Education and Information Technologies
https://doi.org/10.1007/s10639-024-12959-7

The impact of presence on the perceptions of adolescents toward immersive laboratory learning

Muhua Zhang[1] · **Chien-Yuan Su**[2]

Received: 19 May 2023 / Accepted: 7 August 2024

Abstract

Immersive virtual reality (IVR) is expected to create a greater sense of presence that might improve students' laboratory learning experiences. However, little research has verified the influence of presence on students' perceptions toward immersive laboratory learning. The current study, which is based on the expectation confirmation model, attempts to investigate the ways in which presence influences secondary school student perceived laboratory learning in an IVR setting. Data for this study were gathered from 167 Chinese students aged 13–18 who had experience in using IVR. According to the results of the partial least squares structural equation modelling (PLS-SEM) analysis, physical presence in the IVR environment had a favourable direct impact on students' perceived usefulness as well as indirect effects on their learning satisfaction with and intention to continue using IVR. Self-presence had indirect impacts on students' perceived usefulness, satisfaction, and continued intention to utilize IVR. Students' expectation confirmation regarding the use of IVR for laboratory learning plays a crucial role in shaping their overall experience. It not only mediates the relationships between their perceptions of presence and perceived usefulness and satisfaction but also directly influences their intention to continue engaging in IVR-supported laboratory learning.

Keywords Physical presence · Self-presence · Immersive virtual reality · Laboratory learning · Continuance intention · Expectation confirmation model

---

✉ Chien-Yuan Su
bredysu@gmail.com

[1] College of Elementary Education, Capital Normal University, Haidian District, No.105 North Road, West Third Ring, Beijing 100048, China

[2] Department of Education, National University of Tainan, 33, Sec. 2, Shu-Lin St, Tainan 700, Taiwan

1 Introduction

Immersive Virtual Reality (IVR) is considered a potentially cost-effective means for providing students with compelling learning experiences (Hite, 2022; Makransky et al., 2020). IVR employs head-mounted displays to immerse students in an interactive environment, incorporating intuitive features, such as head tracking and body movement (Meyer et al., 2019). Furthermore, IVR can offer a high level of environment representational fidelity, including consistent object behavior, seamless perspective changes, and realistic displays (Dalgarno & Lee, 2010). Recent research has demonstrated that IVR significantly enhances the facilitation of various scientific activities that are otherwise unrealistic or impossible-to-perform for K-12 students (Di Natale et al., 2020; Wu et al., 2020). For instance, IVR can simulate a physical scientific laboratory through a computer-generated, immersive environment that allows for intimate and intuitive engagement. This allows students to interact with the displayed artifacts in virtual laboratory activities (Chan et al., 2021; Naz et al., 2024), avoiding constraints imposed by expensive equipment and materials, time limitations, or safety concerns in the real world (Potkonjak et al., 2016). Evidence indicates that the use of IVR in the laboratory or in science learning influences student outcomes in a way that is either superior to or comparable to traditional laboratory education (Reeves & Crippen, 2021). This may be attributed to the ability of IVR to immerse students in laboratory learning, creating a strong "sense of presence" that leads to increased engagement and involvement, ultimately enhancing learning outcomes (Klingenberg et al., 2020; Makransky & Lilleholt, 2018; Tsirulnikov et al., 2023). Presence can be understood as the psychological sensation of "being there" (Ijsselsteijn & Riva, 2003). When students are fully immersed in a virtual world, they may experience an authentic sense of being present, which can be described from three dimensions—physical, social and self-presence—in accordance with human experience in real life (Lee, 2004; Makransky et al., 2017). Some researchers highlight that IVR applications enhance the sense of physical presence, thereby facilitating scientific learning by increasing situational interest and enjoyment, which subsequently improves their retention of scientific knowledge (Makransky & Mayer, 2022; Petersen et al., 2022).

However, it is worth noting that most students in prior studies were new to IVR technology, and thus potentially influenced by its novelty (Makransky & Lilleholt, 2018; Reeves & Crippen, 2021). The unique advantage of IVR for offering presence, with its ability to stimulate situational interest, enjoyment, and satisfaction, may diminish over time as students become more accustomed to it (Makransky & Petersen, 2021). Therefore, there is a critical need to investigate the sustained affordance of presence in long-term IVR applications. As Matovu et al. (2022) highlighted in their systematic review of IVR for science learning, most learners in reviewed studies were first-time IVR users. Furthermore, Reeves et al. (2021) contended that most studies on laboratory learning have primarily focused on comparing students' knowledge acquisition in VR Labs with that in traditional physical laboratories, often overlooking their perceptions of learning in an IVR environment. This underscores a significant research gap in understanding students' perceptions regarding the sustained use of IVR for laboratory learning and the evolving role of presence in their experiences, especially over an extended period. Hence, our primary objective is to investigate students' perceptions of learning in IVR-supported laboratory environments and the evolving impact of presence as IVR becomes a regular fixture in secondary science instruction.

To achieve this, we adopt the Expectation Confirmation Model (ECM), chosen for its suitability in elucidating student perceptions post-IVR experience. Our focus centres on the concept of expectation confirmation, examining how students align their initial expectations about the impact IVRs on laboratory learning with their actual experiences. Drawing from established research (Chang et al., 2018; Makransky & Lilleholt, 2018; Pedram et al., 2020), we also consider factors such as perceived usefulness, satisfaction, and the intention to persist in using IVR for laboratory learning. Furthermore, we delve into the pivotal role of presence, an antecedent variable known to influence students' perceptions of IVR-supported learning within the context of science education (Andersen et al., 2023; Makransky & Lilleholt, 2018; Petersen et al., 2022). In summary, our study aims to address the following key questions:

(1) How do students perceive learning in VR Labs as IVR becomes integrated into routine science instruction?
(2) What impact does the sense of presence have on student perceptions of learning in VR Labs as IVR becomes standard in daily science instruction?

2 Literature review and hypotheses

2.1 The affordance of IVR on laboratory learning and the role of presence

Virtual experiments delivered through IVR enhance traditional physical experiments by enabling students to explore unobservable phenomena and correlate them with observable phenomena. This facilitates the conducting of multiple experiments within a condensed timeframe, while also highlighting pertinent information and offering immediate feedback and adaptive guidance (de Jong, et al., 2013). A recent systematic review (Reeves & Crippen, 2021) demonstrated that IVR yields positive outcomes in laboratory learning, such as promoting affective outcomes (e.g., intrinsic motivation, interest, and self-efficacy), enhancing students' understanding of complex scientific knowledge and their ability to transfer scientific knowledge to real-world situations. Regarding virtual hands-on laboratory activities, Makransky et al. (2020) conducted a study in which a total of ninety-nine students between the ages of 13 and 16 participated in IVR laboratory experiences. The findings of the research demonstrated a significant enhancement in students' interest, self-efficacy, and safety perceptions with regard to laboratory work. In another study, Naz et al. (2024) discovered that interactive laboratory activities utilizing IVR significantly improved senior high school students' practical skills and their comprehension of chemical processes. Moreover, Gao et al. (2023) found that Chinese junior secondary students using IVR for hands-on physical experiments demonstrated significantly improved knowledge transfer to real-world problem-solving tasks compared to video-based learning. The aforementioned studies demonstrate compelling evidence that leveraging IVR in laboratory learning significantly enhances student learning outcomes, thus fostering advancements in both cognitive understanding and affective engagement, while surpassing outcomes achieved through conventional methods.

In IVR, presence is deemed a crucial factor that can significantly impact student learning, as per the cognitive affective model of immersive learning (CAMIL) created by Makransky and Petersen (2021). The research conducted by Makransky and Lilleholt (2018) confirms that presence in a virtual laboratory simulation serves as a moderator when predicting students' perceived learning outcomes, satisfaction levels, and behavioral intentions through motivation and enjoyment. Petersen et al. (2022) discovered that students' perceived presence in an immersive virtual museum exhibition favorably influences their scientific knowledge retention via intrinsic motivation and situational interest. Pedram et al. (2020) revealed that students' feelings of presence boost their actual and perceived learning using IVR in the context of safety instruction. Thus, prior studies indicate that the sense of presence may impact students' perceptions of IVR learning during their initial experience. However, it remains unclear how presence affects their perceptions of engagement and intention to persist in IVR-supported learning as they become more accustomed to it. Furthermore, the aforementioned studies (Makransky & Lilleholt, 2018; Pedram et al., 2020; Petersen et al., 2022) did not consider presence as a multifaceted construct and overlooked the aspect of self-presence, which may be perceived by students in VR Labs with hands-on activities, thus failing to provide a comprehensive understanding of the relationship between presence and student perceptions of IVR-supported laboratory learning.

2.2 Student perceptions toward IVR based on the expectation confirmation model

Unlike Davis' (1989) technology acceptance model (TAM), which focuses on users' initial behaviour intention to use technology, the expectation confirmation model (ECM) is a post-acceptance model that explains why users continue to use an information system (IS) after accumulating some degree of usage experience (Bhattacherjee, 2001). The ECM includes four post-consumption variables: continuance intention, satisfaction, expectation confirmation, and perceived usefulness. Continuance intention refers to users' intention to continue using an IS, satisfaction reflects users' feelings about past IS usage, expectation confirmation gauges the match between users' expectations and IS performance, and perceived usefulness assesses users' perception of IS benefits. Bhattacherjee (2001) proposed hypotheses stating that continuance intention is influenced by perceived usefulness and satisfaction, perceived usefulness and expectation confirmation positively affect satisfaction, and expectation confirmation influences perceived usefulness.

ECM may also be used to explain student behaviour towards a product or service associated with virtual reality. For example, Jung (2011) used ECM to examine the factors that influence users' continued use of virtual social worlds in the context of the platform Second Life. Chang et al. (2018) employed ECM to explore college students' acceptance of VR-based mental rotation training systems. Zhang et al. (2020) examined college students' continuance intention towards virtual and remote laboratories by reference to ECM and flow theory. The results of previous research have demonstrated the capability of ECM to explore VR-related topics. Thus, the following hypotheses were proposed:

H1. Students' confirmation of expectations has positive effects on their perceived usefulness of IVR.

H2. Students' confirmation of expectations has positive effects on their satisfaction with IVR.

H3. Students' perceived usefulness has positive effects on their satisfaction with IVR.

H4. Students' perceived usefulness has positive effects on their continuance intention towards IVR.

H5. Students' satisfaction with IVR has positive effects on their continuance intention.

In addition, Alhumaid et al. (2021) discovered that expectation confirmation positively affected students' intention to continue using mobile learning platforms during the COVID-19 epidemic. Pasha et al. (2021) also investigated the impact of virtual reality with respect to enhancing students' behavioural intention towards learning management systems and found a direct relationship between expectation confirmation and behavioural intention. The following hypothesis was therefore proposed:

H6. Students' confirmation of expectations has positive effects on their continuance intention of IVR.

2.3 The impact of presence on user perception and intention toward IVR

Presence in the context of virtual environments refers to users' subjective feelings of being in an environment generated by computers instead of a real physical location (Witmer & Singer, 1998). Following a review of previous research on presence, Lee (2004, p.27) redefined presence as "a psychological state in which virtual objects are experienced as actual objects in either sensory or nonsensory ways" from the perspective of human experience. Felton and Jackson (2022) adopted a different viewpoint and argued that presence is not merely a technology-induced phenomenon. They defined presence as "the extent to which something (environment, person, object, or any other stimulus) appears to exist in the same physical world as the observer" (Felton & Jackson, 2022, p.1). Regardless of these different definitions of presence, it is prudent to understand presence in a virtual world from several perspectives. By reference to Lee (2004) and Makransky et al. (2017), Table 1 indicates three dimensions of presence in a virtual environment.

Previous research has thoroughly examined the importance of physical presence with respect to user perception and behavioural intention. For instance, Pedram et al. (2020) discovered that learners' sense of physical presence in IVR influences their perceived usefulness of the VR safety training system. Melo et al. (2022) discovered that the physical presence experienced by consumers in the context of virtual tourism increases their happiness and behavioural intention towards tourism products. Ammann et al. (2020) used a VR intervention to validate the causal association between physical presence and participants' behavioural intention to consume a foodstuff. Shin et al. (2013) observed that presence has a favourable influence on the confirmation of students' expectations regarding a 3D virtual learning system.

In the realm of IVR-supported science education, presence has been recognized as a critical factor influencing students' positive perceptions and behavioral intentions regarding immersive scientific learning. This is because physical presence can create a more immersive and engaging experience, making the technology more appealing and enjoyable to use, as well as more practical and applicable for learning. For instance, Makransky and Lilleholt (2018) observed an unexpected role of presence in predicting students' satisfaction with and willingness to use IVR for science education. Petersen et al. (2020) demonstrated that presence can particularly enhance students' self-efficacy, STEM-related intentions, and outcome expectations in IVR-supported inquiry-based science learning. Furthermore, Andersen et al. (2023) found that immersive virtual field trips, which elicit a higher level of presence, have a more pronounced impact on students' self-efficacy and outcome expectations in science compared to video-based virtual field trips. As a result, the following hypotheses were developed to expand upon the original ECM based on the preceding discussion:

H7. Physical presence positively affects students' expectation confirmation of IVR.
H8. Physical presence positively affects students' perceived usefulness of IVR.
H9. Physical presence positively affects students' satisfaction with IVR.
H10. Physical presence positively affects students' intention to continue using IVR.

Previous research has explored self-presence as a crucial component influencing user perception and behavioural intention in virtual environments. For example, Behm-Morawitz (2013) found that users' self-presence is positively associated with their satisfaction with their connection with the virtual world. Kim (2020) verified that users' experiences of self-presence significantly impact their satisfaction with a virtual sports experience. According to the findings of Sun et al. (2015), participants' perceived presence in the context of VR boxing training influences their perceived usability of the VR training system. Previous studies utilizing ECM have demonstrated that users' experiences of self-presence directly influence their behavioural intention, such as their continuance intention regarding virtual worlds (Hooi & Cho, 2017) and to engage in healthy eating (Wang et al., 2020). When students

Table 1 The three dimensions of presence in a virtual environment (Lee, 2004; Makransky et al., 2017)

Dimension	Definition	Area attributes
Physical presence	A psychological state in which users perceive para-authentic or artificial entities and/or surroundings in a virtual world as physical entities and/or surroundings in the real world in sensory or nonsensory ways	Physical realism Being unaware of physical locales Being unaware of physical mediations Feeling in control of a virtual environment Being in the virtual environment in an intuitive way
Social presence	A psychological state in which users experience para-authentic or artificial social actors in a virtual environment as actual social actors in the real world in sensory or nonsensory ways	Experiencing human realism Being unaware of social mediations Being unaware of artificiality during social interactions Feeling a sense of coexistence
Self-presence	A psychological state in which users experience a para-authentic or artificial self/selves in a virtual environment as their actual self in the real world in sensory or nonsensory ways	Experiencing a feeling of self-being in the virtual environment Experiencing a feeling of bodily connectivity and extension Experiencing a feeling of emotional connectivity

interact with different virtual apparatuses through virtual embodiment (i.e., a pair of virtual hands) in the context of immersive laboratory learning, they may feel a projection of their actual arms into the virtual world, resulting in a perceived sensation of self-presence. The ease with which students engage with the virtual world might strengthen their sensation of self-presence and their perceptions/impression of learning. Consequently, we formulated the following hypotheses:

H11. Self-presence positively affects students' expectation confirmation of IVR.
H12. Self-presence positively affects students' perceived usefulness of IVR.
H13. Self-presence positively affects students' satisfaction with IVR.
H14. Self-presence positively affects students' intention to continue using IVR.

Because social presence is concerned with the user's perceptions of interacting with other avatars in a virtual world, a phenomenon which is not considered in this work, this topic was not explored in this study. As a result, this research regarded physical presence and self-presence as antecedent influencing factors relevant to the tasks of explaining and predicting students' perceptions toward IVR-supported laboratory learning. The research model is presented in Fig. 1.

3 Methods

3.1 Participants and contexts

To examine the incorporation of IVR technology into science curricula, the Chinese government carefully selected a cohort of over 60 primary and secondary schools across six cities in 2020 to serve as the inaugural group of pilot schools. The selection process took into consideration various factors, including students' academic performance, the geographic location of the schools, and the adequacy of their

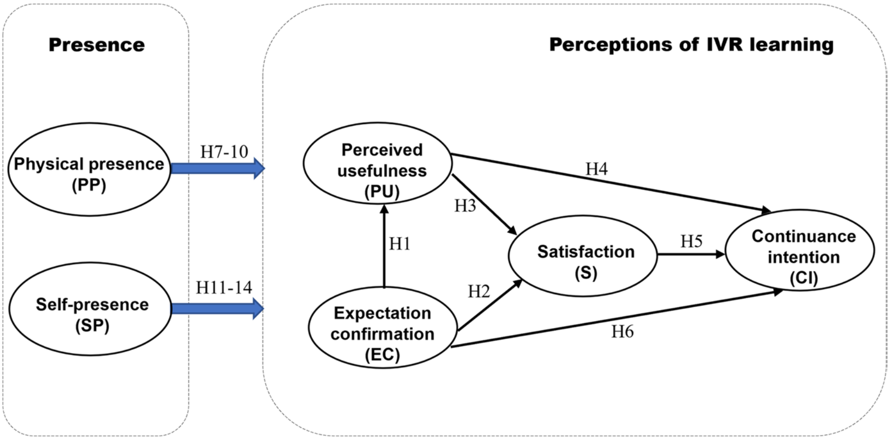

Fig. 1 The research model

network infrastructure for supporting IVR-assisted science learning. First and foremost, these pilot schools were required to possess the necessary information technology infrastructure to facilitate immersive scientific instruction. This encompassed having well-equipped computer laboratories, interactive whiteboards, VR devices, and high-speed internet access with a total bandwidth exceeding one gigabit. Additionally, science teachers in these pilot schools needed to be proficient in utilizing IVR teaching applications as an integral part of their daily instruction. Meanwhile, pilot schools needed to provide equipment training before IVR-supported science classes are conducted in order to ensure students can use the head-mounted displays and controllers effectively. Moreover, the school principals in these pilot institutions were tasked with providing clear directives to encourage teachers to seamlessly integrate IVR resources into their science courses and instructional methods. For example, teachers were instructed to initially utilize IVR resources to assist students in conducting experiments, allowing them to test hypotheses or theories from their textbooks. In subsequent sharing and discussion sessions, teachers were expected to invite students to share their observations and conclusions from the experiments. At the same time, teachers were encouraged to guide students toward a deeper understanding of scientific concepts and principles. Consequently, these pilot schools were obligated to routinely offer students a comprehensive scientific education that seamlessly integrated IVR technology through a shared virtual laboratory platform.

Following communication with the directors of these pilot schools, four institutions expressed interest in participating in our study. Ultimately, we recruited a total of 167 students aged 13 to 18 (87 boys and 80 girls) from these four pilot schools to participate in our study. These participants used the same equipment to complete IVR science-related programs, and each had completed at least three to four separate IVR science-related programs while wearing a head-mounted display in prior science courses. Furthermore, the IVR resources were employed in these pilot schools to aid students in conducting their scientific experiments and were integrated into the science lessons in a similar manner. As a consequence, they all grew acquainted with the technology and had comparable IVR experiences. Detailed demographic information and their IVR usage experiences regarding the sample of students are presented in Table 2.

In this investigation, a sensitivity power analysis was conducted with G*Power 3.0 software to determine an appropriate sample size. According to Faul et al. (2009), sensitivity analyses are employed to afford information about the effect size

Table 2 The students' demographic profile and IVR usage experiences

Grade	School	Number of students (*n*)	Number of IVR science-related programs completed (*n*)	IVR science-related program length (in minutes)
Junior secondary	School A	119	4	40–60
	School B	13	4	40–60
Senior secondary	School C	20	3	30–45
	School D	15	3	30–45

that research can detect with a certain power given the chosen alpha level and its sample size. Ultimately, the minimum sample size was determined to be 138 with a power level of 0.95, $\alpha = 0.05$, and $f^2 = 0.15$ (medium effect size). As a result, the obtained sample exceeded the specified sample size and had sufficient statistical power to determine the study model.

3.2 IVR materials and apparatus

This study makes use of IVR learning materials provided by the virtual lab platform (https://vlab.eduyun.cn/portal/home) which are approved for K-12 scientific instruction. These IVR materials on the platform cover a wide spectrum, ranging from elementary school science to secondary school subjects such as physics, chemistry, and biology. They can be experienced by wearing a head-mounted display (e.g., HTC Vive) or other interactive devices. Within the pilot schools we surveyed, several noteworthy IVR learning materials were incorporated into standard science classes; these are detailed in Table 3. The selection process for these representative learning materials in our study adhered to specific criteria, requiring that these materials had been adopted and integrated into science instruction in at least two pilot schools. The instructors strategically included these IVR materials in science courses across different grade levels to align with student's learning progress.

To set up teaching materials on the IVR device, users need to install the STEAM VR and VIVE PORT applications. VIVE PORT guides users to install drivers for IVR hardware. The head-mounted display can then be connected to a desktop computer via cables and a streaming box. Interactive controllers are paired with the display by pressing buttons. The STEAM VR window displays the connection status of the headset and controllers. A steady green light indicates they are operational. Once connected, students can access virtual experiments on the virtual lab platform. Figure 2 illustrates how students explore the virtual scene using the head-mounted display and manipulate the virtual apparatus with interactive controllers.

In the virtual science experiment "Observing chloroplast and cytoplasmic flow using high-power microscopes" (see Fig. 2), Fig. 2(a) depicts the virtual environment and apparatus, such as the lab workbench, beakers, and microscopes; Fig. 2(b)

Table 3 IVR material blended in science lessons in junior or senior secondary schools

Name	Grade level
Examining the germination rate of a seed	Junior Secondary
Exploring the dredging function of the stem	
Observing the process of convex lens imaging	
Measuring the resistance of a conductor according to Ohm's law	
Practising the use of a high-power microscope to observe several types of cells	Senior Secondary
Observing chloroplast and cytoplasmic flow with high-power microscopes	
Learning to produce sodium hydroxide	
Observing the capacitor charging and discharging process	

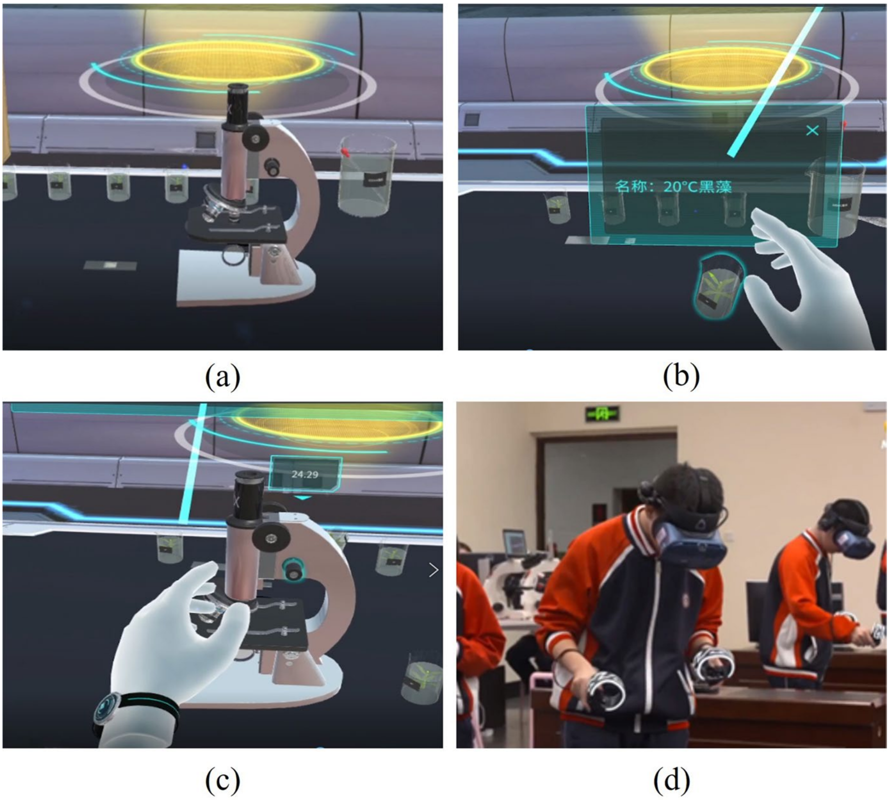

Fig. 2 The interfaces of the virtual experiment and the equipment used by students

shows an operation involving the grasping of a beaker with virtual hands by pressing the trigger button on the controller, while the name of whatever is placed in the captured beaker is automatically displayed; Fig. 2(c) depicts an operation involving manipulating the fine focus knob of microscopes with virtual hands by pressing the menu button on the controller to receive action prompts, with the parameter information of the manipulation automatically displayed; and Fig. 2(d) shows the devices used by the students during the virtual experiment, including a head-mounted display and a pair of interactive controllers.

The IVR examinations on the virtual lab platform share a common scenario but feature different instruments depending on numerous scientific themes. For example, the experiment “Observing chloroplast and cytoplasmic flow using high-power microscopes” includes a virtual microscope, while “Measuring the resistance of a conductor according to Ohm’s law” incorporates a virtual slide rheostat, ammeter, and voltmeter. Figure 3 depicts the consistent setting with different instruments for these experiments. Elements like the lab workbench, surrounding walls, and the decorations are fixed and visible through the head-mounted display. Apparatus on

光照处理放在25°C清水中培养的黑藻一段时间。

学会用伏安法（即用电压表和电流表）测量定值电阻的阻值。

Fig. 3 The screen shots of two different virtual experiments

the lab workbench, such as beaker and instruments, can be operated using controllers. Consequently, interactive equipment and technology enable students to have hands-on experiences that closely resemble those seen in the actual world. As the result, students may have comparable engaging experiences when conducting virtual experiments on a variety of scientific topics. Moreover, these virtual lab hands-on activities were designed based on the guided activity principle (Moreno & Mayer, 2007), enabling students to complete the science experiments with step-by-step procedural guidance.

3.3 Instruments

A three-part questionnaire was developed to assess students' presence in and perceptions of immersive laboratory learning. The first portion of the questionnaire gathered the demographic information of participants, such as their gender, age, and grade. The second portion investigated students' perceived presence in IVR. Because the IVR contents did not present students with social actors, only physical presence and self-presence were examined in this study. Finally, 9 items were adopted from Makransky et al. (2017) to measure students' perceived presence in IVR. The following 14 items were modified from the ECM scale developed by Bhattacherjee (2001) to measure students' perceptions of immersive laboratory learning. All items were measured on a five-point Likert scale with 5 indicating ‘‘strongly agree” and 1 indicating ‘‘strongly disagree”. The items were translated into Chinese, and slight modifications were made to suit the purposes of the present study. To maintain the original meanings, we had an educational technology specialist assess the revised items. A middle school teacher then reviewed them to ensure clarity for students. Finally, five to eight students from a pilot school, but not involved in the study, tested the revised items and found them clear and understandable. Table 4 shows all the items included in the questionnaire.

Table 4 Constructs and items included in the questionnaire

Construct	No	Items	Sources
Physical presence (PP)	PP1	I experienced a sense of "being there" while in the virtual lab	Makransky et al. (2017)
	PP2	I felt that the virtual lab seemed to be genuine	
	PP3	I received the impression that I was acting in the virtual lab instead of controlling anything from the outside	
	PP4	The experiences in the virtual lab appeared to be similar to my real-world encounters	
Self-presence (SP)	SP1	While conducting an experiment, I had the impression that the virtual embodiment in virtual lab was an extension of my physical body	
	SP2	If anything occurred to the virtual body during the experiment, I felt as if it were happening to my actual body	
	SP3	During an experiment, I felt as though my arms were projected into the virtual environment via the virtual body	
	SP4	I had a feeling that my hands were inside the virtual world while conducting an experiment	
	SP5	While performing an experiment, I felt as if my actual body and my virtual body became the same	

Table 4 (continued)

Construct	No	Items	Sources
Perceived usefulness (PU)	PU1	Overall, the virtual lab helped facilitate my learning	Bhattacherjee (2001)
	PU2	I think the virtual lab stimulated my interest in learning	
	PU3	I think the virtual lab improved my learning efficiency	
	PU4	I think the virtual lab enhanced my learning outcomes	
Satisfaction (S)	S1	Overall, I feel very satisfied with the experience of the virtual lab	
	S2	Overall, I feel very pleased with the experience of the virtual lab	
	S3	Overall, I feel very content with the experience of the virtual lab	
	S4	Overall, I feel absolutely delighted with the experience of the virtual lab	
Expectation confirmation (EC)	EC1	The learning experience with the virtual lab exceeded my expectations	
	EC2	The virtual lab led to learning outcomes that exceeded my expectations	
	EC3	Most of my predictions regarding the virtual lab were verified to a considerable degree	
Continuance intention (CI)	CI1	I shall continue to use virtual labs in my future investigations rather than discontinue such use	
	CI2	In the future, I want to experience more types of virtual labs	
	CI3	In the future, I aspire to have more opportunities to use virtual labs	

3.4 Procedure

The survey was conducted with the consent and approval of school administrators and teachers, in close collaboration with relevant government agencies overseeing experimentation. All procedures involving student participants in this study adhered to the ethical requirements set forth by the funding agency concerning research with human subjects. Given that the majority of participants were minors, parental forms were distributed to their parents through the assistance of teachers prior to the survey. Additionally, we ensured that participants were informed about the voluntary nature of their participation, affirming their right to withdraw from the study at any point. We emphasized that their responses would be kept anonymous and confidential, thereby mitigating potential bias arising from nonresponse.

To efficiently collect data from diverse regions, online survey questionnaires were distributed. The questionnaires were distributed to students by their teachers immediately after completing a virtual experiment, in alignment with their ongoing learning progress. In order to ensure data quality, students were required to complete the questionnaire on the same day they received it if they wished to participate. The survey took place from March 2022 and spanned a period of three months, in line with the teaching schedule of each pilot school.

4 Results

In this work, we employed partial least squares structural equation modelling (PLS-SEM) (Hair et al., 2014) to examine the structural relationships among different variables due to its advantages in dealing with small sample sizes or nonnormal data with a focus on prediction. Furthermore, PLS-SEM has been used extensively in e-learning research (Lin et al., 2020). The reliability and construct validity of the measurement model were first evaluated by confirmatory factor analysis (CFA). Subsequently, the structural model was evaluated to test the hypothesized links among variables.

4.1 Measurement model

To evaluate the measurement model, we examined the reliability and construct validity, which consisted of convergent validity and discriminant validity.

As shown in Table 5, the Cronbach's α values (0.861 ~ 0.963) and composite reliability (CR) values of each construct (0.905 ~ 0.976) were larger than 0.7, thus indicating good construct reliability (Hair et al., 1998). Regarding convergent validity, the value of the average variance extracted (AVE) of each construct ranged from 0.706 to 0.930, exceeding the minimum required level of 0.7. The value of the factor loading of each measured item exceeded the cut-off value of 0.5, with loading values ranging from 0.763 to 0.972. These results indicate that the convergent validity of

Table 5 Construct reliability and convergent validity

Constructs and indicators	*Mean*	*S.D*	Factor loading	Cronbach's α	CR	AVE
Physical presence (PP)	4.157	.747		.861	.905	.706
PP1			.894			
PP2			.879			
PP3			.763			
PP4			.819			
Self-presence (SP)	4.065	.841		.939	.954	.805
SP1			.866			
SP2			.905			
SP3			.907			
SP4			.885			
SP5			.920			
Perceived usefulness (PU)	4.422	.696		.943	.959	.853
PU1			.940			
PU2			.905			
PU3			.932			
PU4			.917			
Satisfaction (S)	4.401	.714		.963	.973	.900
S1			.942			
S2			.931			
S3			.959			
S4			.963			
Expectation confirmation (EC)	4.377	.732		.954	.970	.916
EC1			.949			
EC2			.958			
EC3			.964			
Continuance intention (CI)	4.391	.740		.962	.976	.930
CI1			.972			
CI2			.957			
CI3			.965			

each construct was satisfactory (Fornell & Larcker, 1981). We also evaluated the discriminant validity of the measurement model to determine whether the latent variables were independent of each other (Tsai et al., 2011).

As presented in Table 6, all the square roots of the AVE of the constructs were larger than the correlation coefficients among each construct, exceeding the cut-off value of 0.5. According to the Fornell-Larcker criterion (Fornell & Larcker, 1981), these results indicate good discriminant validity. Overall, the results reported above indicate that the measurement model used for our study of each of the constructs exhibited good reliability and validity. The model fit is also favorable with a Standardized Root Mean Square Residual (SRMR) value of 0.050, below the recommended threshold of 0.08 according to Hu and Bentler (1999). Additionally,

Table 6 Discriminant validity (Fornell-Larcker criterion)

Construct	1	2	3	4	5	6
1 Physical presence	**.840**					
2 Self-presence	.809	**.897**				
3 Perceived usefulness	.761	.682	**.924**			
4 Satisfaction	.746	.704	.806	**.949**		
5 Expectation confirmation	.731	.728	.788	.922	**.957**	
6 Continuance intention	.727	.722	.793	.929	.944	**.964**

The square roots of AVE are highlighted in bold on the diagonal. The correlations among constructs are represented by elements off the diagonal

considering distance measures like d_ULS and d_G for bootstrap-based model fit assessment, we found values of 0.390 and 0.812, respectively, both below the recommended threshold of 0.95 (Henseler et al., 2016).

4.2 Structural model and hypothesis testing

The statistical significance of the PLS path model was estimated using the bootstrapping resampling approach. According to previous studies (Lin et al., 2020; Streukens & Leroi-Werelds, 2016), bootstrapping with 5000 subsamples is recommended as a minimum requirement for PLS-SEM analysis. Thus, this study examined the structural relationships among the different latent variables proposed in the research model using 5000 bootstrap subsamples. As displayed in Fig. 4, eight significant predictive relations were identified in the model.

As shown in Fig. 4, expectation confirmation positively affected perceived usefulness ($\beta = 0.499$, $p < 0.001$), satisfaction ($\beta = 0.759$, $p < 0.001$), and continuance intention ($\beta = 0.583$, $p < 0.001$), thereby supporting H1, H2, and H6. Perceived usefulness had a positive impact on satisfaction ($\beta = 0.207$, $p < 0.01$) but no impact on

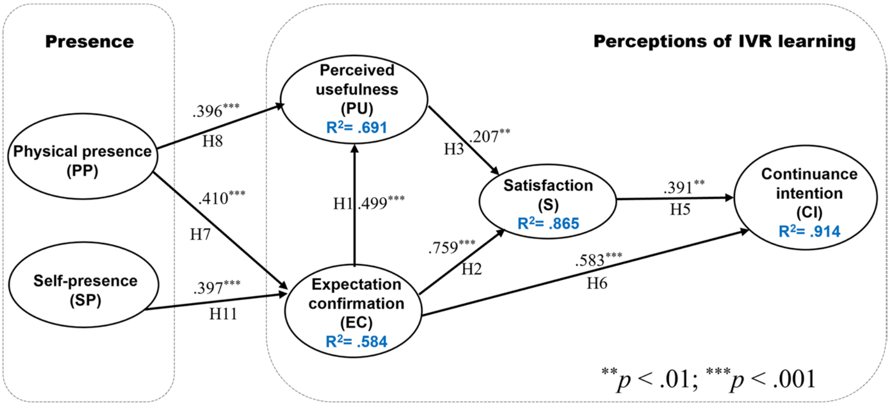

Fig. 4 The structural model

continuance intention, thus supporting H3 and rejecting H4. In addition, satisfaction positively affected continuance intention ($\beta = 0.391$, $p < 0.01$), supporting H5. Physical presence not only positively affected expectation confirmation ($\beta = 0.410$, $p < 0.001$) but also positively affected perceived usefulness ($\beta = 0.396$, $p < 0.001$), supporting H7 and H8. There were no significant relationships between physical presence and satisfaction or between physical presence and continuance intention, thereby rejecting H9 and H10. Self-presence had a positive impact on expectation confirmation ($\beta = 0.397$, $p < 0.001$) but no direct effect on perceived usefulness, satisfaction, or continuance intention; thus, H11 was supported, while H12, H13, and H14 were rejected.

The results of our study show that students' perceived presence can positively predict their confirmation of expectations regarding IVR-supported science learning, explaining 58.4% of the total variance ($R^2 = 0.584$). In addition, students' perceived physical presence in the IVR environment and confirmation of their expectations regarding its actual performance jointly predicted students' perceived usefulness of IVR-supported science learning, explaining 69.1% of the total variance ($R^2 = 0.691$). Both perceived usefulness and expectation confirmation had positive impacts on satisfaction, explaining 86.5% of the total variance ($R^2 = 0.865$). In addition, students' satisfaction with the learning experience in the IVR environment and confirmation of their expectations of the actual performance of IVR jointly predicted their continuance intention towards IVR-supported science learning, explaining 91.4% of the total variance ($R^2 = 0.914$).

In addition to the use of R^2 to assess the model's explanatory power, Stone-Geisser's Q^2 statistic was also employed to examine the predictive relevance of the endogenous constructs. The Q^2 values of expectation confirmation, perceived usefulness, satisfaction, and continuance intention were 0.527, 0.582, 0.773, and 0.843, respectively. According to Hair et al. (2019), Q^2 values greater than 0.50, 0.25, and 0 indicate large, medium, and small predictive relevance of the PLS-path model, respectively. Overall, the proposed model indicated good predictive accuracy according to the results of the Q^2 value (Hair et al., 2019).

Table 7 shows the outcomes of the hypothesis testing. Our results verified 8 of 14 total hypotheses. According to Cohen (1988), f^2 values greater than 0.02, 0.15, and 0.35 indicate small, medium, and large effect sizes, respectively. Thus, the effects of physical presence on expectation confirmation ($f^2 = 0.142$) and perceived usefulness ($f^2 = 0.239$) were close to medium and exceeded medium, respectively. The effect of self-presence on expectation confirmation ($f^2 = 0.132$) was close to medium. Furthermore, expectation confirmation had substantial effects on perceived usefulness ($f^2 = 0.379$), satisfaction ($f^2 = 1.642$), and continuance intention ($f^2 = 0.595$). In addition, the effects of perceived usefulness on satisfaction ($f^2 = 0.122$) were close to medium. According to these results, students' perceived physical and self-presence in the virtual environment had a relatively modest influence on their confirmation of expectations regarding IVR. Likewise, expectation confirmation had a significant influence on students' perceived usefulness of IVR learning, satisfaction with the IVR learning experience, and intention to continue using IVR.

Table 8 shows the indirect effects of the latent variables alongside several significant mediated paths. A general guideline in this case is that if the value of VAF (the

Table 7 Summary of hypothesis tests

Hypothesis	Path	Standardized estimate					Hypothesis supported?
		Direct effects	t	Indirect effects (95% CI*)	Total effects	Effect size f^2	
H1	EC → PU	.499***	6.530		.499***	0.379	Yes
H2	EC → S	.760***	19.543	.103** [0.041; 0.206]	.863***	1.642	Yes
H3	PU → S	.207**	2.997		.207**	0.122	Yes
H4	PU → CI		1.895	.081[0.02; 0.19]	.081	NA	No
H5	S → CI	.391**	3.383		.391**	0.267	Yes
H6	EC → CI	.584***	35.462	.337*** [0.145; 0.525]	.921***	0.595	Yes
H7	PP → EC	.410***	3.78		.410***	0.142	Yes
H8	PP → PU	.396***	9.901	.205** [0.090; 0.358]	.601***	0.239	Yes
H9	PP → S		4.579	.436*** [0.248; 0.614]	.436***	NA	No
H10	PP → CI		4.092	.410*** [0.211; 0.598]	.410***	NA	No
H11	SP → EC	.397***	3.639		.397***	0.132	Yes
H12	SP → PU		3.437	.198** [0.096; 0.318]	.198**	NA	No
H13	SP → S		3.520	.342*** [0.156; 0.530]	.342***	NA	No
H14	SP → CI		3.595	.365*** [0.168; 0.560]	.365***	NA	No

$^{**}p<.01$; $^{***}p<.001$

ratio of the indirect-to-total effect) is less than 0.2, no mediating effect is evident; if the VAF value is between 0.2 and 0.8, a partial mediating effect is in play; and if the value of VAF is more than 0.8, a full mediating effect is detected (Hair et al., 2016; Nitzl et al., 2016). The results of the mediation analysis are displayed in the last column of Table 8.

According to these findings, expectation confirmation plays an essential mediating role in the associations between students' perceptions of presence and their perceived immersive laboratory learning, including perceived usefulness of IVR, satisfaction with the IVR learning experience, and their intentions to continue using

Table 8 Specific indirect mediating effects

Path	Indirect effect	*t*	*p*	Total effect	VAF	Mediation
PP → EC → CI	.239**	2.843	.004	.410***	0.583	Partial
PP → EC → S → CI	.122**	2.756	.006	.410***	0.298	Partial
PP → EC → PU	.205**	2.975	.003	.601***	0.341	Partial
PP → EC → S	.312***	3.679	.000	.436***	0.716	Partial
PP → PU → S	.082**	2.635	.008	.436***	0.188	None
SP → EC → CI	.231**	2.907	.004	.365***	0.633	Partial
SP → EC → S → CI	.118*	2.499	.012	.365***	0.323	Partial
SP → EC → PU	.198**	3.437	.001	.198**	1.000	Full
SP → EC → S	.301**	3.237	.001	.342***	0.880	Full
SP → EC → PU → S	.041*	2.388	.017	.342***	0.120	None
EC → S → CI	.297***	3.596	.000	.921***	0.322	Partial
EC → PU → S	.103*	2.561	.010	.863***	0.119	None

VAF variance accounted for, *PP* Physical presence, *SP* self-presence, *PU* perceived usefulness, *S* satisfaction, *EC* expectation confirmation, *CI* continuance intention; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$

IVR to learn science in the future. Specifically, expectation confirmation partially mediates the influence of physical presence on continuance intention. Additionally, expectation confirmation mediates the relationship between self-presence and continuance intention to some degree. In terms of satisfaction, expectation confirmation partially mediates between physical presence and satisfaction. Expectation confirmation fully mediates the effect of self-presence on satisfaction. Regarding perceived usefulness, expectation confirmation partially mediates the influence of physical presence on perceived usefulness. Expectation confirmation also fully mediates the impact of self-presence on perceived usefulness. In addition, satisfaction partially mediates the influence of expectation confirmation on continuance intention.

5 Discussion

The current study investigated the impact of the ECM, encompassing expectation confirmation, perceived usefulness, satisfaction, and continued intention—along with the two additional variables physical presence and self-presence—on the perceptual experiences of immersive laboratory learning among secondary students. According to our results, students' confirmation of IVR expectations influences their perceived usefulness of IVR learning as well as their satisfaction with the IVR learning experience. Students' satisfaction with the IVR learning experience can be positively predicted by their perceived usefulness of IVR, and their degree of satisfaction impacts their intention to continue using IVR to learn science. These outcomes align with previous studies on 3D virtual learning environments (Shin et al., 2013) and virtual communities (Feng et al., 2019), providing further validation for the idea that students' intention to continue using IVR for laboratory education is indirectly affected by both physical presence and self-presence. Thus, to promote the sustained use of IVR for laboratory education, it is sensible to maintain students' experiences with physical presence and self-presence via IVR learning.

The aforementioned results show that it is essential to improve the confirmation of students' expectations of IVR-supported laboratory learning. Students are more inclined to continue using IVR to carry out laboratory learning if they experience a greater expectation confirmation, since this experience strengthens their perceived benefits of IVR learning and their levels of satisfaction with this approach to learning. Furthermore, our study found that expectation confirmation has a direct effect on students' continuance intention towards IVR-supported laboratory learning, which is consistent with the results reported by Alhumaid et al. (2021), who showed that expectation confirmation is a significant factor in predicting students' intentions regarding the usage of mobile learning throughout the COVID-19 period. In contrast to previous research (Alhumaid et al., 2021; Feng et al., 2019), our analysis did not find any association between perceived usefulness and continuance intention. A reason for this finding might be that students discontinue using IVR to learn science due to cyber sickness (Munafo et al., 2017), even if they recognize the benefits of its use. For example, Dehghani et al. (2022) found that users' perceived health hazards have a detrimental influence on their continuance intention regarding VR gadgets. Therefore, addressing cybersickness in IVR education is crucial to enhance students' perception of the alignment between their expectations and experiences in IVR learning, thereby promoting its sustained use for laboratory education.

Students' experience of physical presence experience in an IVR context has a strong direct impact on their perceived usefulness of IVR learning. This finding is in line with the results reported by Pedram et al. (2020) who showed that students' experience of presence in an IVR environment favourably affects their perceived usefulness of IVR training. Fokides and Atsikpasi (2018) further revealed that participants' perceived presence within a three-dimensional virtual museum positively affects their perceived usefulness of learning. However, Makransky and Lilleholt (2018) found that usability measured in terms of ease of use and perceived usefulness predicts students' experience of presence when students are provided with both desktop VR contents and IVR contents. Furthermore, no correlation was established between perceived usefulness and presence in the context of the desktop VR experience (Ai-Lim Lee et al., 2010; Makransky & Petersen, 2019). This aforementioned inconsistency in the relationship between perceived usefulness and presence may be attributed in part to different understandings of presence and different ways of measuring it. In previous studies (Ai-Lim Lee et al., 2010; Makransky & Petersen, 2019; Pedram et al., 2020), presence has been regarded as a single construct and assessed using a self-developed scale featuring only one item (Ai-Lim Lee et al., 2010) or using measures developed by Witmer and Singer (1998) or Sutcliffe et al. (2005). In contrast, our research considered presence to be a multidimensional sense construct and assessed it using two subscales—namely, physical presence and self-presence. On the other hand, the diverse degrees of presence that may be achieved by different research environments, such as desktop VR and IVR, may result in inconsistent outcomes. It is apparent that students' experiences of presence are substantially stronger in IVR than in desktop VR settings (Makransky & Lilleholt, 2018; Zhao et al., 2020).

In this research, we discovered that physical presence and self-presence play distinct roles in influencing students' perceived laboratory learning in an IVR environment. Physical presence has a direct influence on perceived usefulness and an indirect impact on satisfaction with and intention to continue using IVR. These results were also discovered by Makransky and Lilleholt (2018), who found that presence makes an indirect impact on students' perceived IVR learning (e.g., satisfaction, behavioural intention). A recent study also confirmed that physical presence favourably affects student learning outcomes in IVR via situational interest and intrinsic motivation (Petersen et al., 2022). The aforementioned findings highlighted the fact that physical presence is a significant component influencing student learning perception in an IVR environment, particularly in the context of a VR Lab. A strong experience of physical presence may be created throughout the design process by offering users fluidly displayed object movements and changes of perspective, a realistic display of the object and surroundings, a high degree of freedom regarding controlling views and manipulating objects, and 3-D audio technology as well as force feedback upon touching virtual objects (Chan et al., 2021; Dalgarno & Lee, 2010; Makransky & Petersen, 2019). Namely, these sophisticated techniques create a highly immersive and engaging virtual world, and both immersion in and the interactivity of the virtual environment have been verified to predict students' experience of physical presence in IVR learning (Petersen et al., 2022).

Unlike physical presence, perceived self-presence in the IVR environment has an indirect influence on students' satisfaction, perceived usefulness, and continuance intention towards IVR use. This result is in line with the findings of previous research that examined self-presence in persuasive virtual environments, such as virtual sports (Kim, 2020; Sun et al., 2015), VR tourism (Adachi et al., 2022; Tussyadiah et al., 2018), and VR advertising (Jung et al., 2022; Martínez-Molés et al., 2022; Song et al., 2021). For example, users' experience of self-presence has a substantial impact on their satisfaction with and the perceived usability of VR sports (Kim, 2020; Sun et al., 2015). The experience of self-presence in VR tourism influences users' favourable destination image, resulting in a greater level of travel intention (Adachi et al., 2022; Tussyadiah et al., 2018). The sense of self-presence in VR advertising has a favourable influence on consumers' enjoyment, favourable brand attitude, product knowledge, and purchase intention (Jung et al., 2022; Martínez-Molés et al., 2022; Song et al., 2021). These findings highlight the significance of self-presence and its impact on users in VR-related environments, such as IVR environments featuring virtual hands-on activities. To preserve students' self-presence in virtual environments, a well-designed virtual avatar and synchronous visuomotor (or tactile) stimulation has been proven to be effective. For example, Jahn et al. (2020) noted that preserving the congruence of visual stimuli that come into contact with the body and subsequent touch feedback can preserve students' strong sense of self-presence in a virtual environment. In addition, avatar-self similarity in the virtual world has been found to positively affect users' self-presence experience in a virtual environment via self-awareness (Hooi & Cho, 2017), whereas disruption of visuo-tactile synchrony has been found to break the illusion of users' body ownership and can decrease users' feeling of self-presence in virtual environments (Kokkinara & Slater, 2014).

According to our findings, expectation confirmation is a crucial mediator between students' perceptions of presence and their perceived learning. This finding is in accordance with the results delivered by Makransky and Petersen (2021), and Makransky and Lilleholt (2018). In these studies, the mentioned researchers discovered that students' felt presence in an IVR environment can improve their learning and satisfaction via affective mediators such as motivation, enjoyment, and curiosity; however, they caution that these mediators (e.g., curiosity, interest, or enjoyment) may diminish as students become more familiar with IVR. From these findings, it can be inferred that examining the affordance of presence in the long-term application of IVR is essential (Makransky & Lilleholt, 2018; Radianti et al., 2020). By using expectation confirmation as a crucial mediator, our study endeavoured to explore the affordance of presence in laboratory learning when IVR was incorporated into conventional scientific classes.

Contrary to our initial expectations, the findings of our study indicate that neither physical presence nor self-presence have a direct impact on satisfaction or the intention to continue using IVR for laboratory learning. However, they do exert indirect effects on satisfaction and continuance intention. This observation distinguishes our results from prior research on persuasive virtual environments such as virtual sports, VR tourism, and VR advertising. In the context of IVR laboratory learning, students' satisfaction and their intent to continue using this medium may not be directly contingent on their presence experiences in virtual environments. As highlighted by Han (2020), even when students perceive a strong sense of physical presence during virtual field trips, they might still hold high expectations which, if unmet, could lead to dissatisfaction with the immersive learning experience. Additionally, concerns related to social isolation and technology addiction may further complicate students' satisfaction. This observation aligns with the ECM proposed by Bhattacherjee (2001) which suggests that when students' experiences with IVR learning fall short of their expectations, satisfaction is unlikely, and the intention to continue using it diminishes. Our study also underscores the critical role of expectation confirmation as a mediating factor between students' perceptions of presence and their perceived IVR learning, including perceived usefulness, satisfaction, and continuance intention. In summary, our study expands the application of the ECM to immersive laboratory learning and underscores the significance of both physical presence and self-presence as essential antecedent variables that can impact students' favorable perceptions of immersive laboratory learning. Moreover, our findings respond to the call made by Lee (2010) for further investigation into the factors influencing expectation confirmation and how they can be manipulated in future research on ECM to enhance students' overall e-learning experiences.

6 Conclusions and implications

6.1 Conclusions

The present study investigated the ways in which presence affects students' perception toward immersive laboratory learning after they have participated in several topics of scientific programs using IVR equipment. Our results showed students' perceptions of the usefulness of IVR are positively influenced by physical presence in the IVR environment. The perception of physical presence also has an indirect impact on student learning satisfaction and continued intention towards IVR in the context of future study. As per the findings of our study, it has become evident that students' sense of self-presence within the IVR exerts an indirect influence on their satisfaction, perceived usefulness, and their intention to continue using IVR. This influence operates through the mechanism of expectation confirmation. These study outcomes not only build upon the foundations of prior research but also offer empirical support for the significant impact of self-presence on students' perceptions of learning within the IVR context. Moreover, the concept of expectation confirmation plays a pivotal role as a bridge connecting the sense of presence and students' perceptions of immersive laboratory learning. Consequently, when implementing IVR in laboratory education, it is paramount to ensure that students' IVR expectations are met and confirmed.

6.2 Theoretical and practical implications

The implications drawn from findings on physical presence have significant relevance for technology developers involved in the design and development of IVR environments for educational settings. Firstly, it is imperative that the designed virtual environment incorporates a high degree of interactivity and immersion. This is crucial because extant research, such as the work by Petersen et al. (2022), has demonstrated that these factors positively impact the physical presence experienced by learners. To be more specific, the IVR environment should offer students a heightened sense of control within the virtual environments and provide a rich degree of physical realism. Secondly, the chosen interaction techniques integrated into the virtual world should designed with a simplicity that minimizes the perceived extraneous cognitive load stemming from the interaction process. In other words, the interaction methods should be user-friendly and intuitive, as difficulties with the interaction process may detract from students' sense of physical presence, redirecting their attention towards the technical aspects rather than the intended educational content. This observation aligns with the findings of other research, such as a study by Brogni et al. (2003). Furthermore, the findings on self-presence hold practical implications for technology developers. They underscore the critical importance of enhancing students' experience of self-presence, particularly in virtual labs where hands-on activities are integral. To achieve this, it is advisable for developers to consider implementing well-designed virtual avatars (as suggested by Hooi & Cho, 2017) and synchronous visuomotor or tactile stimulation (following the insights from Jahn et al., 2020) in the design of virtual environments. These strategies can effectively preserve and enhance students' self-presence within these educational virtual settings.

According to our findings regarding the significance of presence, educators should prioritize IVR content that offers a high degree of physical realism and instils a strong sense of control among students. Additionally, educators should consider

IVR content with immersive design features, as highlighted by Matovu et al. (2022). Such features may include elements like virtual body ownership, character role-playing, a well-defined storyline, challenging tasks, and opportunities for extensive social interactions. Furthermore, to alleviate the extraneous cognitive load associated with interacting with IVR content, educators should ensure that students receive appropriate guidance on how to effectively engage with immersive technologies. For instance, when the learning task involves interactive 3D object observation, students should be well-informed about how to manipulate visuals to derive meaningful insights, as suggested by Lee (2018). Verstege et al. (2021) also proposed several design requirements and corresponding principles for IVR-supported laboratory learning, which include creating a positive learning experience, facilitating students in achieving intended learning outcomes, and enabling students to complete assignments independently.

Given the crucial influence of expectation confirmation on student perception of IVR learning, educators must implement effective instructional strategies to enhance the actual performance of IVR learning and ensure that it aligns with students' expectations. These strategies can include pre-training, peer instruction, and the use of generative techniques like summarizing or enactment, drawing insights from research such as Meyer et al. (2019), Zhong et al. (2022), Zhao et al. (2020), and Makransky et al. (2021). Furthermore, following the suggestions of Makransky and Lilleholt (2018), a proactive approach is preferred over relying solely on the technology itself. This approach involves careful construction of IVR content to foster a more constructive learning experience. One strategy to achieve this is by incorporating elements of gamification within IVR content, aligning with prior studies such as Shin et al. (2013) and Zhang et al. (2020), so as to reinforce students' confirmation of their expectations regarding learning in virtual environments. In addition to the efforts of educators, it is imperative for policymakers to take action by developing training programs to help teachers address technological and pedagogical challenges, as emphasized by Cardullo and Wang (2021), when integrating IVR into science curricula.

7 Limitations and future works

This research offers intriguing insights but has some limitations. The primary one is the small sample size, with its subjects taken from just four pilot schools; this could introduce selection bias and affect generalizability. To address this, future studies should include a more diverse range of pilot schools. Additionally, given the participation of adolescents aged 13–18, considering potential moderating factors is important for understanding students' intentions to continue using IVR. This may involve including a broader age range in the sample and considering relevant moderating variables (such as spatial ability) in further research (Makransky & Petersen, 2021). Moreover, the participants in our study were drawn from different pilot schools, potentially resulting in a nested data structure. Given our limitation of having fewer than the recommended minimum of 50 schools as per Maas and Hox (2005), it is not feasible to precisely measure the nesting effect in this study. Future research should aim to collect data from a larger number of schools to adequately address this issue. Lastly, it is crucial to note that this study focused exclusively on a specific type of virtual learning environment, namely the virtual lab with hands-on activities, utilizing the virtual lab platform (https://vlab.eduyun.cn/portal/home). Consequently, caution should be exercised when extrapolating the results to other contexts. Future studies should encompass a broader range of IVR learning environments, including emerging platforms like the metaverse, to enhance the understanding of their impact. Additionally, the virtual hands-on activities completed by participants in this study varied based on their individual learning progress, potentially affecting the level of perceived presence. Exploring the influence of presence on perceived learning in diverse educational contexts, such as social and emotional learning within IVR environments (as suggested by Tan et al., 2022), would offer a promising avenue for future research. Moreover, while social presence may exist within IVR learning environments, this aspect was not explored in our study. Thus, investigating its effects in the future would contribute to a more comprehensive understanding of the impact of presence on students' perceived IVR learning.

Acknowledgements We extend our sincere gratitude to Dr. Xiaoqiang Ma and Dr. Yuanyuan Fang from the National Center for Educational Technology for their invaluable assistance in organizing data collection.

Author contributions Conceptualization: Muhua Zhang, Chien-Yuan Su; Methodology: Muhua Zhang; Formal analysis and investigation: Muhua Zhang; Writing—original draft preparation: Muhua Zhang; Writing—review and editing: Chien-Yuan Su; Funding acquisition: Muhua Zhang, Chien-Yuan Su; Supervision: Chien-Yuan Su.

Funding This work was supported by the National Natural Science Foundation of China under Grant 62107003, Humanities and Social Sciences Youth Foundation, Ministry of Education of the People's Republic of China under Grant 21YJC880095, and National Science and Technology Council, Taiwan (R.O.C.) under Grant No. NSTC 112–2410-H-024 -001-MY2.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability Not applicable.

Declarations

Consent to participate This study was conducted after informed consent of the participants.

Consent for publication Not applicable.

Conflicts of interest The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Adachi, R., Cramer, E. M., & Song, H. (2022). Using virtual reality for tourism marketing: A mediating role of self-presence. *The Social Science Journal,59*(4), 657–670. https://doi.org/10.1080/03623319.2020.1727245

Ai-Lim Lee, E., Wong, K. W., & Fung, C. C. (2010). How does desktop virtual reality enhance learning outcomes? A structural equation modeling approach. *Computers & Education,55*(4), 1424–1442. https://doi.org/10.1016/j.compedu.2010.06.006

Alhumaid, K., Habes, M., & Salloum, S. A. (2021). Examining the factors influencing the mobile learning usage during COVID-19 pandemic: An integrated SEM-ANN method. *IEEE Access,9*, 102567–102578. https://doi.org/10.1109/ACCESS.2021.3097753

Ammann, J., Hartmann, C., Peterhans, V., Ropelato, S., & Siegrist, M. (2020). The relationship between disgust sensitivity and behaviour: A virtual reality study on food disgust. *Food Quality and Preference,80*, 1–7. https://doi.org/10.1016/j.foodqual.2019.103833

Andersen, M. S., Klingenberg, S., Petersen, G. B., Creed, P. A., & Makransky, G. (2023). Fostering science interests through head-mounted displays. *Journal of Computer Assisted Learning,39*(2), 369–379. https://doi.org/10.1111/jcal.12749

Behm-Morawitz, E. (2013). Mirrored selves: The influence of self-presence in a virtual world on health, appearance, and well-being. *Computers in Human Behavior,29*(1), 119–128. https://doi.org/10.1016/j.chb.2012.07.023

Bhattacherjee, A. (2001). Understanding information systems continuance: An expectation-confirmation model. *MIS Quarterly,25*(3), 351–370. https://doi.org/10.2307/3250921

Brogni, A., Slater, M., & Steed, A. (2003). More breaks less presence. In E. Granum, G. Sørensen, & S. Livatino (Eds.), *Presence 2003: The 6th Annual International Workshop on Presence* (pp. 41–44). International Society for Presence Research

Cardullo, V., & Wang, C. H. (2021). Pre-service teachers' perspectives of google expedition. *Early Childhood Education Journal,50*(2), 173–183. https://doi.org/10.1007/s10643-020-01136-3

Chan, P., Van Gerven, T., Dubois, J.-L., & Bernaerts, K. (2021). Virtual chemical laboratories: A systematic literature review of research, technologies and instructional design. *Computers and Education Open,2*, 100053. https://doi.org/10.1016/j.caeo.2021.100053

Chang, C. W., Heo, J., Yeh, S. C., Han, H. Y., & Li, M. (2018). The effects of immersion and interactivity on college students' acceptance of a novel VR-supported educational technology for mental rotation. *IEEE Access,6*, 66590–66599. https://doi.org/10.1109/ACCESS.2018.2878270

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Lawrence Erlbaum.

Dalgarno, B., & Lee, M. J. W. (2010). What are the learning affordances of 3-D virtual environments? *British Journal of Educational Technology,41*(1), 10–32. https://doi.org/10.1111/j.1467-8535.2009.01038.x

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly,13*(3), 319–340. https://doi.org/10.2307/249008

de Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science,340*(6130), 305–308. https://doi.org/10.1126/science.1230579

Dehghani, M., Acikgoz, F., Mashatan, A., & Lee, S. H. (2022). A holistic analysis towards understanding consumer perceptions of virtual reality devices in the post-adoption phase. *Behaviour and Information Technology,41*(7), 1453–1471. https://doi.org/10.1080/0144929X.2021.1876767

Di Natale, A. F., Repetto, C., Riva, G., & Villani, D. (2020). Immersive virtual reality in K-12 and higher education: A 10-year systematic review of empirical research. *British Journal of Educational Technology,51*(6), 2006–2033. https://doi.org/10.1111/bjet.13030

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods,41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Felton, W. M., & Jackson, R. E. (2022). Presence: A review. *International Journal of Human-Computer Interaction,38*(1), 1–18. https://doi.org/10.1080/10447318.2021.1921368

Feng, Y., Liu, Z., Qian, W., Guo, M., & Chen, J. (2019). *Research on the influence mechanism of gamification elements on users' willingness to continue using in interest-based virtual communities - Based on ecmisc model* [Paper presentation]. International Conference on Service Systems and Service Management, Shenzhen, China. https://doi.org/10.1109/ICSSSM.2019.8887645

Fokides, E., & Atsikpasi, P. (2018). Development of a model for explaining the learning outcomes when using 3D virtual environments in informal learning settings. *Education and Information Technologies, 23*, 2265–2287. https://doi.org/10.1007/s10639-018-9719-1

Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of Marketing Research,18*(1), 39–50. https://doi.org/10.2307/3151312

Gao, N., Liu, G. P., Xie, T., & Zhang, L. (2023). Research on the effectiveness and efficiency of immersive virtual reality on learners' knowledge transfer. *Journal of Distance Education, 41*(1), 91–101. https://doi.org/10.15881/j.cnki.cn33-1304/g4.2023.01.009

Hair, J. F., Anderson, R. E., Tatham, R. L., & Black, W. C. (1998). *Multivariate data analysis with readings* (5th ed.). Prentice-Hall.

Hair, J. F., Hult, G. T. M., Ringle, C. M., & Sarstedt, M. (2016). *A primer on partial least squares structural equation modeling (PLS-SEM)*. Sage.

Hair, J. F., Risher, J. J., Sarstedt, M., & Ringle, C. M. (2019). When to use and how to report the results of PLS-SEM. *European Business Review,31*(1), 2–24. https://doi.org/10.1108/EBR-11-2018-0203

Hair, J. F., Sarstedt, M., Hopkins, L., & Kuppelwieser, V. G. (2014). Partial least squares structural equation modeling (PLS-SEM): An emerging tool in business research. *European Business Review,26*(2), 106–121. https://doi.org/10.1108/EBR-10-2013-0128

Han, I. (2020). Immersive virtual field trips and elementary students' perceptions. *British Journal of Educational Technology,52*(1), 179–195. https://doi.org/10.1111/bjet.12946

Henseler, J., Hubona, G., & Ray, P. A. (2016). Using PLS path modeling in new technology research: Updated guidelines. *Industrial Management & Data Systems,116*(1), 2–20. https://doi.org/10.1108/IMDS-09-2015-0382

Hite, R. (2022). Virtual reality: Flight of fancy or feasible? Ways to use virtual reality technologies to enhance students' science learning. *American Biology Teacher,84*(2), 106–108. https://doi.org/10.1525/abt.2022.84.2.106

Hooi, R., & Cho, H. (2017). Virtual world continuance intention. *Telematics and Informatics,34*(8), 1454–1464. https://doi.org/10.1016/j.tele.2017.06.009

Hu, L., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling: A Multidisciplinary Journal,6*(1), 1–55. https://doi.org/10.1080/10705519909540118

Ijsselsteijn, W., & Riva, G. (2003). Being there: The experience of presence in mediated environments. In G. Riva, F. Davide, & W. Ijsselsteijn (Eds.), *Being there: Concepts, effects and measurement of user presence in synthetic environments* (pp. 3–16). Ios Press.

Jahn, K., Kordyaka, B., Ressing, C., Roeding, K., & Niehaves, B. (2020). Designing self-presence in immersive virtual reality to improve cognitive performance—A research proposal. *Lecture Notes in Information Systems and Organisation,32*, 83–91. https://doi.org/10.1007/978-3-030-28144-1_9

Jung, Y. (2011). Understanding the role of sense of presence and perceived autonomy in users' continued use of social virtual worlds. *Journal of Computer-Mediated Communication,16*(4), 492–510. https://doi.org/10.1111/j.1083-6101.2011.01540.x

Jung, S., Lee, D., You, S., Biocca, F., & Kum-Biocca, H. (2022). The role of the self-presence for interactive large digital displays: Gesture interactivity and mirrored-self image for advertising content. *International Journal of Human-Computer Interaction,38*(16), 1576–1588. https://doi.org/10.1080/10447318.2021.2009668

Kim, J. (2020). Relationship between self-presence, use immersion, and satisfaction with use through virtual sports experience. *The Korean Journal of Sport, 18*(4), 163–172. https://doi.org/10.46669/kss.2020.18.4.016

Klingenberg, S., Jørgensen, M. L. M., Dandanell, G., Skriver, K., Mottelson, A., & Makransky, G. (2020). Investigating the effect of teaching as a generative learning strategy when learning through desktop and immersive VR: A media and methods experiment. *British Journal of Educational Technology,51*(6), 2115–2138. https://doi.org/10.1111/bjet.13029

Kokkinara, E., & Slater, M. (2014). Measuring the effects through time of the influence of visuomotor and visuotactile synchronous stimulation on a virtual body ownership illusion. *Perception,43*(1), 43–58. https://doi.org/10.1068/p7545

Lee, C. B. (2018). Initial development of the meaningful learning with technology scale (melts) for high-school students. *Interactive Learning Environments,26*(2), 163–174. https://doi.org/10.1080/10494820.2017.1283336

Lee, K. M. (2004). Presence, explicated. *Communication Theory,14*(1), 27–50. https://doi.org/10.1093/ct/14.1.27

Lee, M. C. (2010). Explaining and predicting users' continuance intention toward e-learning: An extension of the expectation-confirmation model. *Computers & Education,54*(2), 506–516. https://doi.org/10.1016/j.compedu.2009.09.002

Lin, H. M., Lee, M. H., Liang, J. C., Chang, H. Y., Huang, P., & Tsai, C. C. (2020). A review of using partial least square structural equation modeling in e-learning research. *British Journal of Educational Technology,51*(4), 1354–1372. https://doi.org/10.1111/bjet.12890

Maas, C. J., & Hox, J. J. (2005). Sufficient sample sizes for multilevel modeling. *Methodology,1*(3), 86–92. https://doi.org/10.1027/1614-2241.1.3.86

Makransky, G., & Lilleholt, L. (2018). A structural equation modeling investigation of the emotional value of immersive virtual reality in education. *Educational Technology Research and Development,66*(5), 1141–1164. https://doi.org/10.1007/s11423-018-9581-2

Makransky, G., & Mayer, R. E. (2022). Benefits of taking a virtual field trip in immersive virtual reality: Evidence for the immersion principle in multimedia learning. *Educational Psychology Review,34*, 1771–1798. https://doi.org/10.1007/s10648-022-09675-4

Makransky, G., & Petersen, G. B. (2019). Investigating the process of learning with desktop virtual reality: A structural equation modeling approach. *Computers & Education,134*, 15–30. https://doi.org/10.1016/j.compedu.2019.02.002

Makransky, G., & Petersen, G. B. (2021). The cognitive affective model of immersive learning (CAMIL): A theoretical research-based model of learning in immersive virtual reality. *Educational Psychology Review,33*(3), 937–958. https://doi.org/10.1007/s10648-020-09586-2

Makransky, G., Lilleholt, L., & Aaby, A. (2017). Development and validation of the multimodal presence scale for virtual reality environments: A confirmatory factor analysis and item response theory approach. *Computers in Human Behavior,72*, 276–285. https://doi.org/10.1016/j.chb.2017.02.066

Makransky, G., Borre-Gude, S., & Mayer, R. E. (2019). Motivational and cognitive benefits of training in immersive virtual reality based on multiple assessments. *Journal of Computer Assisted Learning,35*(6), 691–707. https://doi.org/10.1111/jcal.12375

Makransky, G., Andreasen, N. K., Baceviciute, S., & Mayer, R. E. (2021). Immersive virtual reality increases liking but not learning with a science simulation and generative learning strategies promote learning in immersive virtual reality. *Journal of Educational Psychology,113*(4), 719–735. https://doi.org/10.1037/edu0000473

Makransky, G., Petersen, G. B., & Klingenberg, S. (2020). Can an immersive virtual reality simulation increase students' interest and career aspirations in science? *British Journal of Educational Technology,51*(6), 2079–2097. https://doi.org/10.1111/bjet.12954

Martínez-Molés, V., Jung, T. H., Pérez-Cabañero, C., & Cervera-Taulet, A. (2022). Gathering pre-purchase information for a cruise vacation with virtual reality: The effects of media technology and gender. *International Journal of Contemporary Hospitality Management,34*(1), 407–429. https://doi.org/10.1108/IJCHM-04-2021-0500

Matovu, H., Ungu, D. A. K., Won, M., Tsai, C.-C., Treagust, D. F., Mocerino, M., & Tasker, R. (2022). Immersive virtual reality for science learning: Design, implementation, and evaluation. *Studies in Science Education,59*(2), 205–244. https://doi.org/10.1080/03057267.2022.2082680

Melo, M., Coelho, H., Gonçalves, G., Losada, N., Jorge, F., Teixeira, M. S., & Bessa, M. (2022). Immersive multisensory virtual reality technologies for virtual tourism: A study of the user's sense of presence, satisfaction, emotions, and attitudes. *Multimedia Systems,28*(3), 1027–1037. https://doi.org/10.1007/s00530-022-00898-7

Meyer, O. A., Omdahl, M. K., & Makransky, G. (2019). Investigating the effect of pre-training when learning through immersive virtual reality and video: A media and methods experiment. *Computers & Education,140*, 1–17. https://doi.org/10.1016/j.compedu.2019.103603

Moreno, R., & Mayer, R. (2007). Interactive multimodal learning environments. *Educational Psychology Review,19*(3), 309–326. https://doi.org/10.1007/s10648-007-9047-2

Munafo, J., Diedrick, M., & Stoffregen, T. A. (2017). The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects. *Experimental Brain Research,235*(3), 889–901. https://doi.org/10.1007/s00221-016-4846-7

Naz, Z., Azam, A., & Muhammad, M. (2024). Development and evaluation of immersive VR laboratories of organic chemistry and physics for students education. *Physica Scripta,99*(5), 056101. https://doi.org/10.1088/1402-4896/ad3024

Nitzl, C., Roldan, J. L., & Cepeda, G. (2016). Mediation analysis in partial least squares path modelling, helping researchers discuss more sophisticated models. *Industrial Management and Data Systems,116*(9), 1849–1864. https://doi.org/10.1108/IMDS-07-2015-0302

Pasha, S. A., Youssef, E., & Sharif, H. (2021). Role of virtual reality in improving students' LMS experiences: Structural equation modelling based study [Paper presentation]. *International Conference* *of Modern Trends in Information and Communication Industry*. https://doi.org/10.1109/MTICTI53925.2021.9664769

Pedram, S., Palmisano, S., Skarbez, R., Perez, P., & Farrelly, M. (2020). Investigating the process of mine rescuers' safety training with immersive virtual reality: A structural equation modelling approach. *Computers & Education,153*, 1–30. https://doi.org/10.1016/j.compedu.2020.103891

Petersen, G. B., Klingenberg, S., Mayer, R. E., & Makransky, G. (2020). The virtual field trip: Investigating how to optimize immersive virtual learning in climate change education. *British Journal of Educational Technology,51*(6), 2099–2115. https://doi.org/10.1111/bjet.12991

Petersen, G. B., Petkakis, G., & Makransky, G. (2022). A study of how immersion and interactivity drive VR learning. *Computers & Education,179*, 1–16. https://doi.org/10.1016/j.compedu.2021.104429

Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Computers & Education,95*, 309–327. https://doi.org/10.1016/j.compedu.2016.02.002

Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education,147*, 1–29. https://doi.org/10.1016/j.compedu.2019.103778

Reeves, S. M., & Crippen, K. J. (2021). Virtual laboratories in undergraduate science and engineering courses: A systematic review, 2009–2019. *Journal of Science Education and Technology,30*(1), 16–30. https://doi.org/10.1007/s10956-020-09866-0

Reeves, S. M., Crippen, K. J., & McCray, E. D. (2021). The varied experience of undergraduate students learning chemistry in virtual reality laboratories. *Computers & Education,175*, 104320. https://doi.org/10.1016/j.compedu.2021.104320

Shin, D. H., Biocca, F., & Choo, H. (2013). Exploring the user experience of three-dimensional virtual learning environments. *Behaviour and Information Technology,32*(2), 203–214. https://doi.org/10.1080/0144929X.2011.606334

Song, H., Kim, J., Nguyen, T. P. H., Lee, K. M., & Park, N. (2021). Virtual reality advertising with brand experiences: The effects of media devices, virtual representation of the self, and self-presence. *International Journal of Advertising,40*(7), 1096–1114. https://doi.org/10.1080/02650487.2020.1834210

Streukens, S., & Leroi-Werelds, S. (2016). Bootstrapping and PLS-SEM: A step-by-step guide to get more out of your bootstrap results. *European Management Journal,34*(6), 618–632. https://doi.org/10.1016/j.emj.2016.06.003

Sun, H. M., Li, S. P., Zhu, Y. Q., & Hsiao, B. (2015). The effect of user's perceived presence and promotion focus on usability for interacting in virtual environments. *Applied Ergonomics,50*, 126–132. https://doi.org/10.1016/j.apergo.2015.03.006

Sutcliffe, A., Gault, B., & Shin, J. E. (2005). Presence, memory and interaction in virtual environments. *International Journal of Human Computer Studies,62*(3), 307–327. https://doi.org/10.1016/j.ijhcs.2004.11.010

Tan, M. C. C., Chye, S. Y. L., & Teng, K. S. M. (2022). "In the shoes of another": Immersive technology for social and emotional learning. *Education and Information Technologies, 27*, 8165–8188. https://doi.org/10.1007/s10639-022-10938-4

Tsai, C. C., Jessie Ho, H. N., Liang, J. C., & Lin, H. M. (2011). Scientific epistemic beliefs, conceptions of learning science and self-efficacy of learning science among high school students. *Learning and Instruction,21*(6), 757–769. https://doi.org/10.1016/j.learninstruc.2011.05.002

Tsirulnikov, D., Suart, C., Abdullah, R., Vulcu, F., & Mullarkey, C. E. (2023). Game on: Immersive virtual laboratory simulation improves student learning outcomes & motivation. *FEBS Open Bio,13*(3), 396–407. https://doi.org/10.1002/2211-5463.13567

Tussyadiah, I. P., Wang, D., Jung, T. H., & tom Dieck, M. C. (2018). Virtual reality, presence, and attitude change: Empirical evidence from tourism. *Tourism Management, 66*, 140–154. https://doi.org/10.1016/j.tourman.2017.12.003

Verstege, S., Vincken, J.-P., & Diederen, J. (2021). Blueprint to design virtual experiment environments. *Computers and Education Open,2*, 100039. https://doi.org/10.1016/j.caeo.2021.100039

Wang, X., Butt, A. H., Zhang, Q., Shafique, M. N., Ahmad, H., & Nawaz, Z. (2020). Gaming avatar can influence sustainable healthy lifestyle: Be like an avatar. *Sustainability,12*(5), 1–22. https://doi.org/10.3390/su12051998

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and Virtual Environments, 7*(3), 225–240. https://doi.org/10.1162/105474698565686

Wu, B., Yu, X., & Gu, X. (2020). Effectiveness of immersive virtual reality using head-mounted displays on learning performance: A meta-analysis. *British Journal of Educational Technology,51*(6), 1991–2005. https://doi.org/10.1111/bjet.13023

Zhang, M. H., Su, C. Y., Li, Y., & Li, Y. Y. (2020). Factors affecting Chinese university students' intention to continue using virtual and remote labs. *Australasian Journal of Educational Technology, 36*(2), 169–185. https://doi.org/10.14742/AJET.5939

Zhao, J., Lin, L., Sun, J., & Liao, Y. (2020). Using the summarizing strategy to engage learners: Empirical evidence in an immersive virtual reality environment. *Asia-Pacific Education Researcher,29*(5), 473–482. https://doi.org/10.1007/s40299-020-00499-w

Zhong, Z., Zhang, G., Jin, S., Wang, J., Ma, N., & Feng, S. (2022). Investigating the effect of peer instruction on learners with different cognitive styles in VR-based learning environment. *Education and Information Technologies,27*(8), 11875–11899. https://doi.org/10.1007/s10639-022-11115-3