive experiences. They suggest the need for new assessment methods that can evaluate the experiential and interactive aspects of VR learning. Similarly, Southgate et al. [25] emphasised the need for assessments that capture collaborative and problem-solving skills developed through AR experiences. They argued that traditional multiple-choice tests are insufficient for evaluating the complex learning outcomes associated with AR [25].

3.11. Future Directions

As VR and AR technologies evolve, several promising directions for future development and research in biology education emerged.

3.12. Haptic Feedback and Multi-Sensory Experiences

Incorporating haptic feedback and other sensory inputs into VR and AR experiences could further enhance these technologies' realism and educational value. For example, simulating the texture of different biological tissues or the resistance of muscles during dissection could provide a more comprehensive learning experience. Bork et al. [19] suggested that the addition of haptic feedback in VR could significantly enhance the learning experience in anatomy education by providing tactile sensations that mimic real-life dissections. This could help bridge the gap between virtual and physical experiences, making VR a more effective tool for teaching complex biological processes [19] [27].

3.13. Adaptive Learning and Personalisation

Integrating artificial intelligence and machine learning algorithms with VR and AR technologies could enable more personalised learning experiences [6]. These systems could adapt to individual students' learning styles, pace, and areas of difficulty, providing targeted support and challenges. Huang et al. [4] highlighted the potential of adaptive learning systems in AR to provide personalised learning experiences. They found that AR applications adapted to individual students' needs more effectively improved learning outcomes than static AR applications [4].

3.14. Collaborative Virtual Environments

Developing more sophisticated collaborative VR and AR environments could enhance peer-to-peer learning and enable remote collaboration on complex biological tasks [1]. This could be particularly valuable for distance learning and international collaborations. Liu et al. [9] found that collaborative VR environments facilitated meaningful interactions and teamwork among students, enhancing their problem-solving skills and understanding of complex biological concepts. However, they also noted the need for careful design and facilitation to ensure effective collaboration [9].

3.15. Integration with Other Educational Technologies

Exploring the integration of VR and AR with other educational technologies, such as learning management systems, adaptive learning platforms, and educational games, could create more comprehensive and effective learning ecosystems. Fernandez [27] and Familoni and Onyebuchi [28] emphasised the potential of integrating VR and AR with other educational technologies to create holistic learning environments. They posited that such integration can enhance the overall learning experience by providing multiple avenues for engagement and interaction [27] [28].

3.16. Longitudinal Studies on Learning Outcomes

More long-term studies are needed to assess the impact of VR and AR technologies on learning outcomes, knowledge retention, and skill development in biology education [12] [16] [18] [19]. These studies should compare the effectiveness of these technologies with traditional teaching methods across various biological subdisciplines. Merchant et al. [16] highlighted the need for longitudinal studies to fully understand the long-term impacts of VR and AR on learning outcomes. They asserted that short-term studies may not capture these technologies' full benefits or challenges [16].

4. Conclusion

Virtual reality and augmented reality technologies have demonstrated significant potential to enhance biology education by providing immersive, interactive learning experiences that can improve conceptual understanding, spatial awareness, and student engagement. These technologies offer unique opportunities to visualise complex biological structures and processes, conduct virtual field trips and laboratory experiments, and explore otherwise inaccessible environments.

While the initial results are promising, several challenges remain, including issues of cost and accessibility, technical limitations, content development, curriculum integration, and assessment. Addressing these challenges will be crucial for the widespread adoption and effective implementation of VR and AR in biology education.

As these technologies continue to evolve, future developments in haptic feedback, adaptive learning, collaborative environments, and integration with other educational technologies hold the promise of even more sophisticated and effective learning experiences. However, more research is needed to fully understand the long-term impacts of VR and AR on learning outcomes in biology education and to develop best practices for their implementation.

As such, VR and AR technologies represent powerful tools with the potential to transform biology education, offering new ways to engage students and enhance their understanding of complex biological concepts. As educators and researchers continue to explore and refine the use of these technologies, the future of biology education may be transformed.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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