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Transforming science education with virtual reality: an immersive representations model

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ABSTRACT

Immersive virtual reality (IVR) offers significant transformative potential for science education by supporting learning experiences that deeply engage students and improve their understanding of scientific concepts. Despite considerable interest, research on the use of IVR in science education is still in its formative stage. Currently, there is a substantial gap in a tool that can help stakeholders evaluate key elements of immersive software for science education contexts. This research addresses this gap by conceptualising and applying a framework designed to assist educators, researchers, and designers in assessing essential components of an immersive science application. The framework highlights three key components: IVR technological affordances, the exploration of science within IVR, and scientific representations. These components are synthesised into the Immersive Representations Model (IRM). Employing screen capture methodology, we evaluated the application and significance of the IRM. This study pioneers a structured approach to evaluating immersive technologies in science education.

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Immersive virtual reality; virtual reality; science representations; digital technologies; educational technology

Introduction

Immersive virtual reality and science education

Immersive virtual reality (IVR) is a digital technology that has the potential to transform science education pedagogy. What makes IVR distinct from other mediums is the sense of immersion and presence, a user's sense of leaving their reality and feeling as if they are transported into a new environment (Weech et al., 2019). Proponents of the technology have described IVR as a virtual shared space . . . "an embodied internet where instead of just viewing content – you are in it" (Newton, 2021, para.10). Educators are certainly interested in the potential of IVR; however, research about the practical, ethical, and pedagogical use of the

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technology is only just emerging (Cooper et al., 2019; Park et al., 2022; Southgate, 2020). When discussing virtual reality, it is important to make the distinction between immersive and non-immersive forms. Non-immersive virtual reality (VR) simulates a virtual environment for a user to navigate and interact with on a desktop computer or mobile phone. Although the rendered images look three-dimensional (3D), they are displayed on a flat screen. Conversely, IVR utilises a head-mounted display (HMD) and can be regarded as an interactive, computer-generated environment where immersion is a crucial element (Chalmers, 2017; Tsivitanidou et al., 2021). In the HMD, there is scope for 3D audio tracking capabilities, motion tracking controllers, and haptics-which mimic the experience of touch. The former supports all kinds of interactive possibilities within a virtual environment, including the detection of real-time movements, gestures, and positional tracking.

As the technology advances, it will become more affordable, and immersive learning environments will become more realistic and complex, better allowing multiple users to share the same virtual space. Fifth Generation (5 G) connectivity will reduce latency by pushing data to the cloud, resulting in cheaper headsets that are less reliant on processing and storage (Price Waterhouse Coopers, 2019). Other promising infrastructure includes Low-Earth Orbit (LEO) satellite internet, such as Starlink, which could support the use of IVR, particularly in regional and rural areas. By the end of 2024, IVR headset shipments are forecasted to reach 9.7 million units, marking a year-on-year increase of 44.2% increase (International Data Corporation, 2024). By 2030, it is anticipated that immersive environments will become commonplace for activities such as work, shopping, social interaction, and education (Marr, 2020). If these predictions come to pass, it is likely that significant aspects of human life will occur within virtual realities, profoundly impacting learning environments and teaching pedagogies.

IVR has generated significant interest in different fields of education research. Despite the attention, there is a glut of research which tends to focus on students' excitement or sense of novelty with the technology. For instance, Pellas et al. (2021) reported only 28% of IVR studies in K-12 settings measured students' learning outcomes or achievement in their review of the research. Exceptions to the former include a meta-analysis by Villena-Taranilla et al. (2022), which reported medium to large positive effects on students' learning gains linked to the use of IVR. In terms of science education research, emerging evidence suggests learning impacts associated with the use of IVR. For example, Liu et al. (2020) compared students learning biology in IVR to a group learning the same content through non-immersive methods. Liu's study, involving a sample of 90 students, reported that the experimental group learning in IVR achieved significantly higher academic performance and engagement scores (cognitive, behavioural, emotional, and social) compared to the control group. Similar results were found by Girgin and Sarioğlu (2020) in their study of 100 students learning cellular biology. Sarioglu et al. reported a significant positive effect on students' achievement and attitudes, favouring those who used IVR. An emerging body of evidence supports the use of immersive technologies across various subjects, including science. However, the potential impact of IVR, including its potential benefits, are influenced by a range of factors such as hardware, educational setting, subject area, and software design. In the context of this research, a primary focus is on the immersive software that stakeholders are creating or embedding in their science pedagogy. "Ultimately, content is crucial – without well-designed content that brings increased and long-term learning benefits and engagement to students, it falls back to the novelty of using technology rather than purposing it for a better learning experience" (Cooper et al., 2019, p. 8). Currently, there is a notable absence of a tool to assist stakeholders in evaluating an immersive application for science teaching. Therefore, the aim of this paper is to conceptualise and apply a framework that helps educators, researchers, and designers critically evaluate elements of an immersive science application.

The remainder of the article is divided into four main sections. First, we explore the conceptualisation of our framework. Second, the methodology section discusses the research design. Third, we present the findings, and finally, we discuss the implications of this study, its connections to existing literature, limitations, and future research opportunities.

Conceptual framework

The overall goal of this research is to conceptualise and apply a framework that supports educators, researchers, and designers in evaluating elements of an immersive science application. The first step was to conceptualise a framework specifically for immersive science learning experiences from the existing research base. Based on a review of the literature, the following model was conceptualised:

- IVR technological affordances
- Exploring science in IVR
- Science representations

Together, these three elements form a comprehensive framework for evaluating and designing immersive science learning experiences. This model not only supports the development of high-quality IVR applications but also provides a structured approach for assessing their impact on learning outcomes. Below, we discuss each element of our model and their overlapping synergies.

IVR technological affordances

The technological IVR affordances outlined in the IMR draw from the work of Dincelli and Yayla (2022), where the authors examined existing literature and the technical capabilities of IVRs. Their comprehensive analysis identified five key

Table 1. Focal technology affordances and enablers of hmd-based immersive VR (Dincelli & Yayla, 2022).

Affordance	Definition	Technology Enabler
Embodiment	Users' tendency to perceive the virtual body they control as their own biological body and their actions in VR as their own actions in real life.	6-DoF, standalone HMDs, higher FoV, graphical fidelity, full-body tracking.
Navigability	Ability to freely move the avatar in a navigable space in the virtual environment.	6-DoF, standalone HMDs, higher FoV, graphical fidelity, full-body tracking.
Sense-ability	Ability to sense (e.g., touch, smell, hear, taste) in the virtual environment.	Haptics, smell modules, audio, electrical stimulation.
Interactivity	The extent to which users can engage in reciprocal or non-reciprocal interactions with the virtual objects and agents.	Motion controllers, lighthouse systems, IR cameras, and haptics.
Create-ability	Ability to create aspects that do not exist in the physical world and recreate existing aspects of the physical world to diminish negative and enhance positive aspects of it in VR.	Development platforms, game creation systems, AI, virtual object marketplaces.

affordances: Embodiment, Navigability, Sense-ability, Interactivity, and Create-ability. These affordances are detailed in Table 1. Each of these affordances enhances users' sense of immersion within the virtual environment through a range of advanced technological enablers, including six degrees of freedom (6-DoF), haptic feedback, eye tracking, and body tracking. These technologies collectively contribute to a more immersive and interactive virtual experience, enabling users to engage more deeply with the virtual environment.

Embodiment describes how enablers such as high-fidelity graphics, spatial audio, virtual hands and the tracking of body/gestural movements extends believability in users perceiving their virtual avatars and its actions as an extension of one's physical self within the IVR environment. *Navigability* can range from a stationary experience to a free-roaming experience, where users freely explore the immersive environment with 6-DoF and interact with objects or characters, even if such engagements were not directly related to the main objective or tasks at hand. *Sense-ability*, achieved by enablers such as haptic feedback through controllers and gloves, simulates the sense of touch to the user, which promotes a sense of interaction with the environment. *Interactivity* offers users a sense of agency to engage with virtual objects and characters within the environment to engage in conversational dialogue, make key decisions to influence outcomes of in-game narratives, or complete objectives in a non-linear trajectory. This is achieved through enablers such as motion controllers and microphones. Lastly, *Create-ability* emphasises on IVR's capabilities in creating fictional environments with different parameters and hypothetical scenarios, enabling designers and educators to design immersive and low-risk learning/training environments beyond real-world constraints. Within the context of this research, stakeholders are encouraged to consider how IVR's technological affordances could be suitably leveraged in the design of the experience to attain desired learning outcomes.

Exploring science in IVR

IVR is increasingly being used as a tool to support science learning experiences. While it is valuable to consider the broad learning affordances of this technology, stakeholders need to critically determine how it is used to promote science-specific knowledge, skills, dispositions, and philosophies (see Table 2). For this part of the IRM, we draw on the work of Tang et al. (2020) who examined the multimodal affordances of IVR as compared to a digital simulation on a flatscreen PC. From the perspective of multimodal affordance, they investigated what an IVR application allows users to learn science that other tools cannot provide. While Tang et al. (2020) study focused on an immersive application designed for chemistry undergraduates, the findings from the study have broader applications across science domains as they revealed five major affordances that IVR provided for science learners: namely, manipulation, scaling, sequencing, modelling, and viewing (see Table 2).

Table 2. Multimodal affordances for science visualization in IVR (Tang et al., 2020).

Multimodal affordances	Definition
Manipulation	Tactile manipulation of digital objects
Scaling	Changing sizes of digital objects by zooming in/out
Sequencing	Animating image sequences (e.g., moving, rotating)
Modelling	Scientific models used
Viewing	Visual objects in terms of environment, perspective, and dimensionality-3D

Manipulation allows users to grab, move, rotate, and assemble digital objects with their virtual hands by using controllers. This could be used to interact and explore complex molecules, for example in Tang et al. (2020), or in biology, different anatomical structures of a living thing from different perspectives, depending on the user's spatial position. *Scaling* affords users to zoom in and out of different substructures, which is particularly important for learners to explore scientific phenomena that span the scale of size in several orders of magnitude; for example, the size of Earth relative to a galaxy. *Sequencing* allows designers to create a series of animations that show the dynamic changes seen in many scientific phenomena, such as catabolism – the breaking down of large molecules into smaller units. *Modelling* allows users to change the representation of objects according to different scientific models, for example, surface, ball-and-stick, mesh for molecules. The *viewing* affordance in IVR provides a 360° viewing experience that allows users to see objects from different perspectives depending on their spatial positions and orientations.

In comparing these affordances with other digital tools, Tang et al. (2020) notes that some of these multimodal affordances (e.g., modelling, sequencing) can be found in digital simulations. However, what is unique about IVR is that it combines all five of the affordances at the same time, thus creating a unique learning experience that cannot be found in other tools. In sum, it is important for educators to have a clear pedagogical rationale for using IVR in their teaching. Critically examining potentially unique and effective learning opportunities is an important step for stakeholders to consider, both in terms of their science pedagogy and in the design of applications. Below, we discuss how salient ideas from the science representations research is embedded in our model.

Science representations

The use of multiple representations has historically received significant attention in the science education research community. Researchers have emphasised the importance of using multiple representations, stating that one root cause in student underachievement can be traced back to a heavy reliance upon textual representations at the expense of more visuospatial representations (Gates, 2018). Educators embed a range of science representations in their pedagogy, including for instance, experiments, diagrams, charts, and animations. These different modes of representation are intended to represent scientific ideas, concepts, or phenomena, and in different ways support the learner to develop their science understanding (Treagust, 2018; Tytler et al., 2013). In the context of our research, immersive environments offer significant potential for users to manipulate 3D digital elements, and potential for students to explore and represent their science understandings in ways not previously possible.

As shown in Table 3, both physics and chemistry domains include three different types of representation including macro, sub-micro and symbolic levels. Biology includes four types of representations including macro, cellular, sub-micro and symbolic levels.

Table 3. Categorisation of science representations in the IRM (Treagust, 2018).

Science domain	Level of representation	Example
Physics/Chemistry		
	Macro	Smell, taste, sight, touch, and hear
	Sub-micro	Particulate interactions- atoms, molecules, ions, electrons, protons, and neutrons
	Symbolic	Freebody diagrams/Chemical symbols, chemical formulas, chemical equations
Biology		
	Macro	Smell, taste, sight, touch, and hear
	Cellular	Plant and animal cell structures visible under a light microscope/sub-cellular structures visible under electron microscope
	Sub-micro	Molecular level e.g DNA or proteins
	Symbolic	Metabolic pathways with chemical equations

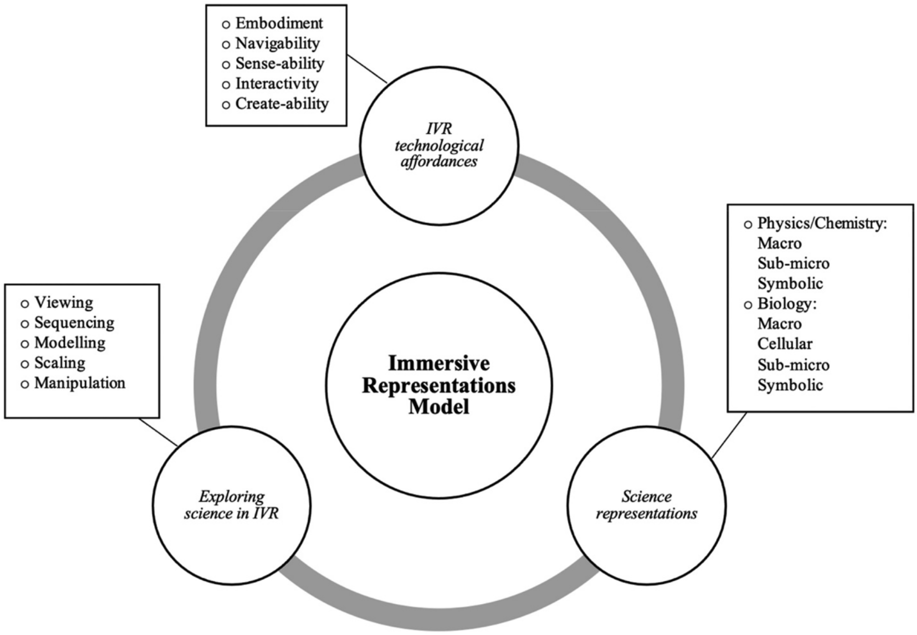

Figure 1. The immersive representations Model (IRM).

Immersive representations Model

Integration and synergy

As shown in Figure 1, the IRM is conceptualised as a series of interconnected circles, emphasising the synergies between the three core components-*IVR technological affordances*, *Exploring science in IVR* and *Science representations*. To illustrate the interconnections within the model, we provide examples below of the IRM framework applied in various learning contexts.

Understanding cellular biology

The IVR technological affordances, such as embodiment and sense-ability, enable students to perceive their virtual hands as extensions of their physical selves and to sense touch through haptic feedback. This aligns with the first element, IVR technological affordances. Exploring science in IVR allows students to navigate through a cell's interior, utilising multimodal affordances like manipulation to grab and move organelles, and scaling to zoom in and out of cellular structures. This aspect addresses the second element, exploring science in IVR. Science representations in IVR headsets, such as an immersive model demonstrating the processes of cellular functions, provide multiple ways to visualise and interact with cellular mechanisms. These representations in IVR support learners by making complex biological processes more accessible and immersive, enhancing their understanding and engagement (Cooper et al., 2019), which is crucial given the historical reliance on textual representations that can sometimes hinder comprehension or not engage students (van den Broek, 2010). Sequencing affords the ability to animate cellular processes, such as mitosis, showing dynamic changes step-by-step. Modelling enables students to switch between different scientific models of the cell, such as surface or ball-and-stick representations, while viewing provides a 360° perspective of the cell's environment that can be digitally manipulated in real time by the student's hand gestures. These combined affordances and representations ensure that students experience an immersive and interactive representation of the science content they are learning.

Exploring physics

In a physics classroom for instance, the IVR technological affordances of interactivity and create-ability allow students to engage with virtual objects. Exploring science in IVR, students can manipulate variables like gravity and friction in a controlled virtual space, using manipulation to interact with objects and scaling to adjust their sizes. Sequencing enables the animation of physical phenomena, such as the trajectory of a projectile, illustrating the second element, exploring science in IVR. Science representations, such as visualising magnetic fields or electric circuits, make abstract concepts tangible. These representations include freebody diagrams, chemical symbols, and visual simulations that help students grasp complex physics concepts through visuospatial rather than purely textual means. Modelling allows students to explore different representations of physical systems, such as vector fields or particle simulations, and viewing offers multiple perspectives of these systems in an immersive 3D environment.

Investigating environmental science

The IVR technological affordances of navigability and sense-ability enable students to explore detailed virtual ecosystems, experiencing the environment through touch and other senses. Exploring environmental science in IVR allows students to observe and interact with virtual flora and fauna, leveraging manipulation to explore plant and animal structures and scaling to zoom into different substructures. Sequencing can be used to animate ecological processes, such as predator-prey interactions, which covers the second element, exploring science in IVR. Science representations of life cycles and environmental changes provide visual and interactive learning opportunities. These representations, make complex ecological processes more comprehensible in ways not possible with other representations. Modelling provides various scientific representations of ecosystems, while viewing offers immersive perspectives, allowing students to see the environment from different angles. This integrated approach helps students comprehend the complexities of environmental science at different levels of science representations (e.g., macro, cellular).

In sum, by considering how the technological affordances can be used to support specific scientific learning objectives and how different representations can be integrated to enhance understanding, educators and developers can create effective and engaging educational experiences. The IRM serves as a guide for evaluating IVR-science-related software, ensuring that pedagogically important elements work together harmoniously to support and enrich the learning experience. These examples illustrate how the framework can be applied to various science domains, demonstrating its versatility to be used as a tool to support effective science learning.

Application and evaluation

The IRM offers a robust framework for the application and evaluation of IVR applications in science learning environments. Educators may conduct pilot testing, which is particularly crucial as many science teachers may be unfamiliar with assessing the potential value of immersive applications. Through the IRM, educators can conduct initial trials with a small group of students to gather preliminary feedback on the science learning experience. This iterative process allows for adjustments based on the feedback received, ensuring that the application is refined and tailored to meet the specific needs of learners before it is implemented on a broader scale. The IRM emphasises a user-centred design approach. This ideally means involving end-users, such as students and educators, in the design process to ensure that the final product aligns with their needs and preferences. This approach not only improves the likelihood of software being more user-friendly but also enhances its effectiveness in achieving educational goals. In sum, the IRM is designed to help educators, designers and researchers systematically assess various components of immersive applications, including their usability, educational value, and engagement potential. In the context of this research, IRM was used as a framework to evaluate the elements of each immersive application featured below. Consequently, the research question that guided the study was:

> How do we conceptualise and apply the Immersive Representations Model to evaluate technological affordances, the exploration of science, and science representations in IVR-science-related software?

Methodology

Our exploratory research design, adapted from Southgate's (2020) study, involved recording various immersive science applications using screen-captured video. We also drew inspiration from other research conceptualising the walkthrough method (Light et al., 2018). The walkthrough method is a systematic approach to engaging directly with an app's interface to examine its technological mechanisms. It involves step-by-step observation and documentation of an app's screens, features, and activity flows, which are crucial for understanding how the app guides users and shapes their experiences. The researcher registers and logs into the app, mimicking everyday use where possible (Light et al., 2018). In summary, our method enabled us to capture a first-person perspective of the user's experience with each IVR application. This approach aligns with a form of self-study methodology (Cooper, 2023; Cooper & Tang, 2024), allowing researchers to critically reflect on their own engagement with and experiences of digital technology.

A search for immersive science education software was conducted on the Steam platform, resulting in the analysis of four applications: VR Brain Exploration (Clinical Tools, 2022), Futuclass Chemistry Demo (Futuclass, 2022), The Cell (Holopundits, 2022), and Visualising and Learning Molecular Interactions (Tang et al., 2020). These applications were chosen based on maximum variation sampling to test the robustness of our IRM and demonstrate its applicability across diverse applications. Detailed descriptions of each application are provided below. Each application's screen capture lasted approximately between 4–10 minutes, typically covering an early "level" due to the impracticality of analysing every stage of the application. Table 4 shows the length of time each application was screen-captured.

Table 4. Length of screen capture recording time.

IVR Application	Length of screen capture (minutes/seconds)
VR Brain Exploration	4.37
Futuclass Chemistry Demo	9.55
The Cell	4.45
Visualising and Learning Molecular Interactions	6.54

The screen capture recordings served as data, which we coded into the key components of the IRM. Each researcher on the team individually analysed each IVR application using the IRM framework. This process involved thoroughly examining the immersive applications, noting observations, and coding the data according to the three components of the framework. After the individual analyses were completed, the team came together to engage in "interpretative dialogue" (Southgate, 2020, p. 420). This dialogue is a collaborative process where team members discuss their individual findings, comparing their observations and interpretations. The goals of this dialogue are to identify consistencies, resolve disagreements, and enhance the reliability and validity of the analysis. By comparing individual analyses, the team can identify patterns and consistencies in the data, strengthening the overall conclusions of the study. Differences in interpretation are discussed openly, with each team member presenting their rationale and evidence for their conclusions. This dialogue allows the team to critically evaluate each perspective and come to a consensus or at least understand the reasons behind differing viewpoints. Through this iterative process of discussion and resolution, the reliability of the findings is enhanced because the analysis is subjected to multiple viewpoints and scrutiny. The validity is also strengthened as the team ensures that the interpretations are robust and well-supported by the data. During the interpretative dialogue sessions, specific instances where team members had differing views were examined in detail. For example, if one researcher interpreted a specific technological affordance differently from another, they would discuss their reasoning, referencing specific elements of the application and the framework. By the end of these sessions, the team reach a unified interpretation that accurately reflects the authors' collective insights.

We coded the data by first identifying relevant segments of the video screen captures that aligned with each component of the IRM framework. Each segment was then coded into categories of the IRM framework using the instrument in Appendix A. Each researcher first independently assigned codes to the data, annotating specific examples and observations that demonstrated these categories. Once the initial coding was completed, the team compared and discussed each other's coded segments during the interpretative dialogue sessions, refining and adjusting the codes as necessary to ensure consistency and accuracy. This coding process allowed us to systematically analyse the immersive applications and extract meaningful insights into their learning potential. We used two IVR devices for testing purposes in this study: the Meta Quest 2 and the HTC Vive. The Meta Quest 2 is a standalone head-mounted display (HMD) with wireless motion controllers, it retails for ~$240 USD. One application was tested on the HTC Vive, which requires a standalone computer and is priced ~$800 USD for the updated, standalone model (HTC Vive Pro 2). The decreasing cost and increasing processing power of IVR headsets is making this technology more accessible for science educators, a trend that is likely to continue.

Findings

We draw on the use of the IRM to evaluate the four immersive applications we have included in our analysis. In Table 5, VR Brain Exploration allows users to explore the anatomical structure and physiology of the brain. Labels detailing substructures appear when the user points with their hand controller to different parts of the brain. Users can explore the function of different processes in the brain, including pathway connections between structures. A video clip demonstrating the application may be viewed at Clincial tools (2020). Copyright restrictions prevent us from directly using a screenshot of applications, but using ChatGPT/DALLE 3, images below show a stylised visual representation of a user interacting with the application (Figure 2). YouTube links to screen capture of applications are included below.

The Futuclass application allows users to engage with concepts in different science domains including chemistry, physics, and biology (Table 6). In our use of the software, we explored chemistry learning. The experiences included, for example, reaction balancing, identifying acids, bases, and salts, and creating atoms with proton, neutron, and electron "ball guns". The focus in this analysis is a reaction balancing task. In the reaction balancing task, the learning goals include how to use coefficients and subscripts correctly in a reaction equation. A video clip

Table 5. VR brain exploration analysis.

VR Brain Exploration	
IVR technological affordances	**Embodiment**: The ability for users to situate themselves at different viewpoints/ angles of the detailed 3D model of a brain allows for a comprehensive view of neural pathways. **Navigability**: Dual-controller input, point-click and thumb stick controls as main interactions within the scene. Full agency in examining the digital artefact and its intricate inner details up-close. **Sense-ability**: No audio in this IVR experience, however animations offer visual feedback of neural pathways. **Interactivity**: Interactivity is designed for scene exploration – several configurations available for object display and viewpoints (orbit, rotate, drone view, etc) within the 3D space, enabling fluid display of close-ups of the model in full 360 view at user's self-paced control. **Create-ability**: The flythrough exploration allows users to position themselves within the brain and see unique spatial/scale insights.
Exploring science in IVR	The **viewing** experience allows users to explore mesolimbic pathways in the brain from multiple perspectives. The **sequencing** of the experience promotes a sense of being in, and moving around, a functioning brain. The **modelling** used in the experience includes exploration of the biological structures and the physiological process of different experiences or stimuli (e.g., neurotransmitter pathway when experiencing pleasure). The use of hand controllers allows tactile **manipulation** of different parts of the brain through hand movements, helping users to zoom in and out of different substructures (**scaling**).
Representations of science	The representations include both the **macro** level of identifying biological structures of the brain in addition to **symbolic** representations exploring the physiology of the brain processing stimuli of different kinds. The experience is likely to be of value to students studying secondary biology, psychology, and health science courses.

Figure 2. A stylised visual likeness of a user interacting with the immersive application.

demonstrating the application may be viewed at Futuclass (2021) and a stylised visual representation is shown in Figure 3.

The Cell was designed for users to explore the structure and function of cells (Table 7). In our use of the application, we explored a module that describes cell

Table 6. Futuclass analysis.

Futuclass	
IVR technological affordances	**Embodiment**: Dual-controller input, featuring virtual hands. Direct interaction replicates real-world motions (ie pulling levers, picking up objects) offers intuitive user experience. Spatial sound effects, in addition to background music and instructions/feedback, and may add to the sense of user's presence within the environment. **Navigability**: Users are allowed a degree of agency in engaging with content to explore surroundings in 360 degrees and interact with objects at their own pace. **Interactivity**: Interactable 3D objects used to visually convey complex chemistry concepts. Grabbing and manipulating virtual objects offers instantaneous response and feedback to users. **Sense-ability**: Haptic feedback on controllers mimics a sense of touch as users interact with virtual objects. **Create-ability**: Students are able to apply science abstract concepts and experiment in a safe and engaging fictional environment.
Exploring science in IVR	The **viewing** experience takes place in a 3D warehouse-like environment. The **sequencing** of the experience promotes a sense of being in an immersive learning environment with different tasks to complete. The **modelling** presented in the experience includes balancing reactions presented both in visual and written forms. The use of hand controllers allows tactile **manipulation** of particles into either the 'reagents' and 'products' baskets.
Representations of science	The representations in this experience include **symbolic** representations, for instance, when combining calcium oxide and water to make calcium hydroxide-the immersive environment shows both the chemical equation (CaO + H2O → Ca(OH) 2) and visually in the form of a molecule model. The experience is likely to be of value to students studying secondary chemistry.

Figure 3. A stylised visual likeness of a user interacting with the immersive application.

junctions and explains the structure and function of various cell junctions, including plasmodesmata and gap junctions. The description and explanation are given by a voice-over narration accompanied by visual animations in the virtual space.

Table 7. The Cell analysis.

The Cell	
IVR technological affordances	**Embodiment**: Experience was primarily designed as screen based and did not utilise the embodiment affordance of IVR. **Navigability**: Users are presented with 3D model as visuals to illustrate concept during lessons. Navigation primarily screen based. Models could be rotated, moved, and scaled for closer examination. **Interactivity**: Single controller pointer-click input with standard user-interface (button controls). Degree of interactivity limited to playback control and 3D object view and rotation. **Sense-ability**: A linear and stationary experience with audible instruction. **Create-ability**: IVR world is confined as content was presented in a linear time-based media format like screen-based animation/videos.
Exploring science in IVR	The **viewing** experience is a 3D environment where the user can look around their surroundings. However, it seems limited as the user's position is fixed at a particular spot. The **sequencing** is achieved through the application's built-in animation that shows for example the movement of virus towards cell barriers and glucose across cell junctions. The **scaling** experience allows the users to change the size of the cell junctions by making them larger to see inside their intricate parts or smaller to gain a broad picture. The **manipulation** using the hand controllers allows the user to rotate the cell junctions to see their different sides.
Representations of science	The representations in this experience include **cellular and sub-micro** representations to show the different parts of a cell (e.g., wall, membrane) as well as glucose and virus. The experience is likely to be of value to students studying secondary or undergraduate biology and health science courses.

At any point during the narration, the user can pause the narration and interact and observe the objects more closely by rotating, moving or scale them. A video clip demonstrating the application may be viewed at HoloPundits (2020) and a stylised visual representation is shown in Figure 4.

Figure 4. A stylised visual likeness of a user interacting with the immersive application.

Table 8. VLMI analysis.

VLMI	
IVR technological affordances	**Embodiment**: Application was designed for two users to interact with one another and see each other's movement in a collaborative virtual space. **Navigability**: Full immersion in allowing users to walk around and examine the molecules and their bonds up-close. **Interactivity**: Dual-controller input, featuring virtual hands for users to touch, drag and rotate molecules. **Sense-ability**: Interface includes play/pause buttons to view pre-programed animations and voice instructions. **Create-ability**: Learners are transported into a microscopic world of atoms and molecules where they can roam around to see molecular structures and features in the environment.
Exploring science in IVR	The **viewing** experience is a 3D environment that allows users to see the molecules from different perspectives depending on their spatial positions and orientations. The orientation of the molecules change depending on where the user is standing and the direction they are looking from. The **sequencing** consists of several animations that were built into the application, for example, the breaking down of acetylcholine molecule into two smaller molecules – acetate and choline. The application allows the users to start and stop the sequencing at any time in order to scaffold the learning process as they watch the animation. The **modelling** is built into the application which allows users to change the views of the molecules according to different scientific models, namely surface, mesh, ball-and-stick, cartoon and ribbon models. The **scaling** experience allows the users to change the size of the molecules in relation to themselves by zooming into and out of the objects. The scaling can occur up to 100 magnification, thus allowing the users to enter virtually into objects and see their constituent parts. The **manipulation** experience allows users to grab, move, rotate and assemble the molecules with their hands by using hand controllers.
Representations of science	This experience includes **sub-micro** representations of different molecular representations according to the chosen model. The ball-and-stick model shows the spatial positions of the constituent atoms and bonds in 3D. The surface model shows the relative electron density on an isosurface of the molecule using a colour scale from blue (electron deficit) to red (electron rich). The mesh model shows a surface region that has an equal electron density. The experience is likely to be of value to chemistry undergraduate students.

The Visualising and Learning Molecular Interactions (VLMI) in Table 8 allows two users to interact with animated molecules as well as each other in a virtual space (Tang et al., 2020). A stylised visual representation of users interacting is shown in Figure 5. The molecules in the application include an enzyme called acetylcholinesterase and a neurotransmitter called acetylcholine. The software was specifically designed for chemistry undergraduates to learn about the structure of acetylcholinesterase and identify a particular gorge that leads into the active site where the reaction of acetylcholine takes place.

Discussion

As mentioned, the overall aim of the study was to conceptualise and apply a framework that supports educators, researchers, and designers to evaluate elements of an immersive science application. We synthesised existing IVR and science education research literature in the design of the IRM. Our model encompasses three elements that starts at a broad level of specificity, examining *IVR technological affordances*. This includes the element of

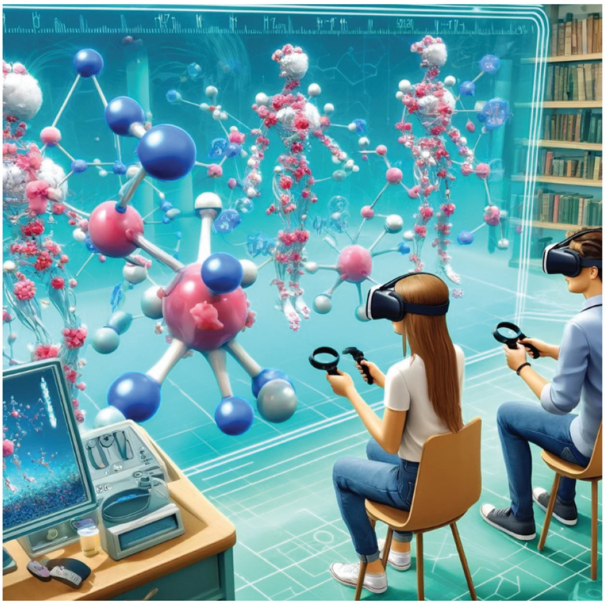

Figure 5. A stylised visual likeness of a user interacting with the immersive application.

embodiment, as discussed in the analysis of Futuclass, which includes spatial sound effects and audible instructor feedback, likely to foster immersion of user's presence within the virtual environment. Futuclass further demonstrates its use of navigability affordance in its IVR design, in which users were given ample agency to explore and interact with virtual objects within the environment at their own pace. The interactivity affordance demonstrates how IVR technology is leveraged to support iterative human-environment exchanges. For example, in the analysis of the VLMI software, the capacity to use virtual hands allowed scope for users to touch, drag and rotate molecules. The sense-ability affordance utilises enablers such as haptic feedback, visual and auditory cues to simulate user senses in IVR environments to varying degrees. For instance, Futuclass utilises haptic feedback in motion controllers to enhance immersion when users pick up a virtual object with virtual hands; whilst The Cell and VLMI utilised audible instructions for a comparatively linear experience in its presentation of learning content. Lastly, create-ability affordance is the scope of the IVR technology to simulate fictional environments to overcome constraints of real-world environments. For example, in VR Brain Exploration, users have agency to position themselves in different parts of the brain and accordingly, experience unique insights in relation to neural pathways, scale and spatial properties. The two remaining elements of the model focus on science-specific analysis of the immersive experience. For example, *Exploring science in IVR* supports stakeholders to evaluate the learning of science in immersive environments.

Evaluations might include, for instance, how the sequencing of animation shows the movement of a virus towards cell barriers or the user's capacity to rotate cell junctions using manipulation. To understand how the immersive technologies may facilitate students' learning, it is necessary to consider how the user's spatial position and orientation impacts the potential for tactile manipulation through hand movements or viewing science-related objects from different perspectives (Tang et al., 2020). In the third level of analysis, *Science representations*, our IRM conceptually aligns with the existing evidence base discussing the importance of representations in the teaching and learning of science (Treagust, 2018; Tytler et al., 2013). Using the IRM, stakeholders classify the different levels of representations in an application, including for example, in our analysis of The Cell, cellular and sub-micro representations.

Evaluating immersive software at the three levels of our IRM is designed to help stakeholders consider possible learning opportunities, limitations, and facilitate pedagogical decisions about the use, or otherwise, of IVR in a science learning experience. It is anticipated that the use of the IRM will simultaneously support educators to judge the benefits and limitations of using an immersive experience in their teaching beyond students' typical "sugar rush of novelty" when first using IVR. As a general note of caution, it is apt to be aware of the "technological evangelist" rhetoric that sometimes surrounds IVR- educators need to avoid a situation where students are "headset on, minds off" (Cooper & Thong, 2018). The model design, and part of its contribution to the field, is to encourage users to focus more on the "*so what*" factor when considering the use of IVR in their science teaching. The challenge for educators is to think critically about the most effective way to teach the science-in some situations, that will be with IVR and in other contexts, it will be without.

It is timely to contemplate the possible research implications of immersive environments for the emerging research themes about science representations. The rapid advancement of immersive technologies presents unprecedented opportunities for reshaping science education. These immersive environments can create highly engaging and interactive experiences that go beyond traditional educational methods, allowing learners to explore scientific concepts in a more intuitive and hands-on manner. We might be at the beginning of a new, significant, and distinct research direction examining immersive representations of science. This new direction has the potential to transform science education by providing immersive experiences that foster deep understanding and retention of scientific knowledge. Related closely to the pillars of the IRM, *immersive representations* are conceptualised here as digital objects intended to promote science-related knowledge, skills, dispositions, and philosophies in an immersive environment. These digital objects can range from 3D models of molecular structures to interactive simulations of complex scientific phenomena, all designed to enhance the learner's experience and engagement with the subject matter. Immersive representations as digital objects hold immense potential to revolutionise science education. By making abstract concepts tangible, providing interactive and adaptive learning experiences, and supporting both individual and collaborative learning, these digital objects can significantly enhance the acquisition of science-related knowledge, skills, dispositions, and knowledge. As the technology continues to advance, the scope and impact of these immersive representations are likely to expand, opening up new frontiers in how we understand and engage with science.

Related to the former, it is yet to be seen how other associated technologies evolve in this space, for instance, haptics. Haptic technology, which involves tactile feedback, has the potential to add a new dimension to immersive learning experiences by allowing users to physically interact with digital objects. The evidence base for the perceived value of haptic feedback in IVR is still emerging, and possible implications for science educators are presently unclear – few currently have access to this technology. The limited availability and high cost of haptic devices have been significant barriers to their widespread adoption in educational settings. Increasingly though, it appears that students will be able to engage with tactile feedback from digital objects in immersive environments, essentially, they will be able to feel the science representation. This tactile engagement can significantly enhance the learning experience by providing a more realistic and tangible connection to abstract scientific concepts. For example, feeling the texture of a cell membrane or the heat generated by a chemical reaction can make these concepts more memorable and understandable.

Design considerations and guidelines for multisensory learning systems, such as haptic technologies, remain challenging and uncertain (Seifi et al., 2020). Developing effective haptic feedback systems requires careful consideration of various factors, including the accuracy and realism of the tactile sensations, the integration with visual and auditory feedback, and the overall user experience. These challenges need to be addressed to create effective and seamless multisensory learning environments. If access to haptics increases as expected, immersive representations of science, such as the feeling of heat or the sensation of smooth surfaces, are likely to be of significant interest to educators and researchers alike. This increased interest could drive further innovation and research in the field, leading to the development of more advanced and accessible haptic technologies. As these technologies become more integrated into educational practices, they may provide new insights into how multisensory experiences can immerse students in their science learning.

Limitations and future research

As discussed, it was not possible to analyse every level or experience of the immersive applications examined in this study. This limitation should be kept in mind when considering the specific applications analysed. This also underscores the need for stakeholders to evaluate software within the context of their unique circumstances. Given the infancy of research about immersive experiences in science education, there is ample opportunity for exploration and innovation. Further research into immersive representations and additional work applying or refining the IRM could be highly productive areas for future investigation. As networked IVR evolves, there will be greater opportunities for peer learning in collaborative virtual environments. This includes the potential for users to simultaneously engage with immersive representations of science, making this an exciting and promising area for future research. Additionally, it might be interesting to see how teachers and students could assess the content using our framework and methods. By evaluating how educators and learners interact with and understand these immersive representations, we may gain insights into the effectiveness of the IRM in different educational settings. This could involve teachers using the framework to structure lessons and activities, and students providing feedback on their learning experiences. Such studies may highlight the practical applications of the IRM and potential benefits in enhancing science education.

Conclusion

In conclusion, the exploration of IVR in science education reveals significant potential to revolutionise pedagogical practices. By creating highly engaging and interactive learning environments, IVR offers unique opportunities for students to deeply understand scientific concepts. The IRM developed in this study provides a robust framework for evaluating and enhancing these immersive learning experiences. Through the integration of IVR technological affordances, exploring science in IVR, and diverse science representations, educators can design and implement effective educational experiences that transcend traditional methods. The ability to interact with immersive learning environments transforms abstract concepts into tangible learning experiences. As the technology continues to advance, the impact of these immersive representations will likely expand, further enriching science education. In sum, the integration of IVR in science education holds promise for creating impactful and engaging learning experiences. The IRM serves as a valuable tool for educators, researchers, and designers to evaluate and enhance these experiences, ensuring that the benefits of immersive technologies are fully realised. As we move forward, continued exploration and innovation in this field will be essential to harness the transformative potential of IVR for science education.

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- Generative artificial intelligence was used in this research article to enhance word selection, flow, and sentence construction. It was also used to create images that appear in this publication. We acknowledgement that authors have reviewed, edited, and take full responsibility for their use of GenAI in the research.

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Appendix A: The Immersive Representations Model (IRM)

Immersive application name:	
IVR technological affordances	Embodiment: Navigability: Sense-ability: Interactivity: Create-ability:
Exploring science in IVR	Viewing: Sequencing: Modelling: Scaling: Manipulation:
Representations of science	Physics/Chemistry: Macro: Sub-micro: Symbolic: Biology: Macro: Cellular: Sub-micro: Symbolic: