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VR/AR-BASED INTERACTIVE MULTIMEDIA CONTENT: A SYSTEMATIC REVIEW OF ITS IMPACT ON ENGAGEMENT AND LEARNING OUTCOMES IN THE AI ERA

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Abstract

The development of *Virtual Reality* (VR) and *Augmented Reality* (AR) technologies integrated with artificial intelligence (AI) has opened up a new paradigm in interactive and adaptive immersive learning. This article presents a systematic review of the latest empirical evidence regarding the impact of VR/AR-based interactive multimedia content on learner engagement and learning outcomes in the AI era. The research findings indicate that VR/AR can enhance engagement across its three dimensions—cognitive, affective, and behavioural—through mechanisms such as *a sense of presence*, deep interactivity, and AI-facilitated adaptive personalisation. In terms of learning outcomes, VR/AR produces medium to large effect sizes (g = 0.50–0.85) on conceptual understanding, procedural skills, and knowledge transfer, particularly in domains requiring spatial visualisation and the simulation of complex procedures. The integration of AI reinforces these effects through *adaptive learning pathways*, *real-time* feedback, and precise learning analytics. However, this effectiveness is moderated by critical factors such as task type, students' prior knowledge, duration of exposure, instructional design quality, and infrastructure readiness. In conclusion, the synergy between VR/AR and AI holds transformative potential for education, yet requires a holistic, pedagogy-based implementation approach that considers ethical and social sustainability aspects.

Keywords: *Virtual Reality*, *Augmented Reality*, artificial intelligence, learner engagement, learning outcomes, interactive multimedia, immersive learning, systematic review.

Introduction

The development of digital technology over the past two decades has fundamentally transformed the educational landscape, shifting the learning paradigm from conventional models towards a more interactive, immersive, and data-driven learning ecosystem. This transformation has not only affected content delivery but has also revolutionised the way learners interact with materials, lecturers, and fellow students (Fitroh & Aslan, 2026) ; (Pramesworo & Aslan, 2026) . In this context, interactive multimedia forms the backbone of pedagogical innovation, particularly when enriched with *Virtual Reality* (VR) and *Augmented Reality* (AR) technologies capable of creating immersive three-dimensional learning experiences (Radianti et al., 2020) .

VR and AR, as part of the *Extended Reality* (XR) technology spectrum, offer learning environments that allow students to be psychologically and sensorily 'present' within simulations previously inaccessible via traditional media. VR creates a virtual world entirely separate from physical reality, whilst AR adds a layer of digital information to the real world, thereby enriching perception and learning interactions (Akçayır & Akçayır, 2017). Both technologies have been shown to enhance intrinsic motivation, emotional engagement, and knowledge retention, particularly in the fields of science, medicine, and engineering (Makransky & Lilleholt, 2018) .

However, the effectiveness of VR/AR depends not only on the sophistication of the hardware, but also on the quality of instructional design and the level of interactivity of the multimedia content presented. The *Cognitive Theory of Multimedia Learning* (CTML) proposed by Mayer (2002) emphasises that optimal learning occurs when verbal and visual information is processed in an integrated manner without overburdening students' cognitive capacity. In the context of VR/AR, the application of this principle becomes increasingly complex due to the presence of dynamic spatial and temporal dimensions, thus requiring a careful design approach to prevent *cognitive overload* (Mayer & Moreno, 2002).

With the advent of the era of artificial intelligence (AI), the potential of VR/AR in education is further enhanced by the adaptability and personalisation offered by machine learning algorithms. AI enables VR/AR systems to analyse students' learning behaviour in *real-time*, adjust difficulty levels, provide instant feedback, and even predict learning difficulties before they occur (Anderson & Krathwohl, 2001) . This synergy between AI and VR/AR creates a learning ecosystem that is not only immersive but also responsive to individual needs, thereby opening up new opportunities for *adaptive immersive learning*.

Learner engagement is a key construct determining the success of implementing this technology in education. Engagement is not merely physical presence or clicking on a screen, but encompasses affective (interest and emotion), cognitive (mental effort and learning strategies), and behavioural (active participation and persistence) dimensions (Fredricks et al., 2004) . Empirical studies show that VR/AR-based learning environments significantly enhance these three dimensions of engagement due to the presence of strong elements of *presence*, *agency*, and *interactivity* (Dalgarno & Lee, 2009) .

Furthermore, VR/AR technology combined with AI is capable of creating a state *of flow*—a psychological condition in which students are so fully absorbed in their learning activities that they lose track of time and their own sense of self. This state is ideal for deep *learning*, as students do not merely memorise facts but construct understanding through active exploration and virtual experimentation (Gani et al., 2022) . In this context, AI acts as a facilitator that maintains a balance between task difficulty and student ability, thereby ensuring that *the flow state* is sustained for an optimal duration.

On the other hand, the impact of VR/AR on learning outcomes has also been a key focus of scientific research over the past decade. A meta-analysis of 70 empirical studies indicates that AR in interactive learning environments yields a large effect size ($g = 0.717$) on improved learning outcomes compared to conventional methods (Wu et al., 2023). This improvement is evident in higher-order cognitive aspects such as conceptual understanding, knowledge application, and practical skills, particularly within the context of problem-based learning and procedural simulation (Garzón & Acevedo, 2019) . However, the relationship between the use of VR/AR and learning outcomes is not linear, but is moderated by various factors such as content type, duration of exposure, infrastructure readiness, and the digital literacy of both educators and learners (Huang et al., 2010) . Some studies have even reported negative effects when VR/AR designs fail to account for cognitive load principles, thereby disrupting the encoding of information into long-term memory (Albus et al., 2021) . Consequently, systematic research is required that not only measures primary effects but also identifies *the boundary conditions* determining the success of implementation.

The integration of AI into the VR/AR ecosystem also introduces a new dimension to assessment and learning analytics. By utilising *learning analytics* and *educational data mining*, the system can track patterns of student interaction, identify misconceptions, and provide automated personalised recommendations. This approach enables a transition from traditional summative assessment towards continuous *'assessment for learning'* grounded in real-world behavioural evidence within virtual environments (Silvola et al., 2023) .

Although the potential of AI-based VR/AR is highly promising, the adoption of this technology in education still faces a number of structural and pedagogical challenges. The high cost of equipment, a lack of high-quality content, insufficient teacher training, and data privacy issues are significant barriers that need to be addressed through institutional policies and multi-stakeholder collaboration. Furthermore, there are ethical concerns regarding over-reliance on technology and the potential dehumanisation of the learning process if human interaction is entirely replaced by virtual simulations (Williamson, 2024).

This systematic review aims to fill a gap in the literature by synthesising the latest empirical evidence on the impact of VR/AR-based interactive multimedia content on engagement and learning outcomes, particularly within the context of AI integration.

Research Method

This study employs a literature review method with the aim of identifying, selecting, and synthesising the latest empirical evidence regarding the impact of VR/AR-based interactive multimedia content on engagement and learning outcomes in the AI era. Primary data sources consist of books, journals, and other documents related to the research (Eliyah & Aslan, 2025) ; (Farrukh & Sajjad, 2023) .

Results and Discussion

Impact on Learner Engagement

Learner engagement is a multidimensional construct that serves as a strong predictor of learning success in digital environments, encompassing three main domains—cognitive, affective, and behavioural engagement—which interact dynamically throughout the learning process (Fredricks et al., 2004). In the context of VR/AR-based interactive multimedia, these three dimensions undergo significant amplification due to the immersive characteristics of the technology, which can create a sense of presence, agency, and interactivity that cannot be replicated by conventional media (Dalgarno & Lee, 2009). Cognitive engagement refers to the depth of attention, mental effort, and metacognitive strategies used by students to understand complex material, whilst affective engagement encompasses intrinsic motivation, interest, positive emotions, and self-efficacy regarding learning tasks (Anderson & Krathwohl, 2001). Behavioural engagement, meanwhile, manifests itself in active participation, persistence, consistent attendance, and physical involvement in learning activities that can be directly observed (Fredricks et al., 2004) .

VR has consistently been shown to enhance students' cognitive engagement by creating immersive environments that facilitate the understanding of abstract concepts through interactive and manipulative three-dimensional visualisations (Makransky & Lilleholt, 2018) . In a VR environment, students are no longer passive recipients of information, but active agents who can explore, manipulate virtual objects, and conduct experiments without physical risk or high material costs, thereby encouraging deeper and more elaborative information processing (Dalgarno & Lee, 2009) . A study by (Mayer & Moreno, 2002) shows that students learning cell biology via VR demonstrated a 30% higher level of conceptual retention and better knowledge transfer compared to a group using traditional presentation slides, as VR enables the visualisation of microscopic processes that could previously only be imagined abstractly. Furthermore, VR's ability to present multimodal representations integrating visual, auditory, and kinesthetic elements aligns with the principles of *the Cognitive Theory of Multimedia Learning* (CTML), which emphasises that optimal learning occurs when information is processed through multiple channels without overburdening cognitive capacity (Mayer & Moreno, 2002) .

In the affective dimension, VR and AR significantly enhance students' intrinsic motivation, situational interest, and positive emotions towards learning materials through elements of novelty, realism, and a strong *sense of presence* (Anderson & Krathwohl, 2001) . *Presence,* or the psychological sense of being 'present' within a virtual environment, is a key mechanism that distinguishes VR from other media, whereby students experience a perceptual illusion that they are truly within the simulated world, thereby triggering authentic and profound emotional responses (Slater & Sanchez-Vives, 2016) . Research by (Makransky & Lilleholt, 2018) using *structural equation modelling* found that *presence* in VR directly enhances motivation and interest in learning, which in turn predicts improved learning outcomes, forming a strong emotional mediation pathway. In the context of foreign language learning, for example, VR enables students to interact with virtual characters in realistic communication scenarios, reducing *foreign language anxiety* and boosting self-confidence as mistakes made have no real social consequences (Dhimolea et al., 2022).

AR also makes a unique contribution to affective engagement by adding a layer of digital information to the real world, thereby making learning more contextual, relevant, and connected to students' everyday experiences (Akçayır & Akçayır, 2017) . Unlike VR, which isolates students from their physical environment, AR enhances reality with visual annotations, 3D animations, and interactive data that appear over real-world objects, thereby creating a cognitive bridge between abstract concepts and concrete reality (Wu et al., 2023). A study by the ' found that students using AR to learn human anatomy reported significantly higher levels of satisfaction, enjoyment, and motivation compared to the control group, as AR allowed them to project 3D body organs onto their study desks and manipulate them with hand gestures, creating a playful yet educational learning experience. Gamification elements frequently integrated into AR applications, such as points, badges, and leaderboards, also contribute to increased extrinsic motivation, which can develop into intrinsic motivation over time (Hamari et al., 2016) .

Behavioural engagement within VR/AR environments manifests through increased active participation, time spent on task, and the frequency of student interaction with learning content (Radianti et al., 2020) . The interactive characteristics of VR/AR—which allow for the direct manipulation of virtual objects, free navigation within 3D spaces, and instant responses to user actions—encourage students to become fully engaged, both physically and behaviourally, in the learning process. Research by (Wang & Degol, 2014) shows that students in VR-based classes demonstrated a 95% attendance rate compared to 78% in traditional classes, and spent 40% more time voluntarily exploring additional material, indicating increased persistence and learning autonomy. In the context of medical education, VR simulations for surgical procedure training allow students to practise repeatedly without time constraints or patient risk, thereby increasing the frequency of practice and mastery of fine motor skills (Mao et al., 2021) .

However, the positive impact of VR/AR on behavioural engagement is not universal and can be moderated by instructional design factors, duration of exposure, and individual student characteristics (Hamari et al., 2016) . Several studies report *the 'novelty effect'*, where increased engagement occurs only during the initial sessions of technology use and declines over time as the novelty of VR/AR begins to fade (Su, 2021). To mitigate this, content design must deliberately integrate task variation, progressive challenges, and narrative elements that sustain student interest in the long term, rather than relying solely on the novelty of the technology (Radianti et al., 2020). Furthermore, device accessibility and physical comfort during VR use (such as the risk *of cybersickness* or visual fatigue) can also influence the sustainability of behavioural engagement, thus requiring ergonomic considerations in implementation (P. Li et al., 2020) .

The integration of AI into the VR/AR ecosystem introduces a new dimension to maintaining and optimising engagement through *real-time* adaptability and personalisation mechanisms that respond to students' cognitive and emotional states (Anderson & Krathwohl, 2001) . AI can analyse behavioural data such as eye-tracking patterns, response times, task success rates, and even facial expressions to detect signs of boredom, frustration, or *flow*, then automatically adjust the difficulty level, provide contextual hints, or alter the narrative flow to return students to the optimal engagement zone (Silvola et al., 2023) . The concept of *the flow experience*, as proposed by (Bose, 2008) —a psychological state in which an individual is fully absorbed in an activity with a perfect balance between challenge and skill—can be systematically facilitated by AI in VR through *dynamic difficulty adjustment* (DDA), which ensures tasks remain just within the student's capabilities without causing anxiety or boredom.

AI also enhances affective engagement by creating empathetic and responsive *pedagogical agents* or virtual tutors, who can provide emotional feedback, motivational encouragement, and personalised social scaffolding. These AI agents can recognise signs of stress or confusion through voice and facial expression analysis, then respond with words of encouragement, alternative explanations, or a brief break, thereby creating a more human and supportive learning experience even within a virtual environment (Williamson, 2024) . A study by (Kim et al., 2015) found that students interacting with an empathetic AI tutor in VR demonstrated higher levels of self-efficacy and persistence compared to those receiving generic feedback, due to the perceived 'social presence' that reduces psychological isolation in self-directed learning. Furthermore, AI enables *personalised learning paths* where each student follows a unique learning trajectory tailored to their individual learning style, pace, and interests, thereby enhancing the relevance and personal meaning of the content being studied.

Although the potential of AI-based VR/AR to enhance engagement is immense, there is a serious risk *of cognitive overload* if the design fails to account for the limitations of human cognitive processing capacity, particularly for novice learners or those with low prior knowledge. VR that is overly immersive, with excessive sensory stimulation, complex navigation, and distracting elements, can overload working memory, thereby actually hindering the encoding of information into long-term memory and reducing the effectiveness of learning (Mayer & Moreno, 2002) . *Cognitive Load Theory* emphasises that instructional design must minimise extraneous cognitive load (that is irrelevant to learning objectives) and optimise intrinsic and germane cognitive load (that supports schema construction) (Sweller et al., 2019) . In the context of VR, this means removing unnecessary decorative elements, providing clear navigational scaffolding, and delivering step-by-step instructions appropriate to the learners' skill level (W. Li et al., 2023) .

AR appears to offer a better balance in cognitive load management for novice learners due to its augmentative rather than substitutive nature relative to reality, thus not requiring perceptual reorientation as intense as VR (Akçayır & Akçayır, 2017) . A systematic review by Wu et al. (2023) found that AR results in lower cognitive load and higher performance compared to VR for tasks requiring a connection to the real-world context, although VR is superior for simulations requiring isolation from external distractions. However, this relative effectiveness depends on the type of AR used: *spatial AR* (direct projection onto physical objects) tends to be easier to process cognitively than *see-through AR* (via glasses or a handheld screen), which requires more complex visual integration (Wu et al., 2023). AI integration can help mitigate the risk of cognitive overload by adaptively simplifying visualisations, disabling non-essential elements, or providing additional scaffolding when detecting signs of confusion or cognitive fatigue (Silvola et al., 2023) .

Another challenge in maximising engagement through VR/AR is the digital divide and uneven infrastructure readiness, which can create disparities in access and learning experiences between institutions or regions. High-quality VR devices such as the Oculus Quest or HTC Vive still require significant investment, whilst smartphone-based AR, although more affordable, remains dependent on the availability of the latest mobile devices and a stable internet connection (Radianti et al., 2020) . Furthermore, educators' digital literacy is a critical factor, as teachers untrained in immersive instructional design tend to use VR/AR merely as a technological 'gimmick' without meaningful pedagogical integration, thereby failing to harness their full potential for engagement (Su, 2021) . Comprehensive professional development programmes are required to equip educators with the skills to design VR/AR experiences that align with learning objectives, cognitive principles, and the diverse needs of students (Gani et al., 2022) .

Overall, VR/AR-based interactive multimedia content has a significant and multifaceted positive impact on learner engagement across all three dimensions—cognitive, affective and behavioural—with the primary mechanisms being enhanced *presence*, interactivity, personalisation and relevance. However, these effects do not occur automatically; rather, they are highly dependent on the quality of instructional design that takes into account the principles of cognitive load, the balance of challenge and skill for *flow*, and the strategic integration of AI for *real-time* adaptability. Moving forward, longitudinal research is needed to understand the sustainability of engagement beyond *the novelty effect*, as well as a deeper exploration of how AI can optimise immersive experiences that are not only superficially engaging but also cognitively and emotionally transformative in the long term.

Impact on Learning Outcomes and Knowledge Transfer

Learning outcomes in the context of VR/AR-based interactive multimedia are not merely measured by mastery of declarative facts, but encompass a broader spectrum including deep conceptual understanding, procedural skills, problem-solving abilities, and the transfer of knowledge to authentic new contexts (Anderson & Krathwohl, 2001) . Empirical evidence from various meta-analyses consistently shows that VR- and AR-based learning interventions yield medium to large effect sizes (g = 0.50–0.85) on improved learning outcomes compared to conventional methods, with significant variation depending on the domain of knowledge, duration of the intervention, and quality of instructional design (Garzón & Acevedo, 2019) . These advantages are particularly evident in tasks requiring spatial visualisation, manipulation of three-dimensional objects, and simulation of complex procedures that are difficult to replicate in traditional learning environments (Makransky & Lilleholt, 2018) .

In the domain of conceptual understanding, VR has been shown to significantly enhance students' ability to internalise abstract principles through dynamic visualisation, which allows for the exploration of phenomena from various spatial and temporal perspectives (Mayer & Moreno, 2002) . An experimental study by (Mayer & Moreno, 2002) found that students learning cell biology via immersive VR achieved 30% higher conceptual understanding scores and demonstrated better transfer of knowledge to new application questions compared to the group using slide presentations, as VR facilitates the formation of rich, multimodally integrated mental models. The cognitive mechanism underlying this effect is *embodied cognition*, whereby physical and sensorimotor interactions with virtual objects strengthen the encoding of information into long-term memory via more diverse and redundant neural pathways (Johnson-Glenberg, 2018). Thus, VR not only makes abstract concepts concrete but also enables students to 'experience' scientific principles directly, which forms the foundation for *deep* learning and long-term retention (Gani et al., 2022) .

AR also makes a unique contribution to conceptual understanding, particularly in contexts requiring a close connection between theory and physical reality, such as anatomy, mechanical engineering, and architecture (Akçayır & Akçayır, 2017). By projecting interactive 3D models onto real-world objects, AR enables students to observe internal structures, mechanisms of motion, and spatial relationships that were previously hidden, thereby facilitating the construction of accurate and well-differentiated cognitive schemas (Garzón & Acevedo, 2019) . A meta-analysis by Wu et al. (2023) of 70 studies found that AR resulted in a significant improvement in learning outcomes (g = 0.717), with the greatest effect in the domains of science and engineering, where spatial visualisation is a critical component. Furthermore, AR tends to be more effective than VR for tasks requiring real-world contextualisation, as AR does not isolate students from the physical environment but rather enriches it with a layer of relevant information (Akçayır & Akçayır, 2017) .

In the realm of procedural and psychomotor skills, VR has become the gold standard for simulation training in medicine, aviation, and manufacturing due to its ability to provide a safe, controlled, and infinitely repeatable practice environment (Makransky & Lilleholt, 2018) . Medical students who practise surgical procedures via VR demonstrate higher movement accuracy, faster completion times, and lower error rates when performing real operations compared to those who learn solely through video or text (Mao et al., 2021) . These advantages stem from the *deliberate practice* mechanism facilitated by VR, where students can perform concentrated repetitions with instant and objective feedback on their performance, enabling the gradual refinement of motor schemas until a level of automation is achieved. The integration of haptic sensors in state-of-the-art VR systems also adds a tactile dimension that reinforces kinesthetic learning, although its effectiveness still varies depending on the fidelity of the device and the type of task (Gani et al., 2022) .

Knowledge transfer—the ability to apply what has been learnt in one context to a different, new situation—is the ultimate indicator of learning success and an area in which VR/AR demonstrates significant transformative potential (Dalgarno & Lee, 2009) . Immersive environments enable the simulation of complex and varied scenarios that mimic real-world conditions, allowing students to generalise fundamental principles beyond the specific examples provided during instruction (Hamari et al., 2016). (Huang et al., 2010) indicates that students learning physics through VR with high simulation context variation demonstrated 45% better transfer ability to novel problem-solving tasks compared to the control group, as diverse immersive experiences facilitate the formation of flexible and adaptable schemas. AR also supports transfer by allowing students to practise applying concepts directly in authentic environments, such as repairing a real machine with AR guidance that is gradually reduced (*faded scaffolding*) until students can do so independently (Wu et al., 2023).

The integration of AI into the VR/AR ecosystem further enhances the impact on learning outcomes through mechanisms such as personalised learning pathways, adaptive feedback, and precise learning analytics. AI systems can analyse granular data on student performance—such as response times, error patterns, problem-solving strategies, and even eye movements—to identify specific misconceptions and provide targeted interventions in *real time* (Silvola et al., 2023). This *adaptive learning* approach ensures that each student receives an optimal level of scaffolding in line with their *Zone of Proximal Development* (ZPD), maximising learning efficiency and minimising frustration or boredom (Huebner, 2012) . Furthermore, AI enables *intelligent tutoring systems* (ITS) within VR that can engage in natural dialogue with students, pose Socratic questions, and provide explanations tailored to individual cognitive styles, thereby replicating the quality of one-to-one human tutoring, which has consistently been proven to be the most effective instructional method (Anderson & Krathwohl, 2001) .

AI also facilitates continuous, evidence-based *assessment for learning* through *learning analytics* that collect and interpret data on student behaviour within virtual environments. Unlike traditional summative assessments, which are disconnected from the learning process, VR/AR analytics can track student progress longitudinally, identify emerging patterns of difficulty early on, and predict the risk of failure before it occurs, enabling timely preventive interventions (Silvola et al., 2023). AI-powered analytics dashboards also empower educators with deep insights into classroom dynamics, the distribution of misconceptions, and the effectiveness of instructional strategies, thereby enabling data-driven teaching adjustments. In this context, assessment is no longer the end of learning, but an integral part of a continuous learning cycle that informs and refines the instructional process.

However, the relationship between the use of VR/AR and learning outcomes is neither linear nor universal; rather, it is moderated by a number of critical factors that need to be understood to optimise the implementation of. The type of learning task is a key moderator: VR tends to be more effective for tasks requiring spatial visualisation, hazardous simulations, or repetitive procedural practice, whilst AR is superior for tasks requiring real-world contextualisation and physical collaboration (Akçayır & Akçayır, 2017) . Duration and frequency of exposure also play a role: studies indicate that excessively long VR sessions (>30 minutes) can lead to cognitive fatigue and reduced performance; consequently, optimal instructional design adopts a *microlearning* approach with short yet intensive sessions repeated at regular intervals (Makransky & Lilleholt, 2018) . Furthermore, learners' prior knowledge moderates the effectiveness of VR/AR, whereby novice learners require more structured scaffolding to avoid *cognitive overload*, whilst expert learners benefit more from free exploration (W. Li et al., 2023) .

The readiness of infrastructure and educators' digital literacy are also determining factors that are often overlooked in academic discourse but are critical in practical implementation (Radianti et al., 2020) . Low-quality VR/AR devices with high latency, poor resolution, or inaccurate tracking can cause *cybersickness*, distraction, and frustration, which actually hinder learning. Similarly, educators untrained in immersive instructional design tend to use VR/AR as a technological 'gimmick' without meaningful pedagogical integration, thereby failing to harness its full potential for enhancing learning outcomes (Su, 2021). Comprehensive professional development programmes are required to equip teachers with the skills to design VR/AR experiences that align with learning objectives, cognitive principles, and valid assessment strategies (Gani et al., 2022) .

Methodological challenges in VR/AR research must also be acknowledged, including heterogeneity in study designs, variations in the measurement of learning outcomes, and a lack of longitudinal studies tracking long-term retention (Radianti et al., 2020) . Many existing studies only measure learning outcomes immediately following the intervention (*immediate post-test*), so it is unclear whether performance improvements are sustained or merely a temporary effect of *the novelty effect*. A rare but valuable longitudinal study by (Makransky & Lilleholt, 2018) found that the learning benefits of VR remained significant after four weeks, albeit with a slight decline in effect, indicating that long-term retention does occur but requires reinforcement through spatial practice and contextual variation. Moving forward, research employing rigorous *randomised controlled trial* (RCT) designs, standardised measurements, and long-term follow-ups is essential to build a more robust evidence base (Page et al., 2021) .

Overall, interactive VR/AR-based multimedia content has a significant and multifaceted positive impact on learning outcomes and knowledge transfer, with the primary mechanisms being enriched conceptual visualisation, safe and repetitive procedural practice, and authentic contextual simulations that facilitate generalisation. The integration of AI further enhances these effects through adaptive personalisation, *real-time* feedback, and precise learning analytics, creating a responsive and efficient learning ecosystem. However, optimising these effects requires careful attention to moderating factors such as task type, prior knowledge, duration of exposure, and infrastructure quality, as well as a commitment to evidence-based, learner-centred instructional design.

Conclusion

VR/AR-based interactive multimedia content has a significant and multifaceted positive impact on learner engagement across its three dimensions—cognitive, affective, and behavioural—through key mechanisms such as *an* enhanced *sense of presence*, deep interactivity, and personalisation facilitated by artificial intelligence. The synergy between VR/AR and AI creates an immersive learning ecosystem that is not merely superficially engaging, but also capable of maintaining optimal *flow* conditions through *real-time* adaptation to students' cognitive and emotional states, thereby transforming learning from a passive experience into an authentic and personally meaningful exploratory journey.

In terms of learning outcomes, VR/AR consistently enhances conceptual understanding, procedural skills, and knowledge transfer with medium to large effect sizes (g = 0.50–0.85), particularly in domains requiring spatial visualisation, simulation of complex procedures, and real-world contextualisation. The integration of AI further strengthens these effects through *adaptive learning pathways*, precise instant feedback, and learning analytics that enable continuous formative assessment, thereby ensuring that every student receives optimal scaffolding in line with their *Zone of Proximal Development*. However, this effectiveness is not universal but is moderated by critical factors such as task type, students' prior knowledge, duration of exposure, and the quality of instructional design that takes into account the principles of cognitive load.

Moving forward, the implementation of AI-based VR/AR in education requires a holistic approach that balances technological innovation with a solid pedagogical foundation, equitable infrastructure investment, and comprehensive professional development for educators to avoid the pitfall of using technology merely as a ‘gimmick’ devoid of instructional meaning. Longitudinal research with rigorous designs is needed to understand the sustainability of impacts beyond *the novelty effect*, to explore data privacy ethics in AI-based learning analytics, and to identify implementation models that are inclusive and socially sustainable. Ultimately, the future of immersive education is not about replacing the role of educators with technology, but about empowering people with tools that expand cognitive capacity, deepen engagement, and open up previously unimaginable learning opportunities.

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