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Science lab safety goes immersive: An ecological media-comparison study with gender analyses assessing iVR's learning effectiveness

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Abstract

We conducted a media-comparison study in ecologically valid settings to understand immersive virtual reality's (iVR's) instructional effectiveness in a university science course. We tested how complementing regular science lab safety instruction with interactive iVR simulation, desktop simulation, or the re-viewing of a text-heavy manual compare with each other in terms of knowledge-related and affective learning outcomes. We also explored gender differences in the outcomes across these instructional conditions. 102 undergraduates (51 females) were randomly assigned to one of the instructional conditions. Throughout the one-day course, all students received the same set of instructions, demonstrations, and hands-on lab safety training except for the following: the iVR group engaged with HMD-based interactive lab safety iVR training simulation; the desktop group interacted with the same simulation on a laptop, whereas the remaining group re-viewed the text-heavy course material in detail. Topic knowledge-related and self-report affective data were collected before and immediately after the course. Statistical analyses revealed that: (i) all three instructional modes helped students gain significant lab safety knowledge, (ii) there were several significant between-group differences in multiple affective measures, and (iii) the instructional modes affected/benefited the two genders considerably differently. Besides extending previous findings, the strong ecological grounding of our results adds important insights into real-life implications of integrating different media in undergraduate education. Our gender-related findings merely scratch the surface on the complex issue of "designing for diversity", inviting scaled-up efforts to develop more equitable technology-enhanced science learning settings to address the cognitive-affective needs of different genders and other diversities.

Keywords: Virtual reality, Science education, Embodied learning, Lab safety, Gender differences, Media comparison



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Introduction

Computer simulation-based learning environments (e.g., virtual labs), particularly those based on immersive virtual reality (hereafter, iVR; Lindgren & Johnson-Glenberg, 2013) offer promising solutions to overcome challenges in the practical aspects of science learning (e.g., lab safety) that rely heavily on hands-on and procedural experiences (Lamb et al., 2018; Rosenblatt et al., 2013).

There is ample evidence in science education literature that desktop-based computer simulations are more efficient and effective in terms of learning outcomes than traditional text or lecture-based pedagogical methods (Coban et al., 2022; Smetana & Bell, 2012). With the evolution and increasing ease-of-availability of head mounted devices (HMDs) for iVR, there appears to be a general shift in the focus of media comparison research measuring educational effectiveness towards understanding how HMD-based iVR compares with desktop-based and/or text-heavy traditional pedagogies (Hew & Cheung, 2010; Makransky et al., 2019; Pande et al., 2021; Plass et al., 2022; Zhao et al., 2021). It is important to know what extra value iVR can add to learning and in facilitating experiential learning of science that desktop or text cannot; especially considering the political, economic, logistical, and/or ethical limitations associated with implementing HMD-based iVR at scale. The three media certainly differ in their affordances, and learning and educational technology designers need to know how to build on each of their affordances in meaningful ways (Holder et al., 2020).

However, existing work comparing the learning effectiveness of desktop with iVR is still largely fragmented in terms of the levels of education investigated (e.g., school, undergraduate; Jensen and Konradsen, 2018; Radianti et al., 2020); content being studied (e.g., laboratory skills, visualization of abstract concepts; Checa et al., 2021; Makransky et al., 2020), results (positive, mixed; Buttussi & Chittaro, 2018; Fabris et al., 2019; Luo et al., 2021), the nature of the iVR experience (depending on aspects of learning design – e.g., the extent of interaction and use of body; sophistication of technology – e.g., hardware and software), and the relationships between these (Luo et al., 2021).

In the context of higher science education, studies have indicated that iVR is effective in improving several affective aspects of student learning (e.g., motivation, self-efficacy, enjoyment) as well as knowledge-retention, either in isolation, or in comparison with other media (e.g., Moro et al., 2017; Parong & Mayer, 2020; Vuchkova et al., 2011). However, results related to conceptual and procedural learning are not conclusive (e.g., Azer & Azer, 2016; Klippel et al., 2020; Moro et al., 2017; Renken & Nunez, 2013; Zhao et al., 2021). It is also not clear how applicable iVR is, in the light of these positive/inconclusive results, to real university-level classrooms (ecological contexts; Hew & Cheung, 2010; Pande et al., 2021; Wu et al., 2020; Zhao et al., 2021), as most studies test iVR learning applications in controlled settings.

We conducted a media-comparison study to contribute to the limited volume of research on iVR's instructional effectiveness in ecological settings in university science courses. In this study, we tested how complementing regular science lab safety instruction with either an interactive and immersive iVR simulation, an interactive desktop simulation, or the reading of a text-heavy manual, compare with each other in terms of knowledge-related and affective learning outcomes. We also tested if and how males and females differ in terms of the learning benefits of each of these technologies in the context of undergraduate science lab safety training.

Previous research on virtual and iVR labs in science education

Computer simulation-based learning environments offer great potential for university laboratory training and education, particularly in the context of science, as they may allow the learners to: run the same experimental activity multiple times without requiring extra resources (or requiring minimal resources such as electricity; Brinson, 2015; Heradio et al., 2016); complete the activities much more quickly and/or easily (e.g., in comparison to the real world; Pyatt & Sims, 2012; West & Veenstra, 2012); and perceive, generate, and/or control different phenomena, and experimental conditions and states (even those that are not plausible in the real world) at will, facilitating more effective observation, interpretation, and shared communication (e.g., between a teacher and their students).

Literature has shown that desktop-based virtual labs (also sometimes referred to as desktop VR, or 'low-immersion' VR; (Merchant et al., 2014) are effective science learning-teaching tools, especially in comparison to traditional text-intensive, lecture or demonstration-based methods (e.g., Flint & Stewart, 2010; Slotta & Linn, 2009; Su & Cheng, 2013). Research has also shown that desktop virtual labs are equally effective when compared with hands-on learning activities performed in actual labs (e.g., Ma & Nickerson, 2006; Mione et al., 2013); although, a significant strand of research argues and demonstrates that learning-teaching is more efficient when such virtual labs are used to prepare students for real laboratory experiments (Dalgarno et al., 2009; Dyrberg et al., 2017; Flint & Stewart, 2010; Hurtado-Bermúdez & Romero-Abrio, 2020; Koretsky et al., 2011; Makransky et al., 2016); thus, arguing for a supplementary use of learning technology that helps students 'remember', for instance, the various procedure-steps in lab exercises. Despite their demonstrated teaching efficiency, however, desktop-based virtual labs do not support the development of hands-on skills required to navigate labs and operate lab equipment and material (Gibbons et al., 2004). This is largely because these labs fail to provide students with body-based (e.g., tactile) experiences, and realistic bodily interaction often deemed necessary for such learning (Potkonjak et al., 2016; Šorgo & Špernjak, 2012).

In comparison, iVR offers the possibility of more real-life-like practice in simulated environments, where one can physically interact with, and bodily experience operating,

equipment and material to run experiments. Though the literature provides a range of definitions for iVR (Radianti et al., 2020), it has been widely demonstrated that iVR affords the generation of novel transformations of abstract scientific representations, models, and visualizations into highly realistic interactive, engaging, and body-based experiences (Daugherty et al., 2024; Johnson-Glenberg, 2018; Zacharia et al., 2012). This paper identifies iVR as realistic 3-dimensional virtual environments, accessible via HMDs, that simulate and/or model elements of the world (e.g., a lab), and that isolate the user sensorily from their surroundings (e.g., in terms of visual perception) and hence induce into the user a subjective experience of being present and immersed in those environments (Biocca & Delaney, 1995; Dede, 2009; Han, 2020; Radianti et al., 2020). Elements in such iVR environments can be interacted with via controllers of different types, and to varying degrees, depending on the hardware and software. iVR also affords real-time availability of perceptual input (e.g., as a 3-dimensional visual display) to the user as a response to their interaction. Further, iVR could be easily coupled with other technology (e.g., haptic devices, gesture-based input devices) to further enhance the interactive experience, making the simulated interaction more like ‘real’ interaction, but with less constraints (e.g., on material, economical, and human resources). These characteristics distinguish iVR from desktop VR tools in terms of its cognitive and affective effects (Klippel et al., 2020).

However, as captured in the following two subsections, research on the learning effectiveness of iVR-based instruction in science and allied disciplines is relatively new and fragmented, in terms of the nature of results (e.g., positive learning effects, downsides), the cognitive (e.g., recall/retention, procedural and conceptual understanding) and/or affective aspects (e.g., motivation and interest) of learning under investigation, the topic/domain in which iVR-based instruction is implemented, and the designs of iVR environments (e.g., Coban et al., 2022; Johnson-Glenberg et al., 2021).

Conceptual and procedural learning with iVR in higher education

Recent research in medical education - where most of the iVR-related science education literature is found (Luo et al., 2021) - has shown that instruction and training in iVR help improve procedural and manual skills, and associated affective experience (Parkhomenko et al., 2019; Wismer et al., 2021). Experiencing iVR, as opposed to observing computer tomography scans of kidney stone anatomies, has been found to improve surgeons’ procedural skills such as planning surgical approaches (Parkhomenko et al., 2019). iVR, in this study, also led to significantly higher perceived understanding post intervention than scan-viewing. The iVR environment used in this study, however, afforded only viewing detailed anatomical visualizations as 3D spatial models (e.g., of individual variations in the location of kidney stones), and did not involve the participants acting on/practicing virtual surgery, thus suggesting that the practice aspects of iVR training (and hence, body-

movement/action-related affordances of iVR) had little to do with the positive results on procedural learning (Parkhomenko et al., 2019).

In the context of molecular biology, Lamb et al.'s (2018) study demonstrated that learning science through iVR simulations was cognitively (e.g., in terms of brain activity) equivalent to engagement with serious educational games, as well as hands-on activities. iVR thus not only led to better learning outcomes (i.e., gain in test scores), but also triggered significantly higher cognitive engagement and processing (e.g., neural activation) as compared to video lectures. Similarly, two recent studies from our own group revealed that embodied interactions in an iVR simulation, where a student could “become” a molecule (an enzyme) and enact and experience the various organic chemical reaction mechanisms involved a biochemical phenomenon, helped undergraduates learn significantly more about core biochemistry concepts (Washington et al., 2024) as compared to those students who attended a slide-based traditional lecture (Pande, 2023).

Procedural training in iVR in the context of general lab safety has resulted in better performance on practical tests, and the feeling of self-efficacy, but not on knowledge-retention tests, as compared to training with desktop simulation and text-based manual (Makransky et al., 2019). In contrast, Webster's (2016) use of iVR instruction to teach scientific (e.g., corrosion of metals and its effects on the environment) concepts to US military personnel did result in higher knowledge retention as compared to traditional lecture-based instruction. Similarly, Markowitz et al. (2018) demonstrated, through a series of four studies involving an immersive experience of under-water climate-related phenomena, that knowledge-retention (and topic interest) could be improved with iVR instruction. Pande et al. (2021) showed how interaction with multiple iVR simulations, but not watching their videos, over time resulted in a considerable knowledge gain on multiple topics in environmental science in a longitudinal media comparison study involving science undergraduates. In Plass et al.'s (2022) recent study, iVR instruction attained significantly better scores among middle schoolers than traditional slideshow-based instruction on cell biology topic knowledge-related tests. Similarly, Wismer et al. (2021) in a large-scale study in the context of biopharmaceutical industry demonstrated that iVR was significantly more effective in teaching the theory behind manufacturing procedures (e.g., pH calibration and adjustment) to industry trainees than PowerPoint slide-based reading, but not different from real-life training. In this study, real-life training was the most effective mode to teach practical skills; iVR was significantly more effective than the use of slides.

A different set of studies, however, demonstrate either no or negative effects of iVR-based instruction on the cognitive aspects of learning. Pulijala et al. (2018), for instance, found that a gesture-based interaction with 3D models of facial anatomy in iVR did not differ significantly from a video-viewing intervention in terms of gain in knowledge about

facial surgery; although, the former did result in a significant improvement in self-confidence among the participants as compared to the latter. Makransky et al.'s (2019) study demonstrated that iVR-based instruction did not lead to improved science learning, as compared to other such instructional media as desktop-based simulations, even though students in the iVR conditions report higher presence and enjoyment.

Overall, results on iVR's effects on skill acquisition/training (e.g., procedural learning), recall and knowledge retention, and conceptual learning have been mixed (Concannon et al., 2019; Srivastava et al., 2019; Radianti et al., 2020), especially in comparison to other forms of instructional media (Wu et al., 2020). Further, reports on the testing and implementation of cutting-edge iVR systems for science laboratory training are relatively scarce. Most such reports in the past 10 years can be found in the more applied domains in higher science education such as medical, dentistry, and engineering education (Gunn et al., 2018; Loukas et al., 2011; Roy et al., 2017; Tang et al., 2019).

Affective aspects of learning with iVR

Interest, motivation, self-efficacy, enjoyment, perceived usefulness, and other affective aspects of an intervention, in relation to the content being learned, are considered critical to conceptual and procedural learning in a scientific domain (Pekrun et al., 2002; van Gog et al., 2005). In the context of practical training, one's preparedness (for instance, in a laboratory) is linked to students' self-efficacy (students' perception of their own ability to perform a given task; Bandura, 1986). Self-efficacy is often associated with or considered an influential part of motivation to learn and is included as a variable in this study along with other motivational elements: attainment value, intrinsic value, utility value and cost beliefs.

Previous studies which have focused on assessing learning outcomes have observed that the use of iVR technology led to a greater sense of presence, but lower levels of learning compared to desktop VR (Makransky et al., 2019; Moreno & Mayer, 2000; Richards & Taylor, 2015). In contrast, Alhalabi (2016), Passig et al. (2016), and Webster (2016) found higher levels of learning with iVR technology.

Wismer et al.'s study (2021) found that iVR-based and real-life training induced nearly similar levels of feelings of perceived learning among industry trainees as opposed to reading PowerPoint slides which resulted in very low perceived learning ratings. Real-life training, however, was significantly better than iVR in promoting self-efficacy. On the other hand, learning of complex safety-specific tasks in iVR is statistically equivalent to traditional slide-based video training, even though, iVR presents an overall positive gain on participants' perceived learning and their feeling of presence in the task environment during training (Plass et al., 2022; Poyade et al., 2021). In contrast, while Pande's (2023) study resulted in a significant increase in interactive iVR students' self-efficacy, their

intrinsic motivation and perceived learning gains were surprisingly similar to the students who had received traditional instruction.

Research has broadly demonstrated positive effects of iVR instruction on at least one of the several different affective learning outcomes (e.g., intrinsic motivation, self-efficacy, attitude towards learning; Buttussi & Chittaro, 2018; Han, 2020; Makransky et al., 2019; Pande et al., 2021; Parong & Mayer, 2020).

Theoretical framing: Embodied learning

The characteristics of virtual learning tools, especially the affordances iVR technology offers, couple well with the popular constructivist, constructionist and experiential theories of learning (e.g., Klippel et al., 2020; Lamb et al., 2018). Collectively, these theories have consistently argued that learning is facilitated by the construction of newer interaction/body-mediated experiences based on one's prior knowledge (e.g., Lamb et al., 2020). Recent cognitive mechanism-accounts of science learning, especially embodied and 4E cognition perspectives (Menary, 2010; Newen et al., 2018) have argued that no matter how complex and abstract the content (e.g., concepts and procedures) is, learning is built on top of the diverse sensorimotor/bodily interactions one has with the different interactable forms in which that content is available (e.g., representations such as equations, models; Nathan, 2022; Pande & Chandrasekharan, 2022). By systematically showing how learning emerges from action, sensorimotor engagement, and “doing”, these approaches have implied that richer sensorimotor and bodily engagements with the content, as afforded by iVR and desktop VR, greatly improve the chances of effective science learning (McGowin et al., 2022; Pande, 2021), particularly when compared to text-based instruction.

Consistent with these embodied cognition accounts, affective theories of learning have long emphasized the intricate positive relationships between “doing”, active (e.g., hands-on or bodily) engagement/participation, and non-cognitive aspects of one's learning such as interest, motivation, self-efficacy, overall engagement, and enjoyment (Bandura, 2001; Büssing et al., 2022; Maresky et al., 2019; Stepan et al., 2017; Teranishi & Yamagishi, 2018). In comparison to reading *how* to perform a certain procedure, the opportunity to actually *do* or *enact* that procedure, possibly even repeatedly as allowed by VR simulations, is likely to invoke the feeling of active engagement and self-directed learning, especially when real-world engagement with the procedure is difficult or impossible. In iVR, this feeling is facilitated and enhanced by a combination of high-levels immersion and sense of presence (e.g., sense of “being there” in person), and interactivity (Büssing et al., 2022; Chessa et al., 2019; Johnson-Glenberg, 2018; Kateros et al., 2015). This in turn is shown to support learner interest and motivation, overall engagement, and enjoyment (Maresky et al., 2019; Stepan et al., 2017; Teranishi & Yamagishi, 2018). Further, experiencing higher

levels of interest, engagement, and enjoyment has been linked to higher self-confidence/efficacy (Jang, 2008; Kahu et al., 2017).

Research questions and conjectures

We intended to examine if and how iVR simulation-based, desktop simulation-based, and traditional text/lab manual-based instructions employed ecologically in undergraduate biology courses differed from each other in terms of their learning effectiveness. The study addressed the following research questions (RQs):

1. How does iVR simulation-based instruction compare with desktop VR, and traditional text-heavy instruction on student learning of general science lab safety-related concepts and procedures?
2. How do these modes compare in terms of their effect on student intrinsic motivation, self-efficacy, and overall enjoyment in learning?¹
3. Is there a gender-difference across the instructional conditions in relation to conceptual-procedural learning and/or student intrinsic motivation, self-efficacy, and enjoyment?

Following from embodied and action-based learning theories, we expected iVR-based instruction (where students could dynamically navigate 3D-simulated science labs in 360 degrees, bodily interact with equipment and material, and experience and ‘rehearse’ lab safety protocol) to be more effective in helping students understand and remember lab safety concepts and procedures as opposed to text-based instruction (where students would be unsupported in imagining how to navigate labs and handle relevant equipment, and how safe or unsafe procedures/behavior might “feel” like). Similarly, we expected that iVR simulation’s ability to provide learners with a sense/feeling of the lab environment will make them gain more motivation and self-confidence about navigating and operating a real lab as opposed to the text-heavy instruction. We expected desktop-based instructional mode to perform better than text-heavy but comparatively less than iVR-based instruction in terms of its effectiveness across all the lab safety-related conceptual/procedural and affective measures. This expectation stemmed from the differences in affordances (e.g., extent of interactivity/embodiment, immersion) between iVR, desktop VR, and text-heavy instructional modes as discussed in the previous section.

The study

The study was conducted at an entry-level mandatory one-day course on General Lab Safety (see Supplementary Material for details) offered to all 1st year undergraduate students enrolled in a natural science program at a major Scandinavian University.

Participants

A total of 102 first-year undergraduate students (51 female) with an age-range of 18-25 taking the General Lab Safety course as a part of their natural science program at a major university in Denmark volunteered to participate in our study. The study adhered to the Helsinki Declaration, local university regulations, as well as the European General Data Protection regulations. Accordingly, informed written consents were gathered from all participants in advance to the study.

Procedure

A quasi-experimental pre-test–post-test design was employed for this study.

All students received a manual on general lab safety one week prior to the start of the course/study, and they were expected to read the manual and answer a quiz provided towards the end of the manual beforehand.

The course began with a verbal introduction to the course, the instructors involved, and a general schedule of the present study conducted in the following sequence:

Signing consent forms and assigning instructional groups >>> pre-test >>>
Course Part 1 >>> segregation into different instructional/treatment groups >>>
respective additional instruction (e.g., iVR, desktop VR) >>> Course Part 2 >>>
Course Part 3 >>> post-test >>> end.

The consent form randomly assigned each student a code that indicated their treatment condition (iVR simulation-based: N=31, 14 female; Desktop simulation-based: N=39, 21 female; and Text/manual-only: N=32, 16 female). Each student used this code throughout the study while responding to the data collection tools. On signing the forms, all students were administered a pre-test comprising of general lab safety knowledge-related questions (11 multiple-choice items) and affective questions on intrinsic motivation (8 items) and self-efficacy (6 items).

All students then participated in common theory lectures, and subsequently segregated into three different rooms based on their instruction code (e.g., iVR, desktop, text-heavy) where the materials relevant to their instruction were pre-arranged. Each student in the iVR group (N=31) was provided with a Lenovo Mirage Solo HMD to run the general lab safety iVR simulation used in the study. To make sure they are oriented to iVR, all students in this group first watched a video (link blinded) on how to wear and use the headset and its controller, and how to interact with the iVR environment they will experience after wearing the headset. We also asked students about their familiarity and prior experience with iVR, and if they felt comfortable wearing the headset or if they experienced any cybersickness. Most students had played with iVR multiple times before, and several had at least one prior iVR experience. None reported any cybersickness-related issues. The students also received additional technical help as and when required. In the desktop instruction room,

students (N=39) interacted with a desktop version of the same lab safety simulation using their laptops. The students (N=32) in the text-heavy condition read/reviewed e-copies of the lab safety manual. The students attended in-lab general safety-related demonstrations in batches. Finally, the students responded to a post-test on completion of their respective instructional mode. The post-test was exactly similar to the pre-test, except it included an additional 4-item questionnaire on enjoyment.

A close collaboration with the course coordinator (last author) ensured a smooth and cohesive integration of the experimental material and protocol with the regular course activities, and that the participant groups differed only in terms of the instructional treatment they received (e.g., iVR, desktop). The students in the different groups were encouraged to not discuss about the events occurred during the segregated sessions with students in the other groups.

iVR and desktop simulations

The general lab safety simulation (<https://www.labster.com/simulations/lab-safety>) used in this study was developed by Labster (Labster, Denmark), and its content aligned extremely well with our course learning objectives, topics, and structure. The primary goal of the simulation was to help students learn about the different concepts (ranging from signs/symbols for explosive, flammable, toxic materials, or biohazard to corrosive properties of acids and what does an acid do when your skin/body is exposed to it accidentally) and procedures (e.g., wearing proper lab-gear such as goggles and a lab coat, paying attention and operating certain equipment in the lab) involved in general science lab safety. Inside the simulation (both desktop and iVR modes), the student is orally verbally instructed by a drone-like agent² about each step the student should take in order to proceed through the simulation (e.g., wear a lab-coat and goggles, teleport to another room or a specific desk in the lab, use or run an equipment, read text or view figures on a virtual lab-pad that can be brought up or moved down as necessary). The lab-pad also views the same instruction in text format. Figure 1 shows three different screenshots captured during different stages/activities in the simulation.

The simulation is available for interaction in both iVR and desktop modes. The iVR simulation could be accessed via Google's Daydream platform using Lenovo Mirage Solo headsets that offer interaction in 3 degrees of freedom. In iVR, the student can navigate the lab space by turning their head around to see elements in the 360-degree environment or move the head closer to or away from an object, and use a handheld laser-pointer-like controller to point-and-click and teleport to a different location as well as interact with the simulation elements (e.g., selecting or deselecting a virtual object such as test tubes, interaction with a virtual notepad).

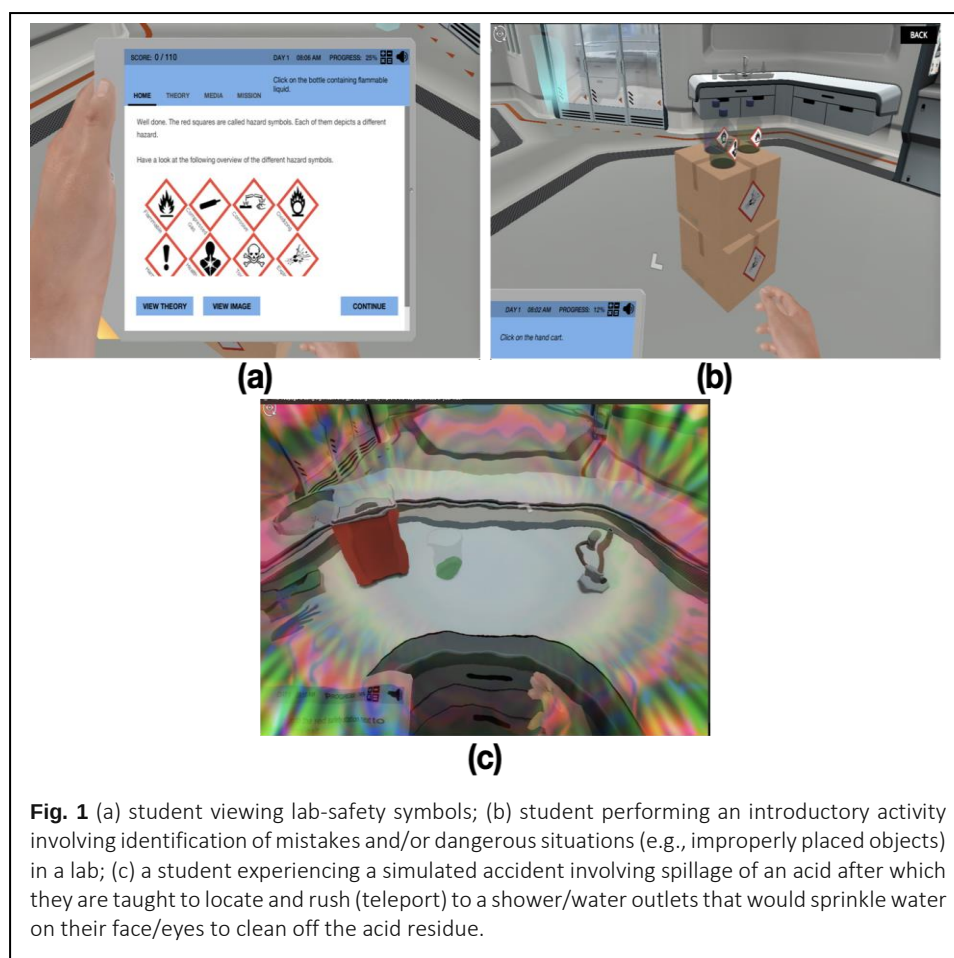


Fig. 1 (a) student viewing lab-safety symbols; (b) student performing an introductory activity involving identification of mistakes and/or dangerous situations (e.g., improperly placed objects) in a lab; (c) a student experiencing a simulated accident involving spillage of an acid after which they are taught to locate and rush (teleport) to a shower/water outlets that would sprinkle water on their face/eyes to clean off the acid residue.

Interaction in the desktop VR version of the simulation is facilitated by mouse or trackpad on a laptop. Virtual lab navigation and interaction with the simulation elements in desktop are primarily done by moving the mouse or laptop's trackpad on a 2D surface and doing a left click as and when required.

The relatively simple as well as less expensive iVR hardware-software platforms used in this study played a key role in making an ecologically valid real-classroom implementation that required ~30 HMD sets possible. Further, the availability of the simulation across the two modes of immersion/interaction was particularly advantageous for a media-comparison study as the simulation offered the exact same content to the participants.

Data collection instruments

The pre- and post-tests included: 11 multiple-choice questions related to knowledge of topics in general lab safety and 14 affective questions from standardized 5-point Likert scales (see Supplementary Material) for assessing students' intrinsic motivation (8 items; Chronbach's α pre-test = 0.87, post-test = 0.88) and self-efficacy (6 items; Chronbach's α pre-test = 0.84, post-test = 0.91) in relation to learning about/following lab safety (Monteiro

et al., 2015; Makransky et al., 2016). Two questions (Q3 and Q9) from the knowledge pre- and post-tests were omitted from analysis to meet acceptable scale-reliability levels (Chronbach's α pre-test = 0.61, post-test = 0.68).

The post-test included an additional measure of intervention enjoyment (adapted from Monteiro et al., 2015) where we used a 5-point Likert scale (Chronbach's α = 0.56; 5 items).

All the tests were administered using SurveyXact (Rambøll Management Consulting, 2014).

Data analysis tools

IBM SPSS Statistics 28 was used to analyze Chronbach's alpha reliability scores for the test-instruments, while the rest of the statistical analysis was performed using either JASP 0.11.1 (JASP Team, 2019) or Sigmaplot 12.3.

We tested for group equivalence (e.g., for prior knowledge, gender) using one-way ANOVA and Chi-square tests. All datasets for the knowledge-related and affective metrics were first tested with Levene's test (homogeneity of variance). Subsequently, all main effects on gains in knowledge, intrinsic motivation, and self-efficacy were tested with a one-way ANCOVA (homogeneity of regression slopes assumption was met whenever not reported in the results). In addition, a post-hoc Holm's test was performed wherever ANCOVA yielded significant results. Between-group differences on the enjoyment scale (post-test only) were analyzed using a Rank Sum Test or a two-tailed t-test.

Finally, we used MANOVA to test for the interaction effect (instruction*gender).

Results

Equivalence of instructional groups

A one-way ANOVA performed on pre-intervention test showed that the three groups did not differ significantly on prior knowledge ($F(2,102) = 1.51, p = .225$). A chi-square test indicated that the groups did not differ significantly in the proportion of men and women, $\chi^2(2, N = 105) = 2.722, p = .256$. Therefore, the treatment groups (iVR, desktop, and text-heavy conditions) could be considered equivalent and fit for instructional effectiveness comparison across our three RQs.

Lab safety knowledge gain (RQ1)

Table 1 shows the mean scores and standard deviation values for the groups on the different measures of performance. The table also shows p values for the main effects as well as the between-group differences as obtained through post-hoc test.

Table 1 Main and between-group effects

	Groups (mean & SD)			Main effect (time/measures)	Main group effect (<i>p</i> value)	Between-group differences (<i>p</i> value)		
	iVR	Desktop	Text-heavy			iVR-Desktop	iVR-Text	Desktop-Text
Gain in knowledge	0.08 (0.15)	0.07 (0.20)	0.11 (0.12)	< 0.002*	0.07	NA	NA	NA
Gain in intrinsic motivation	0.30 (0.45)	0.04 (0.61)	-0.11 (0.35)	< 0.001*	0.01	0.021*	< 0.001*	0.116
Gain in self-efficacy	0.58 (0.60)	0.50 (0.71)	0.14 (0.42)	< 0.001*	< 0.001	0.175	< 0.001*	0.009*
Enjoyment	3.4 (0.45)	3.08 (0.81)	-	NA		0.06	NA	NA

* Statistically significant

The data were tested with a Levene's test with the results $F(2, 99) = 4.33, p = 0.01$. Thereafter, a one-way between-subjects ANCOVA, with the pre-test knowledge score as the covariate and the post-test knowledge score as the dependent variable, and group as fixed factor, were setup. We found a statistically significant main effect across the pre and post knowledge tests at $F(1, 98) = 9.86, p < 0.002, \eta_p^2 = 0.09, r = 0.31$. All three groups gained significant lab safety knowledge.

We found no main effect for groups at $F(2, 98) = 2.69, p = 0.07, \eta_p^2 = 0.05$.

Performance on affective tests (RQ2)

Intrinsic motivation

The data were tested with a Levene's test with the results $F(2, 99) = 4.59, p = 0.01$. A one-way between-subjects ANCOVA was then performed with the pre-test score as the covariate, the post-test score as the dependent variable, and treatment condition as the fixed factor. We found significant improvements for the iVR and desktop groups, and decrease for the text-heavy group across the tests at $F(1, 98) = 162.25, p < 0.001, \eta_p^2 = 0.62, r = 0.78$.

The main group effect was also found to be statistically significant at $F(2, 98) = 8.01, p < 0.001, \eta_p^2 = 0.14$. A post-hoc test (Holm) showed that the iVR group differed significantly from both the text-heavy ($p < 0.001$) and the desktop ($p = 0.021$) conditions. Text-heavy and desktop conditions did not differ from each other ($p = 0.116$). iVR thus helped students gain significantly more intrinsic motivation as opposed to the other two instructional condition.

Self-efficacy

A Levene's test resulted in $F(2, 99) = 1.66, p = 0.20$. A subsequent one-way between-subjects ANCOVA with the pre-test score as the covariate, the post-test score as the dependent variable, and treatment condition as the fixed factor yielded the following statistically significant main effect across the pre- and post- tests: $F(1, 98) = 53.15, p < 0.001, \eta_p^2 = 0.35, r = 0.59$. This indicated that the groups gained self-efficacy from the interventions.

The main effect for between-group differences was statistically significant at $F(2, 98) = 8.59, p < 0.001, \eta_p^2 = 0.15$. A post-hoc test (Holm) showed that the text-heavy group was statistically significant different from both desktop ($p = 0.009$) and iVR ($p < 0.001$). iVR and desktop did not differ from each other ($p = 0.175$). Hence, the desktop and iVR-based conditions performed significantly better than text-heavy instructions in terms of their respective effects on students' self-efficacy.

Enjoyment

A Rank Sum Test found that there were no statistically significant differences between the Desktop and iVR condition on enjoyment scores; although students exposed to iVR ($M = 3.4, SD = 0.5$) enjoyed the simulation more $t(1255) u = 449.5 (p = 0.06)$ than the students who interacted with the same simulation in a desktop environment ($M = 3.0, SD = 0.8$).

Gender differences (RQ3)

Through a multivariate ANOVA analysis, we found an interaction effect for gender on gain in self-efficacy ($p = 0.036$). Pair-wise post-hoc analyses revealed that the only statistically significant difference was that the females in the desktop group benefited significantly more in gain in self-efficacy as compared to females in the text-heavy group at $p = 0.012$.

We found no statistically significant within or between-group interaction effect for gain in knowledge ($p = 0.339$) and intrinsic motivation ($p = 0.791$); although, males seemed to benefit considerably more in terms of lab safety knowledge gain from simulation-based instructions (iVR: $M = 0.13, SD = 0.11$; Desktop: $M = 0.12, SD = 0.14$) than their female counterparts (iVR: $M = 0.02, SD = 0.17$; Desktop: $M = 0.04, SD = 0.24$). The knowledge gains for males ($M = 0.1, SD = 0.11$) and females ($M = 0.11, SD = 0.13$) in the text group were similar. While the knowledge gain scores were very similar for males across the three conditions, for females, the text-based instruction resulted in the highest mean knowledge gain, followed by desktop, with iVR recording the least knowledge gain for females.

Also, females in the iVR group seemed to have gained considerably more intrinsic motivation ($M = 0.37, SD = 0.45$) as compared to males in that group ($M = 0.24, SD = 0.44$).

Finally, we found a statistically significant difference between the genders on enjoyment scores for the desktop simulation-based instruction. A t-test found that there was a statistically significant difference between the genders at $t(-2,4) = -0.6, p = .02$. While both the genders enjoyed the desktop simulation experience, females ($M = 3.4, SD = 0.9$) reported significantly higher mean gain scores on enjoyment as opposed to males ($M = 2.7, SD = 0.6$). The gender differences in the iVR condition were not statistically significant.

Discussion, implications, and limitations of the study

Our study examined three research questions: how do iVR simulation-based, desktop-simulation based, and traditional text-heavy instructional modes compare in helping students learn science lab safety-related conceptual knowledge and procedures (RQ1), and in improving their overall affective engagement (intrinsic motivation, self-efficacy, and enjoyment) with the topics (RQ2); as well as if and how the genders benefit differently from each mode of instruction (RQ3). We use these RQs to organize our discussion of the results, their implications, and the general as well as RQ-specific limitations of this study in the following sub-sections.

Lab safety knowledge (RQ1)

We found that all three instructional modes resulted in significant knowledge gain. However, this gain was not significantly different across the three groups – unlike conjectured, interactions in iVR and desktop did not add any significant advantage in terms of knowledge gains. This may be interpreted to imply that educators incorporate one or more of these instructional modes that best suit their resources and goals to help students learn lab safety knowledge (e.g., in relation to lab safety).

The effectiveness of different technology-enhanced instructional modes, especially those involving iVR, however, depends heavily on the design of the simulation, the hardware used, and the nature of interaction. While combining immersion and enriched multimedia that appeal multiple senses are commonplace in most iVR-based (STEM) learning interface designs, the extent of use of sensorimotor engagement required to operate in such systems is often ignored as a design principle (Johnson-Glenberg et al., 2021). Such iVR simulation designs thus fail to utilize some of the most powerful affordances technologies such as iVR have to offer (e.g., embodiment; Johnson-Glenberg, 2018). While graphically appealing (and possibly awe-inducing for a novice user), the iVR lab safety simulation we used in this study was not particularly interactive in the above-discussed sense. In addition, both the iVR and desktop simulations primarily relied on a point-and-click mode of interaction with 3-degrees-of-freedom, and are nearly equally interactive in both iVR and desktop modes excluding immersion. These factors possibly contributed to the lack of between-group differences in our results in knowledge tests (Pande et al., 2021).

The text-heavy nature of evaluation measures used to assess conceptual/procedural knowledge may also have played some role. Using more enactive/practical tests to measure interventions' effectiveness on learning lab safety-like topics and skills may be more meaningful. Recently, Makransky et al. (2020), for instance, reported positive effects of enaction on student knowledge-gain evaluations through action/behavior-based tests. Though, from a critical perspective, it may be deemed obvious that using similar modes across training and evaluations yield favorable results (e.g., text-heavy instruction doing better in text-heavy tests but comparatively worse in action-based tests such as having participants enact a learned procedure. Similarly, action-based instruction (e.g., sensorimotor engagement and enaction in iVR) may do better in action-based tests but not in text-heavy tests). To make media comparison studies more meaningful, this issue demands a reflection on the nature of knowledge evaluation tests. Media-neutral tests are required that eliminate such effects, or tests that evaluate transfer of learning across media.

Improvements across affective measures (RQ2)

As conjectured, iVR and desktop simulation resulted in statistically significant gains in intrinsic motivation and self-efficacy, indicating that these modes help students in feeling motivated and self-confident about lab safety topics and procedures, and in believing in their abilities to safely operate in the lab. The text-heavy instruction had a significantly negative affect on students' intrinsic motivation, but had an overall positive affect on self-efficacy.

In further consistency with our embodied learning theory-based predictions, iVR was significantly better in terms of intrinsic motivation gains among students than the other two modes (desktop and text) which did not differ significantly from each other. For self-efficacy, our results were partially consistent with our conjectures. Both iVR and desktop were highly significantly better than text, with iVR doing slightly but not significantly better than desktop. These findings confirm and add more insights to the results from media comparison studies on iVR's significantly more positive impact on students' affective engagement with concepts and procedures in the STEM education (Han, 2020; Makransky et al., 2019; Pande et al., 2021).

In terms of post-intervention enjoyment, iVR performed considerably ($p = 0.06$) better than desktop. As outlined in the study's theoretical framing, the dynamic and interactive nature of new media, which allows students to actively participate in, and at times, even take control over the learning experience as opposed to just passively reading text, critically contributes to these effectiveness differences between the iVR/desktop versus text-heavy instructional modes. In addition, as opposed to the traditional text-based instruction, the desktop and iVR instruction involved formative mini-quizzes embedded within the simulation where students scored for providing correct answers.

Finally, given that the only major difference between our desktop and iVR simulation experiences was the degree of immersion, iVR-based instruction's consistently better performance than desktop VR across the affective outcomes studied in this research indicates their direct relationship with the sense/feeling of immersion. This result is consistent with findings from much of the previous work (e.g., Kahu et al., 2017; Maresky et al., 2019; Stepan et al., 2017; also for science learning through augmented reality: Cheng & Tsai, 2013; Georgiou & Kyza, 2018; and in personality/social psychology: Weinstein et al., 2018). As a methodological limitation due to serious time and personnel-dependent factors, however, our study did not explicitly incorporate measurements for presence and immersion. More studies, particularly those examining the relationships between these factors, and learning outcomes (e.g., through regression models) are required. As iVR hardware and simulation environments become more and more sophisticated (e.g., in terms of degrees of freedom, resolution, interactivity), it is becoming increasingly pertinent to examine, alongside above-mentioned relationships, how bodily/sensorimotor engagement interacts with immersion.

Gender differences (RQ3)

Overall, despite a scarcity of statistically significant interaction effects and post hoc analyses (Garofalo et al., 2022), our results indicated that the instructional modes affect/benefit the two genders differently. Based on visual differences, while the knowledge gains for males were considerably higher than their female counterparts in both simulation groups (iVR and desktop), these VR instructional modes proved to be more beneficial to females in terms of affective aspects of learning (e.g., significant gains in self-efficacy, considerable gain in intrinsic motivation, and high enjoyment scores). Particularly among females, we found that desktop worked significantly better in improving self-efficacy than text.

Better affective outcomes for females have been largely argued to be related to factors such as the tightly intertwined feelings of presence and immersion. Though scarce in science education, varying extents of such links have been reported in multiple contexts involving diverse levels of immersion ranging from television (Lombard, 1995), flight simulators (Nicovich et al., 2005), to simulations of social interactions (Felnhofer et al., 2014).

However, it is important to note that the results on presence and immersion-related gender differences seldom are mixed and inconclusive (e.g., Felnhofer et al, 2014; Osunde et al., 2018;), and the feedback loops and interactions between factors such as degrees of presence, immersion, spatial ability, in-environment bodily movement/action and sense of agency, navigation, input-output mapping, visual and graphic appeal, and the nature of content might be much more complex in nature than currently understood.

On the other hand, comparatively better science topic knowledge gains for males receiving computer simulation-based instructions are common throughout the literature, particularly in the context of the widely reported spatial ability-related gender differences (e.g., Lee & Wong, 2014). Science learning is heavy in terms of recruiting one's visuospatial capacities, and males and females are known to exhibit different generalizable patterns of visuospatial abilities (Höffler & Leutner, 2007). Studies have reported significant differences in learning outcomes between males and females, and between people with different (e.g., low or high) spatial abilities in the context of learning/navigation with virtual simulations or iVR environments (e.g., Lee et al., 2010; Merchant et al., 2014; Wong et al., 2015). The alleged stronger spatial abilities among males, we suggest, thus may be giving them an advantage over females in using iVR for learning science, particularly the topics that require engaging higher spatial abilities.

However, we are aware that the relationship between spatial abilities and interactive 3D content is quite complex. However, as another limitation of our study, we did not measure participants' spatial abilities and their relationship with learning outcomes. This makes it particularly difficult to provide sufficient evidence for, and explain, the gender differences in our sample. For instance, it is difficult to understand if just immersion in 3D environments in the context of any scientific content is enough to recruit/engage one's spatial capacities to measurable extents, and in ways that significantly influence learning outcomes. In other words, regardless of whether the intervention involves spatial tasks/content, it is difficult to know if and what degrees of immersion relate to a recruitment of one's spatial abilities.

Similarly, we initially believed that our desktop and iVR simulation designs did not differ much besides the immersion factor, and that both systems were interacted with using a comparable point-and-click action. Retrospectively, however, it appears that even though their output/effects are similar, the point-and-click interactions in iVR and desktop are not entirely similar: mouse movements generally happen on a 2D surface, whereas the iVR pointer allows 3D movements (holding and moving it in the air as opposed to the mouse that is stuck to a flat surface). Therefore, whether and how even slight variations in only interaction (e.g., only point and click using a mouse vs. point and click using a small clicker), or both interaction and immersion (e.g., point and click using a mouse that allows movements on 2D surfaces in less immersive desktop system vs. point and click using a smaller pointer/clicker that is not stuck to a surface and can be moved in 3D in iVR system) affects cognition and spatial abilities, and how these variations trickle into learning outcomes, are matters of many nuances.

In summary, besides being somewhat controversial, research on spatial ability-related gender differences, and related learning effects, may be getting relatively outdated, particularly in the still underexplored iVR and iVR-supported science education contexts.

Much of this research has examined spatial abilities in diverse computer-supported environments and contexts, and that these environments and contexts may have varied greatly in terms of the “spatial” nature of their content and experience, thus, making it difficult to causally pinpoint their outcomes to a specific (spatial) design element. Considering the rapid advances in iVR designs, iVR’s availability and accessibility, and general socio-cultural developments, studies that specifically investigate learning differences in relation to spatial ability, technology-exposure, and other relevant factors may be needed in the future. It is also equally pertinent to explore these differences across diverse iVR environments (e.g., environments with varying degrees of reliance on spatial skills and navigation abilities) to better understand if and how the spatial affordances, spatial abilities, learning outcomes, and gender are interacting with each other.

Conclusion

This research investigated the learning effectiveness of integrating iVR and desktop simulations in a science lab safety course in comparison with each other, as well as in contrast to the traditional text-heavy lab safety manual-based instruction. We maintained the real-life relevance of this research and its implications by situating this media-comparison investigation in actual university science education settings.

We found that iVR simulation-based, desktop-based, and traditional text-heavy instruction were equally effective in terms of conceptual-procedural knowledge gain in the context of university science lab safety. While this confirms findings from multiple iVR-employing higher science education studies, we believe that more probing, with the help of media-neutral test instruments, and in relation to diverse iVR environment designs, is required to further insights on how iVR affects conceptual-procedural learning. Between-group analyses showed that iVR had the most positive (often significantly better) impact on students’ overall affective and emotional engagement with the lab safety content. Text-heavy instruction was found to be quite demotivating. These findings are in line with previous research on students’ emotions, attitudes, and beliefs in iVR-based science education.

Further, our analyses of gender differences showed that the instructional modes, particularly iVR and desktop, affected/benefited the two genders differently in terms of their quality and quantity of engagement with the content. This warrants an elaborate effort to understand the role gender plays in iVR-based technology-enhanced science learning settings.

Considering that positive affect and favorable cognitive outcomes are related, and that a bulk of research already confirms iVR’s affective effectiveness, various communities of teachers, educators, learning technology designers, and other stakeholders must consider the best ways for bringing iVR into mainstream education as a powerful medium despite

the inconclusive reports on its effects on the different cognitive aspects of learning. This is particularly important as we reckon that the technology-enhanced learning design and implementation efforts may fail to keep up with the pace at which iVR technology is developing/changing if these communities wait till significant and conclusive research on how iVR interacts with cognitive aspects of science learning is out.

Parallel concerted efforts, however, are needed among basic as well as practice-driven research communities to understand and adopt iVR and related technological advances in science pedagogies as holistically and inclusively as possible. It is pertinent to research how gender as well as other forms of diversities beyond gender interact with iVR-based technology-enhanced science learning, and what would be some of the best design practices to make iVR-based science instruction more inviting and equally effective for everyone (e.g., in terms of its learning benefits), and more broadly, equitable.

Abbreviations

iVR: Immersive virtual reality; HMD: Head mounted device; RQ: Research question.

Endnotes

¹ Besides these affective variables based on the theoretical rationale explained in the section “Theoretical framing: Embodied learning”, we also aimed to measure presence and spatial ability (due to their supposed influence on 3D and iVR learning), and self-reports of extents of embodiment felt by desktop and iVR group participants (Gonzalez-Franco & Peck, 2018). Due to several practical (e.g., time-constraints) and strategic factors (e.g., limiting the number of questions students respond to in order to avoid a burn out; findings from a previous pilot study), however, we could not include them in this study.

² Note that the drone-like agent was common to (and thus controlled for in) the iVR and desktop conditions. This agent was not present in the text-heavy manual condition and its role was, in part, performed by the lab instructor during the in-lab batch-wise demonstration sessions.

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Authors' contributions

Both authors collectively designed and conducted the experiment at the site. The second author was one of the coordinating teachers for the course, where the experiment was conducted. Each author carried out data analysis independently as well as collaboratively with the other author. The first author wrote the manuscript. Both authors critically reviewed and edited the manuscript. The first author supervised the study.

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Availability of data and materials

The datasets used and/or analyzed during the current study may not be shared due to data privacy and protection policies. Some processed datasets/results other than those already included in the manuscript may be made available by the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Alhalabi, W. (2016). Virtual reality systems enhance students' achievements in engineering education. *Behaviour & Information Technology*, 35(11), 919–925. <https://doi.org/10.1080/0144929X.2016.1212931>
- Azer, S. A., & Azer, S. (2016). 3D anatomy models and impact on learning: A review of the quality of the literature. *Health Professions Education*, 2(2), 80–98. <https://doi.org/10.1016/j.hpe.2016.05.002>
- Bandura, A. (1986). The explanatory and predictive scope of self-efficacy theory. *Journal of Social and Clinical Psychology*, 4(3), 359–373. <https://doi.org/10.1521/jscp.1986.4.3.359>
- Bandura, A. (2001). Social cognitive theory: An agentic perspective. *Annual Review of Psychology*, 52(1), 1–26. <https://doi.org/10.1146/annurev.psych.52.1.1>
- Biocca, F., & Delaney, B. (1995). Immersive virtual reality technology. *Communication in the Age of Virtual Reality*, 15(32), 10–5555.
- Brinson, J. R. (2015). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research. *Computers & Education*, 87, 218–237. <https://doi.org/10.1016/j.compedu.2015.07.003>
- Buttussi, F., & Chittaro, L. (2018). Effects of different types of virtual reality display on presence and learning in a safety training scenario. *IEEE Transactions on Visualization and Computer Graphics*, 24(2), 1063–1076. <https://doi.org/10.1109/TVCG.2017.2653117>
- Büssing, A. G., Thomsen, D., & Braun, N. (2022). Linking technology usage to instructional quality: Immersive virtual reality increases presence, positive emotions, and cognitive activation. Authors Preprint Accessed at: <https://osf.io/preprints/p9esz/>
- Checa, D., Miguel-Alonso, I., & Bustillo, A. (2021). Immersive virtual-reality computer-assembly serious game to enhance autonomous learning. *Virtual Reality*, 27, 3301–3318. <https://doi.org/10.1007/s10055-021-00607-1>
- Cheng, K. H., & Tsai, C. C. (2013). Affordances of augmented reality in science learning: Suggestions for future research. *Journal of Science Education and Technology*, 22, 449–462. <https://doi.org/10.1007/s10956-012-9405-9>
- Chessa, M., Maiello, G., Borsari, A., & Bex, P. J. (2019). The perceptual quality of the oculus rift for immersive virtual reality. *Human-Computer Interaction*, 34(1), 51–82. <https://doi.org/10.1080/07370024.2016.1243478>
- Coban, M., Bolat, Y. I., & Goksu, I. (2022). The potential of immersive virtual reality to enhance learning: A meta-analysis. *Educational Research Review*, 36, 100452. <https://doi.org/10.1016/j.edurev.2022.100452>
- Concannon, B. J., Esmail, S., & Roduta Roberts, M. (2019). Head-mounted display virtual reality in post-secondary education and skill training. *Frontiers in Education*, 4. <https://doi.org/10.3389/educ.2019.00080>
- Dalgarno, B., Bishop, A. G., Adlong, W., & Bedgood, D. R. (2009). Effectiveness of a virtual laboratory as a preparatory resource for distance education chemistry students. *Computers & Education*, 53(3), 853–865. <https://doi.org/10.1016/j.compedu.2009.05.005>
- Daugherty, L., Walkington, C., Sherard, M., Pande, P., Beauchamp, T., & Cuevas, A. (in print). From abstract to tangible: Leveraging virtual reality and GeoGebra for playful math education. Paper accepted to *The 2024 Annual Meeting of the International Society of the Learning Sciences*.
- Dede, C. (2009). Immersive interfaces for engagement and learning. *Science*, 323(5910), 66–69. <https://doi.org/10.1126/science.1167311>

- Dyrberg, N. R., Treusch, A. H., & Wiegand, C. (2017). Virtual laboratories in science education: Students' motivation and experiences in two tertiary biology courses. *Journal of Biological Education*, 51(4), 358–374. <https://doi.org/10.1080/00219266.2016.1257498>
- Fabris, C. P., Rathner, J. A., Fong, A. Y., & Seigny, C. P. (2019). Virtual reality in higher education. *International Journal of Innovation in Science and Mathematics Education*, 27(8). <https://doi.org/10.30722/IJISME.27.08.006>
- Felnhöfer, A., Kothgassner, O. D., Hauk, N., Beutl, L., Hlavacs, H., & Kryspin-Exner, I. (2014). Physical and social presence in collaborative virtual environments: Exploring age and gender differences with respect to empathy. *Computers in Human Behavior*, 31, 272–279. <https://doi.org/10.1016/j.chb.2013.10.045>
- Felnhöfer, A., Kothgassner, O. D., Schmidt, M., Heinzle, A. K., Beutl, L., Hlavacs, H., & Kryspin-Exner, I. (2015). Is virtual reality emotionally arousing? Investigating five emotion inducing virtual park scenarios. *International Journal of Human-Computer Studies*, 82, 48–56. <https://doi.org/10.1016/j.ijhcs.2015.05.004>
- Flint, S., & Stewart, T. (2010). Food microbiology-design and testing of a virtual laboratory exercise. *Journal of Food Science Education*, 9(4), 84–89. <https://doi.org/10.1111/j.1541-4329.2010.00108.x>
- Garofalo, S., Giovagnoli, S., Orsoni, M., Starita, F., & Benassi, M. (2022). Interaction effect: Are you doing the right thing? *PLoS ONE*, 17(7), e0271668. <https://doi.org/10.1371/journal.pone.0271668>
- Georgiou, Y., & Kyza, E. A. (2018). Relations between student motivation, immersion and learning outcomes in location-based augmented reality settings. *Computers in Human Behavior*, 89, 173–181. <https://doi.org/10.1016/j.chb.2018.08.011>
- Gibbons, N. J., Evans, C., Payne, A., Shah, K., & Griffin, D. K. (2004). Computer simulations improve university instructional laboratories. *Cell Biology Education*, 3(4), 263–269. <https://doi.org/10.1187/cbe.04-06-0040>
- Gonzalez-Franco, M., & Peck, T. C. (2018). Avatar embodiment. Towards a standardized questionnaire. *Frontiers in Robotics and AI*, 5, 74. <https://doi.org/10.3389/frobt.2018.00074>
- Gunn, T., Jones, L., Bridge, P., Rowntree, P., & Nissen, L. (2018). The use of virtual reality simulation to improve technical skill in the undergraduate medical imaging student. *Interactive Learning Environments*, 26(5), 613–620. <https://doi.org/10.1080/10494820.2017.1374981>
- Han, I. (2020). Immersive virtual field trips in education: A mixed-methods study on elementary students' presence and perceived learning. *British Journal of Educational Technology*, 51(2), 420–435. <https://doi.org/10.1111/bjet.12842>
- Heradio, R., de la Torre, L., Galan, D., Cabrerizo, F. J., Herrera-Viedma, E., & Dormido, S. (2016). Virtual and remote labs in education: A bibliometric analysis. *Computers & Education*, 98, 14–38. <https://doi.org/10.1016/j.compedu.2016.03.010>
- Hew, K. F., & Cheung, W. S. (2010). Use of three-dimensional (3-D) immersive virtual worlds in K-12 and higher education settings: A review of the research. *British Journal of Educational Technology*, 41(1), 33–55. <https://doi.org/10.1111/j.1467-8535.2008.00900.x>
- Höfller, T. N., & Leutner, D. (2007). Instructional animation versus static pictures: A meta-analysis. *Learning and Instruction*, 17(6), 722–738. <https://doi.org/10.1016/j.learninstruc.2007.09.013>
- Holder, R., Carey, M., & Keir, P. (2020). Virtual reality vs pancake environments: A comparison of interaction on immersive and traditional screens. In L. De Paolis & P. Bourdot (Eds.), *Augmented Reality, Virtual Reality, and Computer Graphics. AVR 2020. Lecture Notes in Computer Science*, vol 12242 (pp. 114–129). Springer, Cham. https://doi.org/10.1007/978-3-030-58465-8_8
- Hurtado-Bermúdez, S., & Romero-Abrio, A. (2020). The effects of combining virtual laboratory and advanced technology research laboratory on university students' conceptual understanding of electron microscopy. *Interactive Learning Environments*, 31(2), 1126–1141. <https://doi.org/10.1080/10494820.2020.1821716>
- Jang, H. (2008). Supporting students' motivation, engagement, and learning during an uninteresting activity. *Journal of Educational Psychology*, 100(4), 798–811. <https://doi.org/10.1037/a0012841>
- JASP Team. (2019). *JASP* (Version 0.10.1) [Computer software].
- Jensen, L., & Konradsen, F. (2018). A review of the use of virtual reality head-mounted displays in education and training. *Education and Information Technologies*, 23(4), 1515–1529. <https://doi.org/10.1007/s10639-017-9676-0>
- Johnson-Glenberg, M. C. (2018). Immersive VR and education: Embodied design principles that include gesture and hand controls. *Frontiers in Robotics and AI*, 5. <https://doi.org/10.3389/frobt.2018.00081>
- Johnson-Glenberg, M. C., Bartolomea, H., & Kalina, E. (2021). Platform is not destiny: Embodied learning effects comparing 2D-desktop to 3D-virtual reality STEM experiences. *Journal of Computer Assisted Learning*, 37(5), 1263–1284. <https://doi.org/10.1111/jcal.12567>
- Kahu, E., Nelson, K., & Picton, C. (2017). Student interest as a key driver of engagement for first year students. *Student Success*, 8(2), 55–66. <https://doi.org/10.5204/ssj.v8i2.379>
- Kateros, S., Georgiou, S., Papaefthymiou, M., Papagiannakis, G., & Tsioumas, M. (2015). A comparison of gamified, immersive VR curation methods for enhanced presence and human-computer interaction in digital humanities. *International Journal of Heritage in the Digital Era*, 4(2), 221–233. <https://doi.org/10.1260/2047-4970.4.2.221>
- Klippel, A., Zhao, J., Oprean, D., Wallgrün, J. O., Stubbs, C., La Femina, P., & Jackson, K. L. (2020). The value of being there: toward a science of immersive virtual field trips. *Virtual Reality*, 24(4), 753–770. <https://doi.org/10.1007/s10055-019-00418-5>
- Koretsky, M., Kelly, C., & Gummer, E. (2011). Student perceptions of learning in the laboratory: Comparison of industrially situated virtual laboratories to capstone physical laboratories. *Journal of Engineering Education*, 100(3), 540–573. <https://doi.org/10.1002/j.2168-9830.2011.tb00026.x>

- Lamb, R., Antonenko, P., Etio, E., & Seccia, A. (2018). Comparison of virtual reality and hands on activities in science education via functional near infrared spectroscopy. *Computers & Education*, 124, 14–26. <https://doi.org/10.1016/j.compedu.2018.05.014>
- Lamb, R., Lin, J., & Firestone, J. B. (2020). Virtual reality laboratories: A way forward for schools? *Eurasia Journal of Mathematics, Science and Technology Education*, 16(6), em1856. <https://doi.org/10.29333/ejmste/8206>
- Lee, O., & Brophy, J. (1996). Motivational patterns observed in sixth-grade science classrooms. *Journal of Research in Science Teaching*, 33(3), 303–318. [https://doi.org/10.1002/\(SICI\)1098-2736\(199603\)33:3%3C303::AID-TEA4%3E3.0.CO;2-X](https://doi.org/10.1002/(SICI)1098-2736(199603)33:3%3C303::AID-TEA4%3E3.0.CO;2-X)
- Lee, E. A. L., & Wong, K. W. (2014). Learning with desktop virtual reality: Low spatial ability learners are more positively affected. *Computers & Education*, 79, 49–58. <https://doi.org/10.1016/j.compedu.2014.07.010>
- Lee, E. A. L., 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>
- Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by embodiment. *Educational Researcher*, 42(8), 445–452. <https://doi.org/10.3102/0013189X13511661>
- Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development*, 56(6), 1479–1498. <https://doi.org/10.2307/1130467>
- Lombard, M. (1995). Direct responses to people on the screen: Television and personal space. *Communication Research*, 22(3), 288–324. <https://doi.org/10.1177/009365095022003002>
- Loukas, C., Nikiteas, N., Kanakis, M., & Georgiou, E. (2011). Deconstructing laparoscopic competence in a virtual reality simulation environment. *Surgery*, 149(6), 750–760. <https://doi.org/10.1016/j.surg.2010.11.012>
- Luo, H., Li, G., Feng, Q., Yang, Y., & Zuo, M. (2021). Virtual reality in K-12 and higher education: A systematic review of the literature from 2000 to 2019. *Journal of Computer Assisted Learning*, 37(3), 887–901. <https://doi.org/10.1111/jcal.12538>
- Ma, J., & Nickerson, J. V. (2006). Hands-on, simulated, and remote laboratories. *ACM Computing Surveys*, 38(3), 7. <https://doi.org/10.1145/1132960.1132961>
- 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., 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>
- Makransky, G., Terkildsen, T. S., & Mayer, R. E. (2019). Adding immersive virtual reality to a science lab simulation causes more presence but less learning. *Learning and Instruction*, 60, 225–236. <https://doi.org/10.1016/j.learninstruc.2017.12.007>
- Makransky, G., Thisgaard, M. W., & Gadegaard, H. (2016). Virtual simulations as preparation for lab exercises: Assessing learning of key laboratory skills in microbiology and improvement of essential non-cognitive skills. *PLoS ONE*, 11(6), e0155895. <https://doi.org/10.1371/journal.pone.0155895>
- Maresky, H. S., Oikonomou, A., Ali, I., Ditzkofsky, N., Pakkal, M., & Ballyk, B. (2019). Virtual reality and cardiac anatomy: Exploring immersive three-dimensional cardiac imaging, a pilot study in undergraduate medical anatomy education. *Clinical Anatomy*, 32(2), 238–243. <https://doi.org/10.1002/ca.23292>
- Markowitz, D. M., Laha, R., Perone, B. P., Pea, R. D., & Bailenson, J. N. (2018). Immersive virtual reality field trips facilitate learning about climate change. *Frontiers in Psychology*, 9. <https://doi.org/10.3389/fpsyg.2018.02364>
- Menary, R. (2010). Introduction to the special issue on 4E cognition. *Phenomenology and the Cognitive Sciences*, 9, 459–463. <https://doi.org/10.1007/s11097-010-9187-6>
- Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., & Davis, T. J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Computers & Education*, 70, 29–40. <https://doi.org/10.1016/j.compedu.2013.07.033>
- Mione, S., Valcke, M., & Cornelissen, M. (2013). Evaluation of virtual microscopy in medical histology teaching. *Anatomical Sciences Education*, 6(5), 307–315. <https://doi.org/10.1002/ase.1353>
- Monteiro, V., Mata, L., & Peixoto, F. (2015). Intrinsic motivation inventory: Psychometric properties in the context of first language and mathematics learning. *Psicologia: Reflexão e Crítica*, 28(3), 434–443. <https://doi.org/10.1590/1678-7153.201528302>
- Moreno, R., & Mayer, R. E. (2000). Engaging students in active learning: The case for personalized multimedia messages. *Journal of Educational Psychology*, 92(4), 724–733. <https://doi.org/10.1037/0022-0663.92.4.724>
- Moro, C., Štromberga, Z., Raikos, A., & Stirling, A. (2017). The effectiveness of virtual and augmented reality in health sciences and medical anatomy. *Anatomical Sciences Education*, 10(6), 549–559. <https://doi.org/10.1002/ase.1696>
- Nathan, M. J. (2021). *Foundations of embodied learning: A paradigm for education*. Routledge.
- Newen, A., De Bruin, L., & Gallagher, S. (Eds.). (2018). *The Oxford handbook of 4E cognition*. Oxford University Press.
- Nicovich, S. G., Boller, G. W., & Cornwell, T. B. (2005). Experienced presence within computer-mediated communications: Initial explorations on the effects of gender with respect to empathy and immersion. *Journal of Computer-Mediated Communication*, 10(2), JCMC1023. <https://doi.org/10.1111/j.1083-6101.2005.tb00243.x>

- Osunde, J., Bacon, L., & MacKinnon, L. (2018, April). Gender differences and digital learning games—one size does not fit all. In A. Azevedo and A. Mesquita (Eds.), *Proceedings of International Conference on Gender Research* (pp. 271–277). Curran Associates, Inc.
- Pande, P. (2021). Learning and expertise with scientific external representations: An embodied and extended cognition model. *Phenomenology and the Cognitive Sciences*, 20, 463–482. <https://doi.org/10.1007/s11097-020-09686-y>
- Pande, P. (2023, December). Enacting biomolecular interactions in VR: Impact on student conceptual understanding in biochemistry. In J.-L. Shih, A. Kashiara, W. Chen & H. Ogata (Eds.), *Proceedings of 31st International Conference on Computers in Education, ICCE 2023* (pp. 317–325). Asia-Pacific Society for Computers in Education.
- Pande, P., & Chandrasekharan, S. (2022). Expertise as sensorimotor tuning: Perceptual navigation patterns mark representational competence in science. *Research in Science Education*, 52(2). <https://doi.org/10.1007/s11165-020-09981-3>
- Pande, P., Thit, A., Sørensen, A. E., Mojsoska, B., Moeller, M. E., & Jepsen, P. M. (2021). Long-term effectiveness of immersive VR simulations in undergraduate science learning: Lessons from a media-comparison study. *Research in Learning Technology*, 29. <https://doi.org/10.25304/rlt.v29.2482>
- Parkhomenko, E., O'Leary, M., Safiullah, S., Walia, S., Owyong, M., Lin, C., James, R., Okhunov, Z., Patel, R. M., Kaler, K. S., Landman, J., & Clayman, R. (2019). Pilot assessment of immersive virtual reality renal models as an educational and preoperative planning tool for percutaneous nephrolithotomy. *Journal of Endourology*, 33(4), 283–288. <https://doi.org/10.1089/end.2018.0626>
- Parong, J., & Mayer, R. E. (2020). Cognitive consequences of playing brain-training games in immersive virtual reality. *Applied Cognitive Psychology*, 34(1), 29–38. <https://doi.org/10.1002/acp.3582>
- Passig, D., Tzuriel, D., & Eshel-Kedmi, G. (2016). Improving children's cognitive modifiability by dynamic assessment in 3D Immersive Virtual Reality environments. *Computers & Education*, 95, 296–308. <https://doi.org/10.1016/j.compedu.2016.01.009>
- Pekrun, R., Goetz, T., Titz, W., & Perry, R. P. (2002). Academic emotions in students' self-regulated learning and achievement: A program of qualitative and quantitative research. *Educational Psychologist*, 37(2), 91–105. https://doi.org/10.1207/S15326985EP3702_4
- Plass, J. L., Perlin, K., Roginska, A., Hovey, C., Fröhlich, F., Maso, A. S., Olsen, A., He, Z., Pahle, R., & Ghosh, S. (2022). Designing effective playful collaborative science learning in VR. In H. Söbke, P. Spangenberg, P. Müller & S. Göbel (Eds.), *Serious Games. JCSG 2022. Lecture Notes in Computer Science*, vol 13476 (pp. 30–35). Springer, Cham. https://doi.org/10.1007/978-3-031-15325-9_3
- 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>
- Poyade, M., Eaglesham, C., Trench, J., & Reid, M. (2021). A transferable psychological evaluation of virtual reality applied to safety training in chemical manufacturing. *ACS Chemical Health & Safety*, 28(1), 55–65. <https://doi.org/10.1021/acs.chas.0c00105>
- Pulijala, Y., Ma, M., Pears, M., Peebles, D., & Ayoub, A. (2018). Effectiveness of immersive virtual reality in surgical training—A randomized control trial. *Journal of Oral and Maxillofacial Surgery*, 76(5), 1065–1072. <https://doi.org/10.1016/j.joms.2017.10.002>
- Pyatt, K., & Sims, R. (2012). Virtual and physical experimentation in inquiry-based science labs: Attitudes, performance and access. *Journal of Science Education and Technology*, 21(1), 133–147. <https://doi.org/10.1007/s10956-011-9291-6>
- 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, 103778. <https://doi.org/10.1016/j.compedu.2019.103778>
- Rambøll Management Consulting. (2014). *SurveyXact*. <https://www.surveymxact.com/>
- Renken, M. D., & Nunez, N. (2013). Computer simulations and clear observations do not guarantee conceptual understanding. *Learning and Instruction*, 23, 10–23. <https://doi.org/10.1016/j.learninstruc.2012.08.006>
- Richards, D., & Taylor, M. (2015). A Comparison of learning gains when using a 2D simulation tool versus a 3D virtual world: An experiment to find the right representation involving the Marginal Value Theorem. *Computers & Education*, 86, 157–171. <https://doi.org/10.1016/j.compedu.2015.03.009>
- Rosenblatt, V., Worthley, R., & MacNab, B. (2013). From contact to development in experiential cultural intelligence education: The mediating influence of expectancy disconfirmation. *Academy of Management Learning & Education*, 12(3), 356–379. <https://doi.org/10.5465/amle.2012.0199>
- Roy, E., Bakr, M. M., & George, R. (2017). The need for virtual reality simulators in dental education: A review. *The Saudi Dental Journal*, 29(2), 41–47. <https://doi.org/10.1016/j.sdentj.2017.02.001>
- Slotta, J. D., & Linn, M. C. (2009). *WISE science: Web-based inquiry in the classroom*. Teachers College Press.
- Smetana, L. K., & Bell, R. L. (2012). Computer simulations to support science instruction and learning: A critical review of the literature. *International Journal of Science Education*, 34(9), 1337–1370. <https://doi.org/10.1080/09500693.2011.605182>
- Šorgo, A., & Špernjak, A. (2012). Practical work in biology, chemistry and physics at lower secondary and general upper secondary schools in Slovenia. *EURASIA Journal of Mathematics, Science and Technology Education*, 8(1), 11–19. <https://doi.org/10.12973/eurasia.2012.813a>

- Srivastava, P., Rimzhim, A., Vijay, P., Singh, S., & Chandra, S. (2019). Desktop VR is better than non-ambulatory HMD VR for spatial learning. *Frontiers in Robotics and AI*, 6, 50. <https://doi.org/10.3389/frobt.2019.00050>
- Stepan, K., Zeiger, J., Hanchuk, S., del Signore, A., Shrivastava, R., Govindaraj, S., & Iloreta, A. (2017). Immersive virtual reality as a teaching tool for neuroanatomy. *International Forum of Allergy & Rhinology*, 7(10), 1006–1013. <https://doi.org/10.1002/alr.21986>
- Su, C.-H., & Cheng, C.-H. (2013). A mobile game-based insect learning system for improving the learning achievements. *Procedia - Social and Behavioral Sciences*, 103, 42–50. <https://doi.org/10.1016/j.sbspro.2013.10.305>
- Tang, K. S., Cheng, D. L., Mi, E., & Greenberg, P. B. (2019). Augmented reality in medical education: A systematic review. *Canadian Medical Education Journal*, 11(1), e81–e96. <https://doi.org/10.36834/cmej.61705>
- Teranishi, S., & Yamagishi, Y. (2018). Educational effects of a virtual reality simulation system for constructing self-built PCs. *Journal of Educational Multimedia and Hypermedia*, 27(3), 411–423.
- Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, 139(2), 352–402. <https://doi.org/10.1037/a0028446>
- van Gog, T., Ericsson, K. A., Rikers, R. M., & Paas, F. (2005). Instructional design for advanced learners: Establishing connections between the theoretical frameworks of cognitive load and deliberate practice. *Educational Technology Research and Development*, 53(3), 73–81. <https://doi.org/10.1007/BF02504799>
- van Limpt-Broers, H., Louwerse, M. M., & Postma, M. (2020). Awe yields learning: A virtual reality study. In S. Denison, M. Mack, Y. Xu & B. C. Armstrong (Eds.), *Proceedings of 42nd Annual Meeting of the Cognitive Science Society* (pp. 488–493). Cognitive Science Society.
- Vuchkova, J., Maybury, T. S., & Farah, C. S. (2011). Testing the educational potential of 3D visualization software in oral radiographic interpretation. *Journal of Dental Education*, 75(11), 1417–1425. <https://doi.org/10.1002/j.0022-0337.2011.75.11.tb05198.x>
- Washington, J., Pande, P., Ramasamy, P., Moeller, M. E., & Mojsoska, B. (2024, March). Enacting molecular interactions in VR: Preliminary relationships between visual navigation and learning outcomes. Paper presented in *The 31st IEEE Conference on Virtual Reality and 3D User Interfaces*. Orlando, FL, United States.
- Webster, R. (2016). Declarative knowledge acquisition in immersive virtual learning environments. *Interactive Learning Environments*, 24(6), 1319–1333. <https://doi.org/10.1080/10494820.2014.994533>
- West, J., & Veenstra, A. (2012). Cane toad or computer mouse? Real and computer-simulated laboratory exercises in physiology classes. *Australian Journal of Education*, 56(1), 56–67. <https://doi.org/10.1177/000494411205600105>
- Weinstein, N., Przybylski, A. K., & Ryan, R. M. (2009). Can nature make us more caring? Effects of immersion in nature on intrinsic aspirations and generosity. *Personality and Social Psychology Bulletin*, 35(10), 1315–1329. <https://doi.org/10.1177/0146167209341649>
- Wismer, P., Lopez Cordoba, A., Baceviciute, S., Clauson-Kaas, F., & Sommer, M. O. A. (2021). Immersive virtual reality as a competitive training strategy for the biopharma industry. *Nature Biotechnology*, 39(1), 116–119. <https://doi.org/10.1038/s41587-020-00784-5>
- Wong, M., Castro-Alonso, J. C., Ayres, P., & Paas, F. (2015). Gender effects when learning manipulative tasks from instructional animations and static presentations. *Journal of Educational Technology & Society*, 18(4), 37–52.
- 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>
- Zacharia, Z. C., Loizou, E., & Papaevripidou, M. (2012). Is physicality an important aspect of learning through science experimentation among kindergarten students? *Early Childhood Research Quarterly*, 27(3), 447–457. <https://doi.org/10.1016/j.ecresq.2012.02.004>
- Zhao, G., Fan, M., Yuan, Y., Zhao, F., & Huang, H. (2021). The comparison of teaching efficiency between virtual reality and traditional education in medical education: A systematic review and meta-analysis. *Annals of Translational Medicine*, 9(3), 252–252. <https://doi.org/10.21037/atm-20-2785>

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