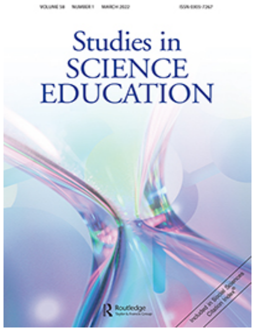

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Immersive virtual reality for science learning: Design, implementation, and evaluation

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ABSTRACT

The advanced visualisation and interactive capabilities make immersive virtual reality (IVR) attractive for educators to investigate its educational benefits. This research reviewed 64 studies published in 2016–2020 to understand how science educators designed, implemented, and evaluated IVR-based learning. The immersive design features (sensory, actional, narrative, and social) originally suggested by Dede provided the framework for the analysis of IVR designs. Educators commonly adopted IVR to better aid visualisation of abstract concepts and enhance learning experience. IVR applications tended to have sensory and actional features, leaving out narrative and social features. Learning theories did not appear to play a strong role in the design, implementation, and evaluation of IVR-based learning. Participants generally reported their IVR experiences as positive on engagement and motivation but the learning outcomes were mixed. No particular immersive design features were identified to result in better learning outcomes. Careful consideration of the immersive design features in alignment with the rationales for adopting IVR and evaluation methods may contribute to more productive investigations of the educational benefits of IVR to improve science teaching and learning.

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Immersive virtual reality; science education; technology-enhanced learning; human-computer interaction; Chemistry education

Introduction

The interest in advanced visualisation technologies, such as immersive virtual reality, has increased in recent years (Radianti et al., 2020). In education, researchers have investigated the technologies to enhance engagement and learning experiences (Di Natale et al., 2020; Radianti et al., 2020). Three forms of visualisation technologies, namely, augmented reality (AR), desktop virtual reality (DVR), and immersive virtual reality (IVR) are often discussed together as 'virtual technologies' (e.g., Martín-Gutiérrez et al., 2017) but they have distinct differences. Augmented reality (AR) involves a device with a camera (such as AR goggles or smartphones) to overlay digital content onto the real-world objects so that users can see

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both the real and virtual environments simultaneously (Garzón, 2021). Desktop virtual reality (DVR) relies on 2D computer screens for display, with a keyboard, mouse, or joystick for interactivity (Di Natale et al., 2020). Immersive virtual reality (IVR), on the other hand, involves a headset to block out the view of the real physical environment and instead provides a stereoscopic display of computer-generated 3D graphics to immerse users in the virtual environment. IVR hardware can track users' body movements in real time to allow them to perform actions and experience the consequences, which may be practically impossible in real life (Slater & Sanchez-Vives, 2016). These technical features of IVR allow learners to believe that they are present in the new virtual environment and the virtual events are really happening to enhance their engagement.

The distinct nature of IVR on graphics, interactivity, and embodied movement opens up new opportunities for learning (Slater & Sanchez-Vives, 2016). These capabilities have prompted more researchers to investigate the educational benefits of IVR (Radianti et al., 2020). Science and engineering education, in particular, have been identified as discipline areas heavily investigating the educational benefits of IVR (Hamilton et al., 2021; Radianti et al., 2020; Villena-Taranilla et al., 2022; Wu et al., 2020).

With increasing interest in adopting IVR in education, researchers have conducted literature reviews on the effects of IVR for engaging learners and achieving learning outcomes (e.g., Coban et al., 2022; Jensen & Konradsen, 2018; Di Natale et al., 2020; Wu et al., 2020). However, despite science education being a major area of educational IVR research, previous reviews have focused on general educational areas without clearly addressing the specific needs of science education. In addition, these reviews tended to overlook the nature of the IVR applications used or the rationales for which educators adopted IVR. Consequently, these reviews did not attempt to explain why some IVR studies resulted in positive learning outcomes while others had mixed or negative outcomes. Other literature reviews identified key design features in educational IVR applications such as perceptual and content stimuli (Suh & Prophet, 2018), fidelity; usability, autonomy, movement, and navigation (Chavez & Bayona, 2018); or realistic surroundings, passive observation, interaction with objects, and immediate feedback (Radianti et al., 2020). Knowing about these design features is helpful in gaining ideas of what is already employed in educational IVR applications but does not provide insight into the levels of the features integrated or their relationship with the rationales for adopting IVR in educational settings.

To design meaningful learning experiences with technological tools, educators need to understand the unique features of the technology that could be used to facilitate learning and offer new educational possibilities (Dalgarno & Lee, 2010; Fowler, 2015; Mikropoulos & Natsis, 2011). The present review was designed to investigate how IVR applications have been designed, implemented, and evaluated in science learning settings and identify what researchers have found in terms of the effectiveness of IVR for achieving different learning outcomes. Based on the available literature of recent years, this review paper investigated the following research questions:

- What were the rationales for adopting IVR in science education?
- What learning theories were identified and incorporated in the design, implementation, and evaluation of IVR learning activities?

- What immersive design features were incorporated in IVR studies?
- Did the immersive design features incorporated differ for different rationales of adopting IVR?
- How were IVR learning activities evaluated and what learning outcomes were achieved through IVR learning activities?
- Did the evaluation of learning activities and achieved learning outcomes differ for different rationales of adopting IVR?
- Did particular immersive design features lead to more positive learning outcomes?
- Did learners with particular characteristics report more positive learning outcomes?

By documenting the common immersive design features and learning outcomes in relation to the rationales for adopting IVR, this review aims to establish how and why researchers adopted different combinations of immersive design features to achieve different learning outcomes in science education.

Immersive design features for educational IVR applications

Immersive virtual reality (IVR) started to gain public attention around 2016. With major breakthroughs in computational powers and display graphics, coupled with heavy investment on IVR development from major technology companies such as Samsung and Facebook (Meta), the IVR technology has become more affordable with high fidelity graphics (Bower et al., 2020; Wu et al., 2020). Educators are now considering IVR in practical terms rather than in hypothetical terms (e.g., Klippel, Zhao, Jackson et al., 2019).

In designing IVR applications for educational purposes, researchers have focused on the unique technical capabilities of IVR: realistic 3D visualisation and real-time motion tracking give users the feeling of being transported into the virtual environment and interacting with virtual objects (Cummings & Bailenson, 2016; Radianti et al., 2020; Suh & Prophet, 2018). The perception of being immersed in a virtual environment, referred to as presence, often serves as the design goal of the IVR applications (Cummings & Bailenson, 2016). To learn science through IVR, students need more than feeling presence in IVR; they also need to be engaged. Researchers (e.g., Mikropoulos & Natsis, 2011; Winn, 1993) have recommended various ways to take advantage of the technical capabilities of IVR for science education. Examples include offering first-order experiences of being able to move and interact with objects in unfamiliar environments (e.g., Kwon, 2019), embodying a different being or object (e.g., Markowitz et al., 2018), or showing extremely small or large objects that are not easily visible (Slater, 2017). These recommendations highlight the technical capabilities of IVR in the context of science learning. However, these recommendations have the risk of undervaluing the importance of the organisation of the learning content and the benefits of social interactions in IVR studies.

To highlight the key aspects in designing IVR applications for educational purposes, Dede and colleagues identified four immersive design features that educators may consider: sensory, actional, narrative, and social (Dede, 2009; Dede et al., 2017). This consideration provided a useful starting point for identifying key features that researchers may wish to consider when designing IVR applications to engage learners and help them learn science. However, those categories are generally broad (except sensory) and do not state how the suggested features could be implemented or how they would support learning. Therefore, in our earlier work (Won et al., under review), we adapted the four categories and expanded them to create a set of immersive design features. In the present paper, we used ten immersive design features for analysis: visual, audio, haptics, interactivity, virtual body ownership, embodied movement, character, challenge, storyline, and social interactions. Below, each design feature is described:

Sensory

Compared to other technological tools (such as AR or DVR), IVR has superior sensory appeals, especially the *visuals*, to induce a perception that users are physically in the virtual environments (Dede, 2009; Dede et al., 2017). Through stereoscopic 3D visual representations, IVR displays realistic, but simulated environments. For example, when the realistic 3D graphics of a wooden plank at the top of a skyscraper and its surroundings is well delivered in an IVR application, users feel the fear of falling off from the skyscraper as they would in real life (Krupić et al., 2021). The perception of being present in the computer-generated location is referred to as 'place illusion' (Slater & Sanchez-Vives, 2016). The 'place illusion' can be induced for both real and imagined virtual environments, such as visiting an old temple to marvel at its architecture and artefacts (real environments e.g., P.-H. Han et al., 2019) or walking across a narrow passageway to the catalytic chamber of an enzyme (imagined environments, e.g., Won et al., 2019).

The visualisation capabilities of IVR can be advantageous for science education because, instead of dealing with abstract science concepts in symbolic representations such as equations and formula, learners can explore science concepts in a concrete way. For example, by moving into human cells to look around and observe different organelles in 3D (e.g., Jian Zhao et al., 2020) or scaling down planets in the solar system and observing them from multiple perspectives (Madden et al., 2020). Such 3D visualisation of scientific phenomena supports the development of learners' conceptualisation as well as their spatial knowledge (Bowman & McMahan, 2007; Dalgarno & Lee, 2010).

In addition to the realistic graphics, the *audio* effects through IVR headsets can enhance the place illusion by providing a sense of direction and distance in virtual environments (Slater, 2017). *Haptic* feedback through IVR controllers or gloves can also enhance the feeling of interacting with virtual objects to increase engagement (Dede, 2009), but compared to other sensory appeals of IVR technology, haptics is least realistic.

Actional

IVR has powerful motion tracking capabilities to map learners' body actions onto the display of the virtual environments to give an illusion that their interactions in virtual environments are real and have real consequences (Slater & Wilbur, 1997). For example, when learners move their heads left and right and arms up and down in the physical environment, they would see a rock from left and right and a virtual ruler moving up and down to measure the dimensions of a rock in the virtual environment (Klippel, Zhao, Jackson et al., 2019). A responsive IVR system with a high degree of user *interactivity* induces the perception that learners themselves are in the virtual environment, making consequential actions (Dede, 2009; Dede et al., 2017). This perception is called 'plausibility illusion' which can be enhanced by interactive interfaces and real-time tracking of embodied movements (Slater, 2017).

The motion tracking capabilities of IVR for *embodied movement* coupled with an interactive interface can be beneficial for science education not only because this combination allows learners to become familiar with dangerous or ethically restrictive procedures such as handling dangerous chemicals (e.g., Broyer et al., 2020) or operating on ill patients (e.g., Lohre et al., 2020), but also because it encourages learning of abstract concepts by engaging embodied cognition (Johnson-Glenberg, 2018).

Related to IVR's motion tracking capabilities is *virtual body ownership*. When learners interact in virtual environments, they can assume either a bodiless spirit or a virtual persona (avatar) to interact and make changes in the virtual environments (Sanchez-Vives & Slater, 2005). When avatars are well constructed to give personal meaning to users, such as going through a job interview as a person of different gender and ethnicity, the users readily assume the virtual bodies and their roles to experience virtual events as avatars (Slater, 2017).

Narrative

Beyond the technical capabilities of IVR, the content of the IVR applications and how to organise the content are critical for educational designers to consider (Suh & Prophet, 2018; Won et al., under review). Based on game design, the authors of the current review paper identified three design components, *character, storylines*, and *challenge*, to engage learners as the main character (protagonist) of an intriguing story that would challenge and improve their knowledge and skills (Dede, 2009; Dede et al., 2017). For example, in a story, learners can assume the character of a soldier in a white blood cell army who patrols a human body and fights off pathogens in case of an infection (Zhang et al., 2019). Learners can identify pathogens, experiment ways to fight off the pathogens without damaging the body and complete the quest of defending the body. Assigning clear character roles to learners offers an opportunity for learners to execute their roles and become emotionally engaged in the learning tasks (Dede, 2009; Dede et al., 2017; Lee, 2004). Making intriguing storylines and assigning appropriate challenges in IVR applications involves knowing where learners are and what they are willing to do in IVR settings. As Csikszentmihalyi (1990) noted, when the learning tasks are comprehensible and aligned to learners' knowledge and skills, learners immerse themselves to complete the learning tasks, losing sense of themselves and the track of time.

Although those three components of narrative design features are drawn from game design, they have a direct link to general educational principles of learning: having ownership of the task, recognising the relevance and importance of the task, and acquiring the feeling of accomplishment from completing and challenging manageable tasks.

Social

Learning occurs not only through the interactions between a learner and the environment, but also through interactions amongst learners and with knowledgeable others (Dede et al., 2017; Vygotsky, 1978). Learning designers consider learners' interactions with other people (peers and teachers) and animated characters (pedagogical agents) in IVR environments (Dede et al., 2017). Recent developments in IVR technology allow learners to interact with others in virtual environments by sharing a virtual space through a network or other means (e.g., Šašinka et al., 2019). Going through learning tasks together with peers in computer-supported collaborative learning environments tends to increase learner motivation and conceptual understanding (Chen et al., 2018; Krämer, 2017). In addition, being there together in a virtual environment increases the sense of belonging in the virtual environment and thus engages learners (Dalgarno & Lee, 2010). On the other hand, social interactions between learners and pedagogical agents in the virtual learning environments or teachers may provide a constructive way to prompt learners to reflect on their progress in the learning tasks, as well as to provide feedback or guidance on the learners' performance. *Social* is the last design feature the authors of this manuscript identified for IVR applications.

Methods

Selection of literature for analysis

To retrieve literature on the use of IVR in science education, we surveyed studies published in the period 2016–2020. The year 2016 was chosen as the starting year because HTC's VIVE and Facebook's Oculus Rift headsets then became available to the general public and the number of studies exploring the potential of IVR in science education increased dramatically. The last literature search for this study was conducted on 18 October 2020. Figure 1 shows a summary of the literature selection process.

Electronic literature search was conducted on five scholarly databases (ProQuest, Google Scholar®, Scopus, Web of Science and Springer Link®). ProQuest, Scopus, and Web of Science were chosen because they contain a large collection of journal articles from a wide range of research fields. Google Scholar and Springer Link were included because they are large repositories of book chapters and conference papers from various research domains.

Initially, a general search term 'virtual reality' was included in the search string. A large number of studies (>30,000) was generated, including those which employed desktop-based applications such as *Second Life*. To limit the search to only studies using head-mounted display (HMD) units in science education fields, we used the search term 'immersive virtual reality' instead of 'virtual reality'. The final search string employed was 'immersive virtual reality' AND (education OR teach OR learn) AND (science OR chemistry OR biology OR physics OR astronomy OR earth) AND NOT (medical OR therapy OR rehabilitation). The specific search terms (education OR teach OR learn) AND (science OR chemistry OR biology OR physics OR astronomy OR earth) were included to restrict the search to only those studies using IVR in science learning disciplines.

The initial automatic database search yielded a total of 5,141 documents (ProQuest 267, Google Scholar 3850, Springer Link 90, Web of Science 70, and Scopus 864). We conducted a supplementary literature search on two other databases, ERIC, and IEEE *Xplore*. The search did not yield any new studies which met the inclusion criteria.

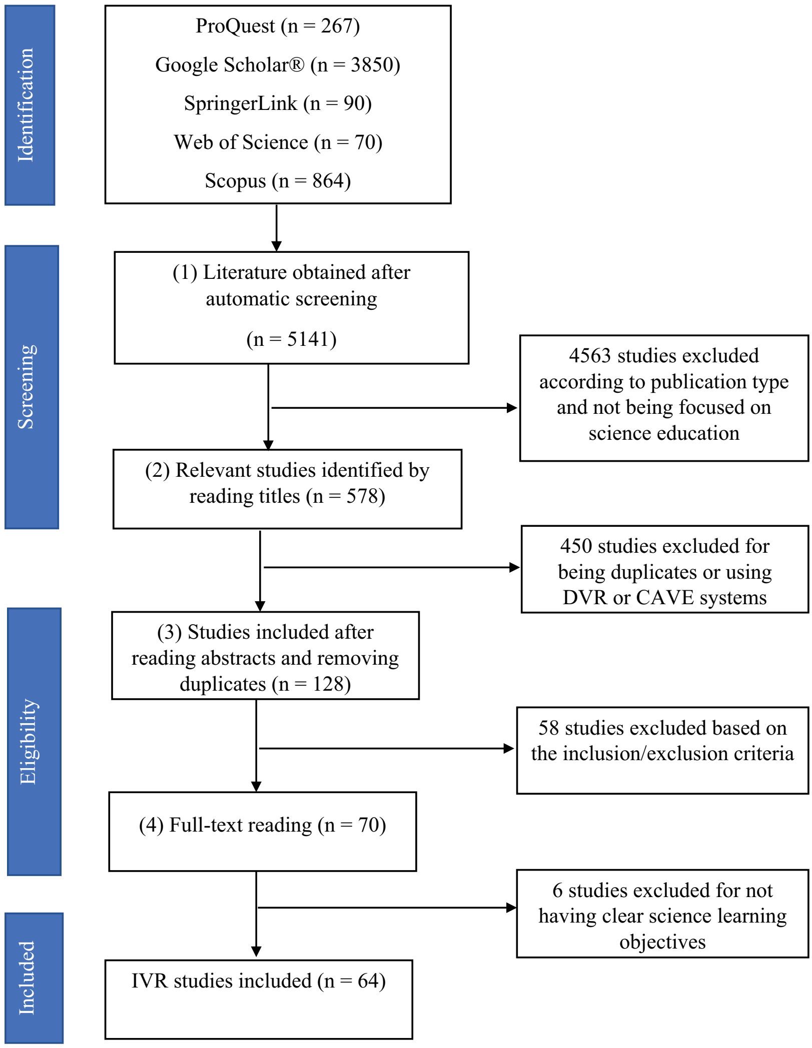

Figure 1. The literature selection chart.

Two of the authors of this paper read through the titles of the studies and initially screened the studies according to document type and field of study. Only documents from sources rated in SciMago Journal and Country Rankings were retained for further review. These included peer-reviewed journal articles, book chapters, and conference papers or proceedings from reputable conferences. The field of study was limited to science education fields (chemistry, biology, physics, astronomy, environmental science, integrated science, and earth science/geology). Studies in the fields of entertainment/ gaming, safety training, computer science, engineering, cognition, medicine, therapy, and rehabilitation (e.g., Feng et al., 2020; Lee et al., 2020) were excluded. Based on these criteria, 4653 studies were excluded.

The same two authors then read through the abstracts of the remaining 578 documents to screen out duplicates and studies which used DVR and Cave Automatic Virtual Environment (CAVE) systems (450 studies). A total of 128 studies remained. The first round of focused reviews of full text with further inclusion and exclusion criteria was conducted. A particular study was included in the review if the full-text was available in English and the study reported use of an IVR headset (HTC VIVE, Oculus Rift or DK, Sony PlayStation VR, or phone-based headset such as Xiaomi Mi VR, Samsung Gear VR or Google Cardboard VR). In addition, only studies reporting empirical evaluations of the students' learning outcomes were included in the review while those only focusing on the design of IVR programs without evaluating learning outcomes (e.g., Salvadori et al., 2018) or those that used secondary data (such as literature reviews) were excluded (e.g., Pellas et al., 2020). The inclusion and exclusion criteria used to screen the studies are outlined in Table 1. After applying the inclusion and exclusion criteria, 70 studies were retained. Six more studies were further removed for lacking clear science learning objectives (e.g., Filter et al., 2020). A total of 64 studies remained.

Analysis of the studies

The 64 studies were analysed qualitatively using a content analysis methodology (Krippendorff, 2018). For each study, information relevant to each research question was identified. We created a spreadsheet to summarise the key information including the science discipline (chemistry, biology, geology/earth science, integrated science,

Table 1. Inclusion and exclusion criteria for the studies.

Screening stage	Category	Inclusion Criteria	Exclusion Criteria
1	Search terms	'immersive virtual reality' AND (education OR teach OR learn) AND (science OR chemistry OR biology OR physics OR astronomy OR earth) AND NOT (medical OR therapy OR rehabilitation)	
	Publication period	Studies published from January 2016 to October 2020	Studies published before January 2016
	Language of publication	Full-text available in English	Full-text available in other languages
2& 3	Study Materials	Studies reporting use of head mounted displays, HMDs (e.g., HTC VIVE, Oculus Rift, Samsung Gear, Google Cardboard)	Not using HMDs (i.e., those reporting use of AR gears, CAVE, or DVR)
	Document Type	Studies published in peer-reviewed journals, books, or conference proceedings rated in Scimago Journal and Country Rankings (SJR)	Studies from sources that are not rated in SJR
	Field of Study	Studies conducted in science education fields	Studies outside science education, such as those in medical, therapy, rehabilitation, or gaming fields
	Type of Study	Studies reporting empirical evaluation of science learning outcomes	Studies focusing on IVR program development without evaluations of learning outcomes; studies using secondary data (e.g., literature reviews, or meta-analyses)
4	Use of IVR in the study	Studies providing clear descriptions of the science learning objectives	Studies without clear science learning objectives

environmental science, physics, and astronomy), the target learners (elementary school, middle school, high school, university levels, or general public), the learning objectives, and the research objectives for each study. When stating the research objectives of the studies, the terms 'effectiveness' and 'impact' were consistently used. The former was used when the studies measured science learning outcomes and the latter when the studies evaluated learners' perceptions such as usability or usefulness of IVR. The 64 studies included in the analysis have been summarised in **Table S1** (online supplementary material).

We then identified the rationales for adopting IVR, the learning theories employed, the integration levels of the immersive design features in IVR studies, the immersive design features for different rationales, the learning outcomes reported, and the methods used to measure the learning outcomes. We also identified the learning outcomes achieved depending on the rationales of adopting IVR, and the design features and learner characteristics that led to positive science learning outcomes. Below we describe the coding process:

Coding of the rationales for adopting IVR

Based on commonly listed educational benefits of IVR (Freina & Ott, 2015; Slater, 2017), we identified five potential categories as the rationales for adopting IVR in science education: visualisation, enhancing learning experience, procedural skills development, field trips, and first-person experience. Researchers tended to explicitly state the rationales for adopting IVR in the introduction or literature review sections of the studies. For instance, Thompson et al. (2020) designed an IVR application with the aim of helping learners visualise human cells. Cells are practically hard to visualise due to their extremely small sizes (Thompson et al., 2020). The rationale for adopting IVR in this study was coded as enhancing visualisation of abstract concepts. In another study, Bibic et al. (2019) designed an IVR application with an explicit aim of improving engagement of learners in learning about the biochemistry behind spider venoms. The rationale for adopting IVR here was coded as enhancing learning experience.

In some studies, however, researchers discussed the rationales for adopting IVR in very general terms, citing several advantages of using IVR or simply comparing learning outcome gains for IVR with other media. In such cases, the authors of the present study inferred the rationale for adopting IVR from the nature of the IVR application used, the nature of the learning tasks, and the learning outcomes evaluated. For example, Meyer et al. (2019) compared the effect of pretraining on declarative knowledge acquisition using a 2D video or an IVR simulation. Although the authors did not explicitly state why they adopted IVR in their study, the nature of the IVR simulation (*The Body VR: Journey Inside a Cell)* suggested that it was meant to help learners visualise organelles and their functions, concepts which are not easily perceptible. Besides, the authors evaluated declarative knowledge about the nature and functions of organelles. In this case, the rationale for adopting IVR was coded as enhancing visualisation of abstract concepts.

Coding of the learning theories identified and incorporated in IVR learning activities

The learning theories that researchers identified and used to design or adopt, implement, and evaluate IVR for science teaching and learning varied in depth and details. In coding these, the theories, models, approaches, or principles were first summarised as they were stated in the introduction, the literature review, and the method sections of the studies. We then identified hierarchical relationships of these specific models, principles or approaches to the broader learning theories, such as cognitive theory of multimedia learning, experiential learning theory, motivational theories, embodied cognition, and social constructivist theory (Pritchard, 2017; Schunk, 2012). For example, Andreasen et al. (2019) designed a study to evaluate the effectiveness of enactment as a way of fostering active cognitive processing of science content learned from IVR. The study was designed and evaluated based on the assumption of active processing of the cognitive theory of multimedia learning. Therefore, for this study the theoretical principle for designing, implementing, and evaluating IVR was identified as fostering generative processing; and the broader learning theory was identified as the cognitive theory of multimedia learning (Mayer, 2005). For each study, information on how the identified learning theory was used to design, implement, or evaluate the IVR application was also extracted from the descriptions provided in the method section of the study. We then referred to the relevant informing literature and compared the descriptions provided in the studies with the principles of the stated theory from literature to confirm if the theory was appropriately employed to design, implement, and evaluate the IVR application.

Coding of the immersive design features in IVR studies

The integration levels of the 10 immersive design features were evaluated for each of the 64 studies. For each study, information about the IVR application used and its design features was obtained from the descriptions and/or screenshots provided in the studies, electronic supplementary materials, or links to promotional YouTube videos of the IVR applications, where available. In some cases, different studies used the same IVR application with very similar hardware. For example, Parong and Mayer (2018), Parong and Mayer (2020), and Jian Zhao et al. (2020) all used the same commercial program *The Body VR: Journey Inside a Cell* with HTC VIVE headsets to conduct their studies. However, because the studies used the IVR application with different groups of learners to obtain different learning outcomes, the IVR studies were coded independently.

For each design feature integration, the authors of the present study devised a 3-level coding scheme – low, medium, or high. Three of the authors initially selected five representative studies and trained on the coding scheme, detailing rules of what constituted each level of integration. The coding of the IVR design features was not a linear process. The three authors went back and forth between the reviewed literature and the coding scheme and held meetings to refine the categories and the descriptors for each immersive design feature until consensus was reached. For example, the level of integration of visuals depended on the type of environment being simulated (real or imaginary), the type of HMD used (lower-end mobile phone-based HMDs such as Samsung Gear, or the high-end HTC VIVE and Oculus Rift HMDs), and the comprehensiveness or realism of the visual representations. Generally, mobile phone-based IVR devices have low screen resolutions, low refresh rates, and small fields of view, and tend to be less effective in sensory immersion (Cummings & Bailenson, 2016). Therefore, if an IVR application displayed very simplified real environments (such as those generated using Minecraft®) in a mobile phone-based HMD, the view is less immersive, and we coded the study as low on visuals. If high-quality images of a real environment were displayed in a high-end HMD, such as HTC VIVE or Oculus Rift, the IVR application was coded high on visuals. For imaginary environments, if representations of the reified science concepts were displayed on a mobile phone-based headset, the level of visuals was coded as medium. This decision is because learners are still likely to have an immersive experience when they have not had any prior physical experience with these objects in the real-world (Lee, 2004). When scientifically comprehensive representations of reified concepts were displayed using a high-end HMD, the study was rated as high on visual immersion. Scientifically inconsistent visual representations of reified concepts were coded as low level.

For the three actional immersive design features, how well an IVR application represented learners' bodies and made learners' actions feel natural and believable within the virtual environment was considered. For example, in terms of *interactivity*, if the learner had limited control over the content presented (such as in 3D movie-type IVR designs), the level of interactivity was coded as low. On the other hand, if the learner could rotate or flip virtual objects and the IVR system responded realistically, the level of integration was coded as medium. A high level of integration of the interactivity feature was assigned when the IVR application afforded the learner to create new artefacts in the virtual environment.

For narrative immersive design features, the extent to which learners were engaged with the learning content and motivated to exert efforts to accomplish the set tasks was considered. For *character*, for example, if the learner simply completed a learning task without any character role they could identify with, the study was coded as low-level. However, when the IVR application assigned to the learner a character role with which they could identify in first-person but the learners did not execute any consequential actions, the level of integration of *character* was coded as medium; such examples of medium-level character are as a coral being affected by climate change (Markowitz et al., 2018) or as a forensic analyst who simply collected evidence from a crime scene (Kader et al., 2020). An IVR application was rated as high level on *character* if the role assigned to the learners allowed them to make decisions which significantly influenced the unfolding of the storyline.

Regarding the social immersive design feature, we considered whether or not the IVR design encouraged social interactions between learners in IVR and their peers to construct knowledge together, or with teachers or pedagogical agents for guidance or feedback on the learners' progress. If the learners went through the learning tasks individually without any form of social interactions during the IVR session, the level of integration of *social* was coded as low. If the learner in IVR engaged in some form of mediated social interactions with peers or teachers who were outside the IVR space, or received feedback from a pedagogical agent in IVR, the level of integration of *social* was coded as medium. However, if the IVR application allowed learners to share the virtual space and work on the IVR learning tasks collaboratively, the level of integration of *social* was coded as high. Descriptors of each integration level of the different design features are detailed in Table 2.

Two of the authors of this paper individually read and coded all the 64 studies using the above criteria. The authors assigned individual scores to the immersive design features in each study and then compared their individual analyses of the studies. To assess the reliability of the coding scheme, Spearman's correlation coefficient (rho) for

Table 2. Coding scheme for evaluation of the immersive design features in IVR studies.

Immersive design features	Level of integration of the immersive design features		
	Low	Medium	High
Visual	Low-fidelity graphics (e.g., low-quality images of real environments rendered in Google Cardboard as in Cheng & Tsai, 2020)	Medium quality graphics (e.g., comprehensive representations of science concepts or realistic graphics of real environments rendered in phone-based headsets as in Makransky, Terkildsen et al., 2019)	High-quality graphics of real and imagined environments (e.g., comprehensive representations of science concepts rendered in high-end devices such as HTC VIVE as in Jian Zhao et al. 2020)
Audio	No audio effects	Background audio in the form of instructions, narrations, or sound from other social agents (e.g., instructions from a pedagogical agent as in Dunnagan et al., 2020)	Immersive sounds to give a sense of distance and direction in the virtual environment (e.g., immersive ocean sounds as in R. L. Lamb et al., 2019)
Haptics	No haptic feedback	Vibration or force feedback from controllers or haptic gloves (e.g., vibrations from controllers as in R. Lamb et al., 2018)	Haptic feedback to give a realistic sense of interacting with virtual objects (e.g., synchronisation of real and virtual environments as in Ahn et al., 2016)
Interactivity	Minimum or no interaction between the learner and the IVR program content (e.g., watching a 3D movie as in Petersen et al., 2020)	Learner can manipulate objects in the virtual environment to observe effects of their actions (e.g., the learner can rotate, or flip virtual objects as in Parong & Mayer, 2018)	High level of user control (e.g., the learner can create a new artefact in IVR as in Southgate et al., 2019)
Virtual body ownership	The learner's body is not represented in any form in the virtual environment (e.g., Jong et al., 2020)	The learner's body is represented partly in the virtual environment (e.g., learner's hands are represented in the form of floating controllers as in Pirker et al., 2017)	Learner assumes a full virtual body (e.g., the learner embodies a coral as in Markowitz et al., 2018)
Embodied movements	Minimum or no embodied movements relevant to the task (e.g., simple head movements while watching a 3D movie as in Fokides & Kefallinou, 2020)	Some embodied movements relevant to the task (e.g., using hand movements to lift and flip objects as in Lui et al., 2020)	Full body engagements relevant to the learning task (e.g., walking and lowering one's body to measure rock dimensions as in Klippel, Zhao, Oprean et al., 2019)
Character	No clear character role assigned to the learner	The learner assumes some form of character role but does not make consequential decisions (e.g., as a forensic analyst who gathers evidence at a crime scene as in Kader et al., 2020)	The learner is a main protagonist responsible for making consequential decisions (e.g., as a commander of white blood cells to fight pathogens and restore life of a host as in Zhang et al., 2019)
Storyline	The storyline is linear without alternative endings	Storyline with some form of alternative endings (e.g., the learner's actions and decisions determine whether the host lives or dies as in Zhang et al., 2019)	The storyline is clear and changes infinitely depending on the decisions made by the learner

(*Continued*)

Table 2. (Continued).

Immersive design features	Level of integration of the immersive design features		
	Low	Medium	High
Challenge	Learning task does not demand integration of prior knowledge or skills (e.g., learners follow simple instructions as in Ferrell et al., 2019)	Task provides some opportunity for integration of prior knowledge and skills (e.g., learner uses prior understanding to complete learning tasks as in Won et al., 2019)	Task requires integration and application of prior knowledge and/or skills, critical reflection and decision making
Social interactions	Learner individually completes the learning task in IVR	Some form of mediated social interactions with peers, teachers, or pedagogical agents (e.g., one learner in IVR talking to peers outside the virtual environment as in Liu et al., 2020)	Extensive social interactions designed to foster collaborative learning in a shared virtual space (e.g., peer to peer collaboration in a networked environment as in Southgate et al., 2019)

ordinal data was calculated between the coders. Interrater reliability was 0.863 ($p < 0.01$). Any disagreements in coding were resolved through extensive discussions between the coders.

Coding of the evaluation of IVR learning activities

The learning outcomes and experience ratings following instruction in IVR were identified as each was discussed in the 64 studies. In some studies, IVR was compared against an alternative learning mode, such as a 2D learning platform or a lecture type of instruction, while in other studies, learning outcomes or experience ratings after IVR were simply compared to those before the IVR session without a separate comparison group. For each study, the alternative learning mode against which IVR was compared (where applicable), and the methods for evaluating learning outcomes or experience ratings were identified from the methodology and results sections.

Coding of the achieved learning outcomes

Learning outcomes are specifications of the kind of knowledge and understanding, skills and competencies, or values and attitudes that learners are expected to have, demonstrate, or hold at the end of a learning experience (Savickiene, 2010). Learning outcomes were identified directly from the studies and coded as declarative knowledge, procedural knowledge, and attitudinal and behavioural change outcomes. Declarative knowledge dealt with students' understanding of scientific facts and concepts (Anderson & Krathwohl, 2001). Procedural knowledge gains were related to students' understanding of practical techniques, processes, or methods (Adams, 2015; Anderson & Krathwohl, 2001). Learning outcomes coded as attitudinal or behavioural change outcomes dealt with changes in students' perceptions, attitudes, and behavioural intentions towards science and socio-scientific issues.

In addition to learning outcomes, several factors related to the students' learning experience in IVR were identified from the studies. These experience ratings were coded as presence ratings, engagement on learning task, motivation, perceived usefulness, and negative effects (such as dizziness, physical discomfort, or simulator sickness) of IVR.

Learning outcomes and experience ratings for IVR were coded as *better* if they were higher than those evaluated before the IVR session or those reported from use of an alternative learning mode. Similarly, a *worse* code was assigned if the IVR experience was rated negatively or resulted in lower learning outcomes compared to an alternative learning mode or a pre-IVR evaluation. Learning outcomes or experience ratings were coded as *similar* if a study reported no significant differences in learning outcomes or experience ratings between IVR and an alternative learning mode or a pre-evaluation.

Identification of immersive design features incorporated for different rationales of using IVR

After coding the rationales of adopting IVR and the immersive design features incorporated in each study, the 64 studies were categorised based on the rationales for adopting IVR. For each category of studies, the average integration level for each of the 10 design features was calculated. In calculating the average integration levels, we assigned a value of 1 to each low integration level, 2 to a medium integration level, and 3 to a high integration level. The averages were then compared to identify similarities and differences in how IVR studies integrated immersive design features depending on their rationales. Immersive design features which were more commonly adopted had the highest average ratings per category.

Coding of the evaluation of learning activities and achieved learning outcomes for the different rationales of adopting IVR

The 64 studies were categorised depending on the rationale for adopting IVR. For each cluster, the number of studies evaluating the different learning outcomes, the methods used to evaluate the outcomes, and the reported outcomes were identified. The number of the studies reporting *better, similar*, or *worse* learning outcomes for IVR compared to other learning modes or pre-tests were documented for each category.

Identification of the immersive design features that led to positive learning outcomes

The 64 studies were combined and categorised based on whether they reported *better, similar*, or *worse* learning outcomes for IVR compared to other learning modes or pre-tests. Average integration levels of the 10 design features were calculated for each cluster. The averages were then compared to identify the design features that might have caused the differences in the reported outcomes. This approach to identifying the immersive design features that led to positive learning outcomes was adopted because IVR research for science education is an emerging field and therefore, for some categories, the number of studies was very low to allow any advanced statistical analyses. For example, only two studies reported positive procedural knowledge gains while three reported no significant differences for IVR compared to alternative learning modes.

Identification of the learner characteristics that led to positive learning outcomes

Learner characteristics such as demographics (age, gender, prior experience with computer games), cognitive characteristics (class level, prior knowledge), and affective characteristics (such as intrinsic motivation and intrinsic self-efficacy) were summarised as reported in the reviewed literature. The methodology and results sections of each study were analysed for any reported influence of learner characteristics on the achieved learning outcomes. Studies were then grouped depending on how the learner characteristics influenced the learning outcomes and patterns were identified from these clusters.

Results

Overview

IVR has been adopted and studied across all science education areas, with most studies in biology (24 out of 64), followed by chemistry and physics (13 and 11, respectively), and geology and environmental sciences (5 and 6, respectively), and general science (5). Participants in the studies were university level students (58% of the studies), high school (9%), middle school (10%), elementary school (9%), while the rest of the studies (14%) recruited participants from more than one educational level. The number of participants in each study varied. About one-third of the studies had less than 50 participants, another third had 50–100 participants, and the rest of the studies involved over 100 participants in each study (**Table S1** in Online supplementary material).

In most of the studies (n = 57), the students were given a one-time opportunity to learn with IVR. Two studies (Markowitz et al., 2018; Sun et al., 2017) provided initial IVR experiences to familiarise the learners with the technology before the target content was introduced. Some studies (n = 5) provided multiple IVR sessions with different learning content each time (e.g., Artun et al., 2020; Boda & Brown, 2020b; Fokides & Kefallinou, 2020).

More than two-thirds of the studies (n = 44) compared IVR against an alternative learning mode. Forty studies investigated educational benefits of IVR separate from routine learning activities while the rest of the studies (n = 24) adopted IVR as part of the routine learning activities to supplement or even substitute alternative learning modes (e.g., Bennie et al., 2019; Ferrell et al., 2019; Klippel, Zhao, Jackson et al., 2019; Klippel, Zhao, Oprean et al., 2019; Kwon, 2019). In some studies (n = 11), educators recognised that IVR sessions may need to be supported with other learning activities and, therefore, integrated IVR into broader lessons (e.g., Fokides & Kefallinou, 2020; Jong et al., 2020; Kader et al., 2020; Petersen et al., 2020). The target concepts were first introduced to the students through lecture or self-study materials and then explored further in IVR. When learners completed the IVR learning activities, they were then engaged in reflection activities such as group discussions.

Rationales for adopting IVR

We identified five different rationales for adopting IVR in science education settings: to improve students' visualisation of abstract concepts; enhance learning experience; provide access to faraway places through virtual field trips; develop practical skills; and to provide first-person learning experiences. Below each rationale is discussed:

Visualisation of abstract concepts

Science content is generally abstract in nature, dominated by unobservable phenomena and extreme sizes which makes it hard to comprehend the content (Mikropoulos & Natsis, 2011). Twenty-two studies used IVR to help students visualise scientific phenomena that are not easily accessible for physical perception. For instance, in biology and chemistry, researchers used IVR to magnify microscopic 3D entities such as organelles and their functions (e.g., Parong & Mayer, 2018, 2020; Jian Zhao et al., 2020) or molecular structures and interactions (Bennie et al., 2019; Ferrell et al., 2019; Won et al., 2019). In physics and astronomy, researchers used IVR to help learners visualise concepts such as electromagnetic field lines (Pirker et al., 2018, 2017) and to reduce the size of extremely large objects such as planets in the solar system (e.g., Madden et al., 2020; Sun et al., 2017).

Enhancing learning experience

Fourteen studies designed or adopted IVR applications to test the general educational effectiveness of the 'new' IVR technology for science teaching and learning. Researchers used IVR to improve learners' engagement (e.g., Bibic et al., 2019; R. Lamb et al., 2018) and motivation towards learning science (e.g., Y. Han et al., 2020). In their IVR applications, some educators adopted game-like strategies such as integrating rewards, rules, and immediate feedback to the users to keep the learners engaged in IVR (e.g., Edwards et al., 2019; Rychkova et al., 2020).

Practical skills development

Science education requires learners to conduct experiments in laboratories to develop competence in observing, predicting, and making inferences about the physical world. In 13 studies, science educators used IVR applications in the form of virtual laboratories to provide learners with an opportunity to access and practice laboratory procedures with virtual laboratory equipment (e.g., Andreasen et al., 2019; Artun et al., 2020; Dunnagan et al., 2020; Klingenberg et al., 2020; Makransky, Terkildsen et al., 2019) or dangerous chemicals (e.g., Broyer et al., 2020; Makransky, Wismer et al., 2019). Engaging with the virtual equipment and chemicals in IVR was anticipated to improve the learners' familiarity with laboratory procedures.

Virtual field trips

Many concepts in science disciplines such as geology and environmental science require learners to visit field sites but organising traditional field trips is costly in terms of time and finances (J. Zhao, LaFemina et al., 2020). To this effect, 11 studies used IVR applications that were specifically designed to teleport learners to the relevant field sites. For example, in geology, Jong et al. (2020) teleported learners to a field site where they explored coastal geological formations. IVR was also used to teleport learners to faraway places to observe environmental issues (e.g., Fokides & Kefallinou, 2020; Petersen et al., 2020; Yu & Lin, 2020). IVR allowed learners to conveniently visit and explore relevant but hard-to-reach sites.

Providing first-person experiential learning opportunities

Some science concepts appear distant to learners making them challenging to teach and learn (Markowitz et al., 2018). For example, it is impossible to experience life as another person, or animal. Four studies used IVR to provide first-person experiential learning opportunities to help learners develop empathy or change attitudes towards community and environmental issues that are normally hard to experience (Ahn et al., 2016; Gochman et al., 2019; Markowitz et al., 2018; Nowak et al., 2020). For instance, instead of simply showing a video of community health problems associated with influenza transmission, Nowak et al. (2020) designed an IVR application which transformed the learner into an unvaccinated person who spreads the flu to vulnerable members of the community. The learner was then shrunk to the size of a cell to experience how one's immune system would be overwhelmed by viruses if they were not vaccinated. In this way, IVR changed the learner's perspective from third-person (as in the case of watching a movie on a 2D screen) to first-person, fostering a psychological illusion of non-mediation of the experience.

Learning theories identified and incorporated in the design, implementation, and evaluation of IVR learning activities

About half of the studies (29 out of 64) explicitly stated the learning theories supporting the designs, implementation, or evaluation of IVR applications. In these studies, a wide range of learning theories were identified, and their application varied from being applied in the design of the program to the design of the study itself. For instance, following the social constructivist theory of learning, Won et al. (2019) designed an IVR study in which learners shared the virtual space and negotiated meanings within the virtual learning environment. Two other studies were based on the same theory to engage learners in group discussions after individually watching 3D videos in IVR (e.g., Jong et al., 2020; Sun et al., 2017).

However, slightly more than half of the studies that identified learning theories (17 out of 29) designed, implemented and evaluated their IVR applications in line with the referred to learning theories. Lui et al. (2020) explicitly applied a learning theory in the design of an IVR learning activity and research. Using the theory of embodied cognition, an IVR application was designed for learners to learn biology concepts by engaging their bodies, either partly (in a seated position) or fully (standing position). The authors evaluated the effect of sensory-motor engagements by monitoring real-time physiological responses, eye-tracking, and a post-test. The study reported that learning outcomes were influenced by the physical position in which learners experienced the IVR application and their prior knowledge.

Several researchers designed, implemented, and evaluated their IVR applications following the cognitive theory of multimedia learning. These researchers often evaluated specific principles of the theory such as the segmentation, coherence (Parong & Mayer, 2018, 2020), and redundancy principles (Makransky, Terkildsen et al., 2019), as well as the effectiveness of strategies aimed at helping students to actively process the target science content. These strategies included pre-training (Meyer et al., 2019; Nie & Wu, 2020) and opportunities for reflection through summarising the learned content, peer tutoring or enactment of the concepts after IVR (Andreasen et al., 2019; Klingenberg et al., 2020; Parong & Mayer, 2018, 2020). The studies contributed to IVR research by providing useful examples of instructional mechanisms to support learning with IVR.

For most studies (55%), it was difficult to discern whether or not theoretical frameworks guided the design, implementation, or evaluation of IVR because theoretical frameworks were not explicitly stated (e.g., Dunnagan et al., 2020; R. L. Lamb et al., 2019; Pirker et al., 2018; Southgate et al., 2019). In addition, although some studies identified the theoretical foundations such as play-based learning (Choi et al., 2018), learning by doing (Bhattacharjee et al., 2018), or social-cognitive theories (Makransky & Lilleholt, 2018), these researchers did not specify how the principles of these theoretical foundations were used in the design, implementation, or evaluation of IVR as a learning intervention.

Immersive design features in IVR studies

In all the learning settings, the major focus of current IVR studies was the visual and audio design features. Ninety-five percent and 83% of the 64 IVR studies integrated at least medium level visual and audio features, respectively (Figure 2). For actional immersive design features, interactivity was the most common design feature with over 60% of the IVR studies employing at least medium-level interactivity in their IVR applications while integration of virtual body ownership and embodied movements was much less. Narrative and social immersive design features were the least integrated in current IVR studies. Over 85% of the studies had low levels of integration of all the narrative

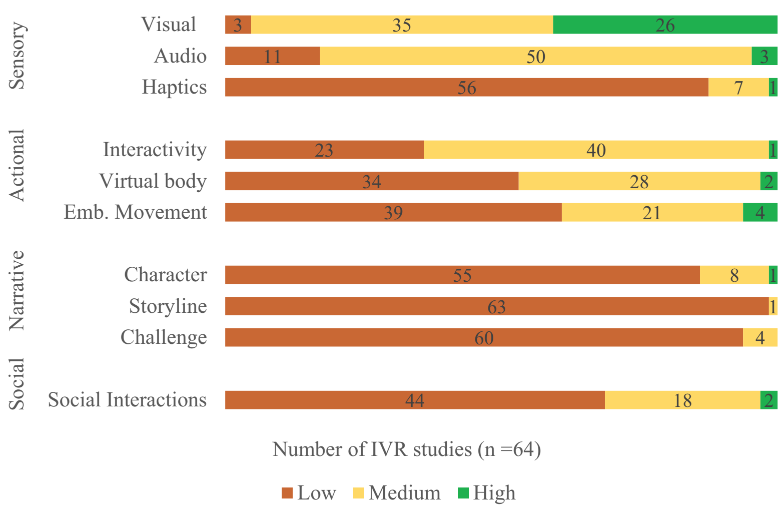

Figure 2. Immersive design features adopted in IVR studies.

immersive design features while over 67% of the studies did not engage learners in any form of social interactions as they completed the learning tasks. Below we further elaborate on these findings:

Sensory – Visual

IVR is a superior 3D visualisation platform which can improve the way we perceive things, and many researchers are utilising this affordance for science education. Twenty-six out of the 64 IVR studies had high level visuals, while 35 studies had medium-level visual representations in their IVR applications. High-level visuals were often integrated in IVR applications to help students recognise spatial relationships in objects that are not easily accessible, such as molecules and planetary systems (e.g., Bennie et al., 2019; Ferrell et al., 2019; Parong & Mayer, 2018). For example, in chemistry, Ferrell et al. (2019) used high-quality 3D graphics in IVR to help students explore non-covalent spatial interactions amongst organic molecules. Some researchers used medium quality graphics to recreate laboratory settings in which learners could practice laboratory procedures (e.g., Broyer et al., 2020; Makransky, Terkildsen et al., 2019).

Sensory – Audio

Fifty-three out of the 64 IVR studies incorporated audio effects of some form in their IVR applications. The majority of the IVR studies provided background audio instructions or narrations (e.g., Bagher et al., 2020; Jong et al., 2020; Klippel, Zhao, Jackson et al., 2019; Nowak et al., 2020; Petersen et al., 2020). In some cases, learners could hear sound from peers outside the VR environment but cooperating on the same learning tasks (e.g., Hsu et al., 2018; Uz-Bilgin et al., 2020). Three IVR studies provided learners with immersive sounds to give them a sense of distance and direction in the virtual environment (Ahn et al., 2016; R. L. Lamb et al., 2019; Won et al., 2019). For example, to fully immerse learners in the virtual environment, R. L. Lamb et al. (2019) used immersive ocean sounds such as that of flowing water and sounds made by marine animals such as whales.

Sensory – Haptics

Haptic feedback was not a major focus in current IVR studies. The majority of the studies (56 out of 64) did not incorporate any form of haptic feedback in their IVR applications. Seven of the IVR studies integrated vibration feedback from the controllers or gloves to provide users with tactile force feedback when they interacted with virtual objects (Edwards et al., 2019; Hsu et al., 2018; R. Lamb et al., 2018; Pirker et al., 2017; Won et al., 2019). Only one study (Ahn et al., 2016) had high-level haptics in their design; the floor in contact with the learners' hands and knees in the real-world was made to vibrate and the learners were poked in the back at the same time as a virtual cattle prod hit their virtual bodies. The synchronisation of the haptic feedback in the real world with actions in the virtual environment was meant to increase the learners' sense of presence in the virtual world.

Actional – Interactivity

An IVR design that affords a level of high user-control and is responsive to the actions of learners is likely to support experiential knowledge construction by encouraging 'learning by doing' (Slater & Sanchez-Vives, 2016). However, about one-third of the IVR studies provided minimal or no opportunities for the learners to interact with the learning content. These studies generally used IVR applications in the form of 360° videos in which learners simply watched the learning content on their headsets and had limited control over the presentation of the content (e.g., Cheng & Tsai, 2020; Meyer et al., 2019; Petersen et al., 2020).

More than 60% of the studies integrated medium-level interactivity in their IVR applications. Using handheld controllers or gloves, learners could manipulate already existing elements in the virtual environment to observe the consequences of their actions. For example, learners could conduct experiments with science equipment (e.g., Makransky, Wismer et al., 2019; Pirker et al., 2017), manipulate the structure of DNA (R. Lamb et al., 2018), or reposition planets in the solar system to observe the moon phases (Madden et al., 2020). A high level of interactivity was provided in only one IVR study (Southgate et al., 2019). The study used Microsoft's Minecraft® in their IVR design which allowed learners to build a model of a plant upon which their discussion of science concepts was based.

Actional – Virtual body

User embodiment using real-time motion capture in IVR encourages transfer of self and the development of soft skills such as empathy through authentic experiences (Slater & Sanchez-Vives, 2016). About one-half of the IVR studies did not represent the learners with any form of virtual body (e.g., Cheng & Tsai, 2020; Fokides & Kefallinou, 2020; Yu & Lin, 2020). Twenty-eight IVR studies represented the learners' bodies in the form of floating controllers or headsets to portray the positions of the learners' hands or heads (e.g., Bennie et al., 2019; Broyer et al., 2020; Klippel, Zhao, Jackson et al., 2019; R. Lamb et al., 2018; Won et al., 2019).

IVR studies in environmental science employed the user embodiment feature more readily than those in other disciplines. For instance, two IVR studies in the environmental science field allowed the learners to inhabit full virtual bodies. Ahn et al. (2016) embodied learners in virtual bodies of animals to induce feelings of empathy towards the animals while Markowitz et al. (2018) embodied learners in the form of corals being affected by climate change to raise awareness of the effects of climate change on marine environments.

Actional – Embodied movements

For embodied movements, more than half of the IVR studies did not incorporate extensive body movements relevant to the learning tasks. In many of these studies, the only body movement was head rotation to change the view of the learning content in IVR (e.g., Artun et al., 2020; Petersen et al., 2020). Medium-level embodied movements in action-based tasks, such as conducting laboratory experiments (e.g., Broyer et al., 2020) or throwing objects to experience gravity on the surface of the moon (Kwon, 2019), to support procedural and declarative knowledge acquisition were integrated in a third of the studies. Four IVR studies integrated full-body movements to allow learners to explore the learning environments in IVR (Klippel, Zhao, Oprean et al., 2019; Klippel, Zhao, Jackson et al., 2019; Won et al., 2019; J. Zhao, LaFemina et al., 2020). In their study, Won et al. (2019) allowed learners to explore protein structures by walking into them, and to rotate, drag, and push substrate molecules through the gorge of the enzyme into the catalytic site.

These actions were designed to help the learners to understand abstract concepts related to catalytic reactions, such as the effect of shapes of the substrate and enzyme on the reaction.

Narrative – Character, storyline, and challenge

Narrative immersive design features were not integrated well in most IVR studies. The majority of the IVR studies (55 out of 64) did not assign any identifiable character roles to the learners, while almost all the IVR studies (63 out of 64) had linear storylines without alternative endings. Nine studies assigned some character roles to the learners, such as being a forensic scientist (Kader et al., 2020), an animal (Ahn et al., 2016), or a space pilot (Rychkova et al., 2020). However, in most cases, the characters had little to no emotions or motivation related to the tasks and their decisions did not significantly influence storylines in the IVR activities. Only one of these studies assigned participants a clear character role to influence the progress of the storyline (Zhang et al., 2019). In this study, the learner assumed the role of the commander of an army of white blood cells. The learner made relevant decisions to fight off pathogens and to restore the health of the host without damaging the body cells, and the outcome of the game was different depending on the learner's decisions.

In terms of challenge, most of the studies (60 out of 64) assigned simplistic tasks to the learners which did not support comprehensive integration of prior knowledge, reflection, or decision-making. Only four studies assigned learners tasks that required some integration of prior knowledge and skills – medium level challenge (Kader et al., 2020; Southgate et al., 2019; Won et al., 2019; Zhang et al., 2019). For example, the learners had to use skills as forensic scientists to identify, with reasons, potential criminal evidence from a crime scene (Kader et al., 2020).

Social immersion – Social interactions

Few studies utilised IVR technology to support collaborative learning. Most of the studies (44 out of 64) were designed for individual participants to explore the virtual environments without any mediated social interactions with other learners, teachers, or pedagogical agents. Only two studies allowed extensive social interactions in the virtual space (Southgate et al., 2019; Won et al., 2019). Learners negotiated meanings and collaborated on the learning tasks within the shared virtual environments.

About one third of the IVR studies integrated some form of mediated social interactions in their IVR applications (rated as medium level on the social immersive design feature). In seven studies, one participant was placed in the virtual world and the peers or teachers watched from a 2D screen (e.g., Gochman et al., 2019; Zhang et al., 2019). In such an arrangement, the learner exploring the virtual world could interact verbally with peers or teachers in the physical world. Two studies (Hsu et al., 2018; Uz-Bilgin et al., 2020) assigned roles of navigator (inside the virtual space) and co-navigator (watching the virtual environment from a 2D screen) to the learners. The learners were required to cooperate and solve the learning tasks in IVR. In six studies (e.g., Dunnagan et al., 2020; Makransky, Terkildsen et al., 2019; Makransky, Wismer et al., 2019), learners followed instructions or received feedback from pedagogical agents to complete the learning tasks in IVR. Overall, the social immersive design feature remains a feature that may require further exploration in future studies.

Table 3. Average levels of integration of the immersive design features depending on the rationales for adopting IVR (N = 64).

Rationale for adopting IVR	Number of studies	Visual	Audio	Haptics	Interactivity	Virtual body	Embodied movements	Character	Storyline	Challenge	Social interactions
Visualisation of abstract concepts	22	2.6	1.8	1.1	1.7	1.6	1.5	1.2	1	1.1	1.3
Enhancing learning experience	14	2.1	1.9	1.3	1.9	1.5	1.5	1.1	1	1.1	1.4
Practical skill development	13	2.1	1.9	1	1.8	1.2	1.2	1.1	1	1.1	1.6
Field trips	11	2.3	2	1	1.3	1.3	1.5	1	1	1	1.2
First-person experience	4	2.8	2	1.5	1.5	2.5	1.5	2	1	1	1.3

1 = low integration; 2 = medium integration; 3 = high integration

Immersive design features for different rationales of adopting IVR

Depending on the rationale for adopting IVR, researchers adopted different immersive design features as shown in Table 3. Below we further elaborate this finding:

Visualisation of abstract concepts

The 22 studies in which IVR was used to aid learners' visualisation of abstract concepts generally integrated high-level visuals in their IVR applications. Medium-level audio effects in the form of background audio instructions were used in the IVR applications and learners had some opportunities to interact with the virtual objects. However, integration of embodied movements in the learning tasks was slightly less. Also, integration of haptics, narrative, and social design features was generally low. Visually representing scientific concepts using high-quality graphics in three-dimensional spaces in IVR and allowing the learners to manipulate 3D objects was aimed at improving the learners' awareness of the relevant spatial relationships in the concepts. For example, in chemistry, Bennie et al. (2019) used high quality graphics delivered in HTC VIVE headsets so that learners could explore molecular interactions in an enzyme reaction. Learners used handheld controllers to bind and unbind functional groups in the virtual molecules while observing the associated molecular rearrangements.

Enhancing learning experience

On average, the 14 IVR studies in this category integrated medium-level graphics in their IVR applications and the designs were moderately interactive to respond to the learners' actions. The levels of integration of embodiment and embodied movement features were slightly less than that of the interactivity feature, while narrative and social design features were generally not integrated well. For example, citing the poor motivation of students towards learning physics, Y. Han et al. (2020) developed an IVR application which placed learners in a 'moving' virtual car as an alternative way to teach learners about velocity-time graphs. The learners could control the speed of the virtual car by simply clicking controls using a handheld controller to observe real-time changes in the car's velocity-time graph. However, learners did not have any character roles assigned and did not engage in any form of plot or constructive social interactions while completing the learning task.

Practical skills development

The 13 studies adopting IVR for this purpose generally incorporated medium-quality visuals and medium-level interactivity in their IVR applications. Step-by-step audio instructions were also provided by pedagogical agents to guide the learners through the IVR learning tasks. Haptics, user embodiment, and embodied movements, as well as narrative immersive design features were not clearly adopted in IVR applications for this purpose. Moreover, one of the studies (Artun et al., 2020) simply showed 3D videos of laboratory activities in IVR to improve learners' science process skills without engaging learners in any relevant body movements that would normally be involved in conducting laboratory procedures.

Virtual field trips

Overall, the 11 studies in this category integrated the least number of immersive design features in their IVR applications compared to studies using IVR for other purposes. Most of the studies in this category (n = 8) used IVR applications in the form of 3D videos (e.g., Boda & Brown, 2020b; Fokides & Kefallinou, 2020; Jong et al., 2020; Petersen et al., 2020). The applications integrated medium-level visual and audio features while actional, narrative, and social design features were generally not integrated well in these designs. However, some researchers made efforts to integrate more design features (Klippel, Zhao, Oprean et al., 2019; Klippel, Zhao, Jackson et al., 2019; J. Zhao, LaFemina et al., 2020). To help university level learners remotely explore regional sedimentary rock formations, the researchers rendered images of geological field sites on high-end HMDs (HTC VIVE). High level actional immersive design features were also integrated in the IVR applications. The students explored the virtual field sites by walking around, lowering their bodies, and taking measurements using a virtual ruler. However, the learners did not have any character roles, or engage in any plots and they did not have opportunities to interact with peers or tutors during learning.

Providing first-person experiential learning opportunities

Unlike studies adopting IVR for other purposes, the four studies in this category generally integrated high-level user embodiment and medium-level character design features in their IVR applications. This was in addition to high-quality graphics and medium-level audio effects. For example, Markowitz et al. (2018) designed an IVR application in which the learner was embodied in the form of a coral in a marine environment. Using high-end (Oculus Rift) HMDs, learners could move their heads around to observe long-term effects of ocean acidification in the marine environment and on their 'own' bodies as corals to appreciate the effect of climate change.

Evaluation of IVR learning activities and achieved learning outcomes

As illustrated in Table 4, declarative knowledge was the most commonly evaluated learning outcome (43 studies), followed by attitudes and behavioural change outcomes (10 studies), while procedural knowledge was the least evaluated (5 studies). Declarative knowledge was evaluated using pre-and post-tests or interviews (40 studies). Multiple

Table 4. Achieved learning outcomes in studies with different rationales of adopting IVR.

		Learning outcomes of IVR vs. other modes				Learning outcomes of IVR vs. pre-test			
Rationale for adopting IVR	Learning outcomes	N	better	similar	worse	N	better	similar	worse
Visualisation	Declarative	12	6	3	3	5	3	2	0
Learning experience	Declarative	8	7	1	0	1	1	0	0
Practical skills	Declarative	6	7	1	0	1	0	0	0
	Procedural	5	1	4	1	1	0	0	0
Fieldtrip	Declarative	7	4	3	0	1	1	0	0
	Attitudes	4	4	0	0	1	1	0	0
First-person	Declarative	0	0	0	0	2	2	0	0
	Attitudes	2	2	0	0	1	1	0	0

N = number of studies; Declarative = declarative knowledge; Procedural = procedural knowledge; Attitudes = Attitudes and behavioural change outcomes choice and short-answer questions testing the students' abilities to recall science content presented in IVR were the most common test items. Few studies (n = 3) used relatively more elaborate methods such as argumentative writing (R. L. Lamb et al., 2019), or drawing tasks (Bagher et al., 2020; Thompson et al., 2020) to evaluate students' knowledge gains. In addition, in most of the studies, evaluation was conducted before and after the IVR session and there was no significant analysis of the learning process or how learning behaviour in IVR influenced the learning outcomes. Procedural knowledge was evaluated using written post-tests only (Artun et al., 2020; Dunnagan et al., 2020) or in combination with behavioural transfer tests (Andreasen et al., 2019; Makransky, Borre-Gude et al., 2019; Nie & Wu, 2020), while attitudes and behavioural change outcomes were often evaluated using surveys and interviews.

In terms of learning experience ratings, motivation to use IVR to learn, presence, perceived usefulness, and engagement on the learning task were the most widely evaluated outcomes (Table 5). These outcomes were evaluated using surveys and interviews. Some studies (n = 4) also used real-time measurements of students' physiological responses to IVR (such as brain activity and skin responses) to track students' cognitive and emotional engagement (e.g., R. Lamb et al., 2018; Lui et al., 2020).

In comparison to alternative learning modes, such as 2D computer displays or lecture-type approaches, IVR was more effective in only 55% of the studies on declarative knowledge gains and less effective in 12% of the studies. However, IVR was more effective than alternative learning modes on attitudes and behavioural change outcomes (100%) and received overwhelmingly positive ratings on motivation (100%), presence (100%), perceived usefulness (80%) and engagement (80%) compared to alternative modes. On the other hand, when compared to pre-test scores without comparison groups, studies found that IVR was effective for learning outcomes (83%) and provided a positive learning experience (100%).

In a small number of studies (n = 6), negative effects of IVR on students' learning experience were reported such as: dizziness (Broyer et al., 2020; Rychkova et al., 2020; Sun et al., 2017), higher levels of simulator sickness (Rupp et al., 2019; J. Zhao, LaFemina et al., 2020), and physical discomfort (Meyer et al., 2019). Surprisingly, the participants in these studies still rated IVR highly on motivation, presence, or perceived usefulness (Broyer et al., 2020; Meyer et al., 2019; Rychkova et al., 2020; Sun et al., 2017; J. Zhao, LaFemina et al., 2020). However, in some of these studies (n = 4), when IVR was compared against other learning modes on declarative knowledge gains, no significant differences in learning gains were found (Broyer et al., 2020; Meyer et al., 2019; Rupp et al., 2019; Rychkova et al., 2020; J. Zhao, LaFemina et al., 2020).

Table 5. Reported learning experience evaluations.

	Learning experience in IVR vs. other modes				Learning experience in IVR vs. pre-test			
Learning experiences	N	better	similar	worse	N	better	similar	worse
Motivation	24	24	0	0	10	10	0	0
Presence	20	20	0	0	11	11	0	0
Perceived usefulness	20	16	4	0	10	10	0	0
Engagement	10	8	0	2	8	8	0	0

N = number of studies

Evaluation of IVR learning activities and achieved learning outcomes for different rationales of adopting IVR

Science educators often evaluated declarative knowledge irrespective of the rationale for adopting IVR and reported mixed outcomes. In addition, in some cases, there was misalignment between the evaluated outcomes and the rationale for adopting IVR. Below we further elaborate on these findings:

Visualisation of abstract concepts

Evaluation of learning outcomes in the studies in this category generally matched the purpose of adopting IVR as most of the studies (17 out of 22) evaluated declarative knowledge gains (Table 4). However, the evaluation focused on low-level cognitive processes. For instance, in most studies (12 out of 17) educators used pre- and post-tests with similar questions before and after the IVR experience to test the students' ability to recall information presented in IVR.

When IVR was compared to alternative learning modes, a half of the studies (6 out of 12) reported positive learning gains for IVR (e.g., Bagher et al., 2020; Ferrell et al., 2019) while the other half reported no significant difference or lower learning gains (e.g., Madden et al., 2020; Parong & Mayer, 2018; Jian Zhao et al., 2020) compared to alternative learning modes. Similarly, when IVR was compared to pre-evaluation without a comparison group, three out of five studies reported positive learning gains (e.g., Won et al., 2019; Zhang et al., 2019) and the rest comparable knowledge gains (Papachristos et al., 2017; Thompson et al., 2020).

Enhancing learning experience

Nine of the 14 studies in this category evaluated declarative knowledge gains. All the studies in this category, except one, reported positive knowledge gains for IVR compared to alternative learning modes (e.g., Bibic et al., 2019; Y. Han et al., 2020; R. Lamb et al., 2018; Webster, 2016). Rychkova et al. (2020) reported comparable learning gains between IVR and a pen and paper condition for learning about electronic configurations in chemistry.

In terms of learning experience, the studies in this category evaluated motivation (n = 10) and engagement (n = 8), but other aspects of learning experience such as presence, perceived mental effort invested in learning and negative effects of IVR were rarely evaluated. IVR was always rated positively in terms of engagement and motivation.

The studies in this category seemed to suggest that IVR induces positive emotions during learning which may also improve the learning outcome gains. However, the positive results reported in these studies need to be interpreted with caution because researchers mainly relied on pre-and post-tests with multiple-choice type of questions. Therefore, the studies targeted only lower-level cognitive outcomes such as simple recall of some scientific facts. In addition, the evaluation of the learning experience was not comprehensive. In most cases, researchers sought simple responses regarding the students' learning experience by asking questions such as 'How much did you enjoy the learning experience?' or 'On a scale of 1–5, how engaging was learning the content in IVR?'. Consequently, learners reported that they felt engaged and that learning in IVR was 'fun' and 'interesting' but did not highlight the reasons that led to the positive learning experience.

Practical skills development

Most of the studies in this category evaluated declarative knowledge (8 studies) and learning experience in the form of presence (5 studies), motivation (6 studies), perceived usefulness (7 studies), rather than procedural knowledge (5 studies). Regarding declarative knowledge gains, only two studies (Bhattacharjee et al., 2018; Makransky, Wismer et al., 2019) reported positive learning gains while five reported either lower or comparable learning gains for IVR in comparison with alternative learning modes (e.g., Andreasen et al., 2019; Klingenberg et al., 2020; Nie & Wu, 2020). The fact that more studies reported lower or comparable declarative knowledge gains than positive gains may partly be attributed to the misalignment between the rationale for adopting IVR and the learning outcome evaluated.

In terms of procedural knowledge gains, IVR did not always yield higher learning gains compared to alternative learning modes. Out of the five studies reporting procedural knowledge gains, only two reported better learning gains (e.g., Nie & Wu, 2020), while the rest reported no significant differences in learning gains for IVR compared to alternative 2D modes (Andreasen et al., 2019; Artun et al., 2020; Dunnagan et al., 2020). Despite the mixed outcomes on knowledge gains, participants in the studies often rated IVR positively on learning experience.

Field trips

The studies in this category evaluated attitudes and behavioural change outcomes and declarative knowledge. For attitudes and behavioural change outcomes, the studies reported positive outcomes for IVR regardless of whether IVR was compared to other learning modes (n = 4; e.g., Boda & Brown, 2020b; Yu & Lin, 2020) or to a pre-test (n = 1; Petersen et al., 2020). Regarding declarative knowledge, about half of the studies (n = 4) reported better knowledge gains (e.g., Fokides & Kefallinou, 2020; Jong et al., 2020) while the rest (n = 3; e.g., Rupp et al., 2019; J. Zhao, LaFemina et al., 2020) reported no significant differences in knowledge gains for IVR compared to alternative learning modes.

Providing first-person experiential learning opportunities

Three studies in this category evaluated attitudes and behavioural change outcomes while two studies evaluated declarative knowledge gains. The studies reported better learning outcomes for IVR when compared to alternative learning modes (Ahn et al., 2016; Nowak et al., 2020) or to a pre-test without a comparison group (Markowitz et al., 2018) on attitudes and behavioural change outcomes. Similarly, in comparison with pre-tests, the two IVR studies that evaluated declarative knowledge reported better learning gains for IVR (Gochman et al., 2019; Markowitz et al., 2018). In addition, students in all the four studies in this category rated IVR positively on presence in the learning environments.

Immersive design features and the achieved learning outcomes

No clear patterns could be identified in immersive design features for studies reporting positive learning outcomes and those reporting lower learning outcomes for IVR. For instance, as shown in Table 6, studies reporting different declarative knowledge outcomes in IVR did not differ much in the nature and levels of IVR design features integrated. In addition, for procedural knowledge, the number of studies was very small to allow

Table 6. Average immersive design feature integration levels and achieved learning outcomes.

Learning outcome evaluation	IVR vs. other modes or pre-test	N	Average immersive design feature integration level: Visual	Audio	Haptics	Virtual body	Embodied movements	Character	Storyline	Challenge	Social interactions	
Declarative knowledge	better	26	2.5	1.7	1.2	1.7	1.5	1.5	1.2	1	1.1	1.3
	similar	13		1.9	1	1.7	1.5	1.5	1.2	1	1	1.4
	worse	4		2	1	1.8	1.5	1	1	1	1	1.3
Procedural knowledge	better	2	2.5	2	1	2	1.5	1.5	1	1	1	1.5
	similar	3		2	1	1.7	1	1	1	1	1	1.7
Attitudes	better	10	2.2	2.1	1.3	1.3	1.6	1.3	1.3	1	1	1.3

N = number of studies; Attitudes = attitudes and behavioural change outcomes; Level of design feature integration: 1 = low; 2 = medium; 3 = high conclusions to be made. The findings suggested that the relationship between the design features and learning outcomes was much more complicated than expected. For instance, the relationship could be affected by a mismatch between the rationales for adopting IVR applications and the learning outcomes evaluated. In such a case, positive learning outcomes may not be obtained even when many desirable immersive design features are incorporated in the IVR applications. Moreover, each of the IVR studies that evaluated attitudes and behavioural change outcomes tended to report positive learning outcomes; consequently, it was difficult to identify which of the combinations of immersive design features were responsible for the positive outcomes.

Learner characteristics and achieved learning outcomes

Most of the studies reported the demographic information of the participants but did not explicitly explore how these characteristics influenced learning in IVR. Only four studies explored the influence of students' intrinsic interest, motivational beliefs, and science self-efficacy on their learning (Boda & Brown, 2020a, 2020b; Cheng & Tsai, 2020; Huang, 2019). In addition, only five studies evaluated the effect of prior knowledge, and the results were mixed. Two studies (Jong et al., 2020; Zinchenko et al., 2020) reported that learners with low prior knowledge learn better with IVR than learners with higher prior knowledge but other studies reported otherwise (Lui et al., 2020; Rodrigues & Prada, 2018; Uz-Bilgin et al., 2020).

Three out of 64 studies explored the effect of gender on learning with IVR simulations and the results were contradicting. Makransky et al. (2020) reported that female students learned better than male students while Madden et al. (2020) reported the opposite. In addition, a study suggested that the choice of the appearance of an on-screen pedagogical agent in IVR influenced the learning gains and the effect was moderated by gender (Makransky, Wismer et al., 2019). In this study, female students recalled more information when they completed tasks under the instruction of a female on-screen agent while boys learned more from a drone.

Overall, although these studies showed that learner characteristics may significantly influence the learning experience and outcomes in IVR, the studies are very limited in number to draw generalisable conclusions regarding the relationship between learner characteristics and the science learning outcomes in IVR.

Discussion

Science education researchers adopted different design features depending on their focus of investigation, but often inconsistently. For example, when the rationale for adopting IVR was to help students visualise abstract science concepts, researchers highlighted the 3D visualisation capabilities of IVR showing reified objects to great amazement of students, but, in some cases, the main mode of learning was receiving information, with limited opportunities to interact with virtual objects or peers. Consequently, students were not engaged in collaborative knowledge construction processes to interrogate their own ideas and build more scientific understanding from the experience. On the other hand, when IVR activities were developed for practicing laboratory procedures, more interactive features were integrated such as selecting apparatus or the next procedural step to build procedural knowledge, but the IVR studies did not necessarily offer haptic feedback or encourage embodied movements to practice the procedures and help build muscle memory of the actions. When the primary goal was for students to experience someone else's life for implicit learning, the virtual body representation was highlighted in the IVR studies, but without intriguing storylines and challenges to emotionally engage learners to trigger behavioural change.

The reasons for inconsistent design implementation may be varied. Instead of making harsh judgements, we need to acknowledge the fact that integrating more design features takes more resources, in terms of the equipment, human resources, time, and effort. Not many educators can afford all these resources; for example, high-end IVR equipment is still expensive and requires special setup that may be out of reach based on the budgets of many researchers. Due to the limited accessibility of high-end IVR equipment, science educators may have opted for lower-end IVR equipment that are more affordable and easier to setup, but would allow very limited interactivity and embodied movement, let alone synchronised networking across multiple students.

In addition, limited technical and human resources may hinder science educators from designing and developing customised IVR activities to suit their educational and research needs. Some researchers adopted readily available off-the-shelf IVR designs such as Google Expeditions and Body VR or created low-budget IVR designs with limited actional and narrative design features. When the design of IVR programs is not fully controlled by the researchers, it is unlikely that the IVR learning activities would align well with the research goals or research designs. Although in some studies there were some efforts to increase the alignment by adding pre and post activities, a misalignment between the designers' and the researchers' goals could have negatively impacted the evaluation of the educational benefits of IVR.

No particular combinations of immersive design features were identified to result in positive learning outcomes, partly because researchers designed, implemented, and evaluated the IVR applications inconsistently. For example, this review found misalignment between the rationale for adopting IVR and the evaluation of learning outcomes in IVR studies targeting practical skills development. The studies often evaluated declarative knowledge and learning experience rather than procedural knowledge gains. Such a misalignment might have complicated the relationship between the design features and the learning outcomes. Considering the rationale of using IVR in the design as well as the evaluation of IVR learning activities may contribute to more productive investigations of the educational benefits of IVR in future studies.

This review also found that irrespective of which design features were implemented or the rationales for adopting IVR, students' evaluation of IVR experience was generally positive in terms of presence, motivation, and engagement. Positive ratings of IVR learning experience were also reported by Checa and Bustillo (2020) in their review of 135 studies on IVR games for education and training. These positive ratings can be explained partly by the fact that, in most of the studies reviewed in the present study, learners were given only a single opportunity to learn with IVR. Therefore, the novelty effect might have enhanced the students' perceptions of learning experience (Clark, 1983). Investigating the effect of novelty in future studies is important because novelty may not only enhance learning experience but also pose challenges in students' learning with new technologies such as IVR. For example, students using IVR for the first time may feel uncomfortable or distracted which may increase extraneous processing and negatively impact on the cognitive outcomes (Hamilton et al., 2021).

Regardless of the dilemmas and limitations, science education researchers are making efforts to investigate the educational benefits of IVR technology. However, the conclusions drawn from current IVR studies in terms of the benefit of using IVR in science learning need to be investigated further because of several reasons such as: the researchers' overreliance on test instruments targeting recall knowledge, or the limited investigation of the students' prior experiences in relation to their learning processes in IVR. Another issue of potential concern is the overreliance on self-report measures for evaluation of learning experience. The outcomes may be prone to social desirability bias (Grimm, 2010). As found in some of the studies, students tended to report their learning experience in IVR positively even when they had difficulties in learning with IVR.

In addition, the majority of the studies investigated the benefits of IVR activities outside the normal school curricula. Like earlier investigations on 'new' educational tools such as computers and mobile phones, research studies need to move beyond highlighting IVR's unique technological capabilities on their own but focus on designing and evaluating learning activities with IVR to enhance students' learning in real educational contexts. Focused research questions could be: What concepts would students learn better from the IVR experience?; How well would IVR support collaborative learning amongst students?; and Why would IVR encourage students to achieve the expected learning outcomes? In designing IVR studies to answer such questions, the immersive design features along with the target learning outcomes could serve as a useful reference point.

Limitations of the study

With a fast-evolving technology such as IVR, it is difficult to capture the 'current' status of educational adoption of the technology. The high-end computer-supported IVR equipment such as Oculus Rift and HTC VIVE in 2016 were eclipsed by higher resolution IVR models such as Oculus Rift S, HTC VIVE Pro, and Valve Index by 2018/2019, and these models are now competing for the market share with emerging stand-alone IVR headsets such as Oculus Quest 2 in 2020. As the content development and the investigation of educational benefits take considerable time, the empirical studies reported in this manuscript may not reflect the most up-to-date IVR technology and educational applications for science teaching and learning. In addition, despite our best effort to include as many empirical studies as possible, our database search may have unintentionally left out some important educational studies. Researchers may want to conduct periodic literature review studies to see the trends in IVR research for science learning.

Conclusion

This study investigated why science educators adopted IVR, what design features were integrated into their IVR studies to investigate its educational benefits, and what researchers found as being the impact of IVR on the learning outcomes. This study aimed to open up the scholarly discussion of identifying, utilising, and evaluating various design features when investigating educational benefits of IVR for different reasons. Generally, science educators focused their attention on the sensory aspects of IVR technology, especially on the 3D visualisation capacity for inducing immersive experience, across diverse learning objectives to obtain mixed learning outcomes. As science educators investigate the educational benefits of IVR, they may wish to consider how various design features would enhance students' learning experiences and their learning of science through IVR.

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*(Studies included in the review have been marked with *. The studies may not appear in the main text)*

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