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From Novelty to Practicality: Stakeholder-Driven Design & Deployment Needs for VR Adoption in Post-Primary Education

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ABSTRACT

Despite widespread enthusiasm for Virtual Reality (VR) in education, its adoption in post-primary schools remains limited by uncertainty over curricular integration, design requirements, and practical deployment considerations. This article reports on a three-phase, mixed-methods participatory study involving 114 co-designers, including post-primary students, parents, post-primary school teachers, subject experts, and VR practitioners. Across the three phases, we conducted co-design brainstorming sessions, semi-structured interviews, administered pre- and post-intervention surveys, and collected in-app interaction metrics to identify the design and deployment requirements for VR in post-primary schools. In Phase One, we identified stakeholders' deployment needs, capturing the socio-technical conditions required for viable classroom integration. In Phase Two, we identified the design requirements through evaluation of an initial prototype. Finally, in Phase Three, we evaluated an advanced prototype with a broader cohort of stakeholders to assess the extent to which the identified needs and requirements supported educationally meaningful and practically deployable VR experiences.

KEYWORDS

Virtual reality; post-primary education; participatory design; curriculum integration; human-computer interaction

1. Introduction

Immersive technologies such as Virtual Reality (VR) and Augmented Reality (AR) have attracted sustained research interest in the context of education and training. A growing body of work highlights attributes that make VR particularly desirable for deployment in education, where such unique affordances position VR as more than just a novel medium. For example, VR has been shown to support the development of spatial reasoning and motor skills (Makransky & Petersen, 2021), provide embodied interaction that deepens conceptual understanding through sensorimotor engagement (Mills et al., 2022), and render abstract or invisible processes visible and manipulable (Walsh et al., 2025). Its capacity for safe, repeatable experimentation enables learners to rehearse hazardous or costly procedures without real-world risk (Chua et al., 2025; Van Dinther et al., 2023), while its immersive qualities foster presence, motivation, and curiosity in ways other mediums cannot (Yahya et al., 2025). Despite these affordances, the overwhelming majority of this work has been situated in higher education (M. Hamash & Tiernan, 2024; Stracke et al., 2025; Van Dinther et al., 2023) and adult vocational and technical training (Chua et al., 2025; Röwer et al., 2025; Sabrie et al., 2025), while the design and deployment of VR for adolescent learning remain underexplored.

Adolescent learning in post-primary education presents a host of systemic and pedagogical constraints that limit the feasibility of providing rich, hands-on learning experiences. For instance, many schools lack the financial resources and spatial infrastructure to maintain fully equipped specialist facilities for every curriculum area, resulting in reduced access to practical learning (Atabek, 2019). Even

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when facilities exist, safety regulations and consumable costs may result in restricting learners' participation. Furthermore, adolescent learners often demonstrate shorter attention spans, shifting interests, and heightened developmental sensitivities (Hobbiss & Lavie, 2024). As such, there is great interest in supporting teachers to move beyond traditional methods and search for alternatives capable of sustaining attention, fostering deep engagement, and enriching the overall learning experience.

A small number of studies have examined AR (Jiang et al., 2025; Singh et al., 2024) and VR (Al-Ansi et al., 2023; Kitson et al., 2024; Thulin et al., 2025) in adolescent education, demonstrating their efficacy in capturing attention, increasing enjoyment, sustaining engagement, and, most importantly, supporting knowledge acquisition. On the other hand, researchers have also expressed substantive concerns associated with adolescent use of immersive technologies, including physical safety, privacy, and data-tracking risks (Bailey et al., 2025; Maloney et al., 2021), exposure to inappropriate content, and the potential replacement of "real" social interaction (Jin et al., 2024a). These tensions underscore the need to investigate how immersive technologies can be designed and deployed in ways that are enjoyable and educationally effective while remaining safe and ethically grounded. Importantly, successful deployment cannot be understood through designing for adolescents alone, as they are not the only stakeholders in the deployment equation. Particularly, there exists limited research work that examines the design and deployment needs of other key stakeholders, such as teachers, school administrators, and technicians (M. Hamash & Tiernan, 2024; Makransky & Petersen, 2021).

As such, this article aims to address these gaps through a three-phase, stakeholder-driven study involving 114 co-designers, including post-primary students, post-primary teachers, post-primary school managerial staff, parents, subject experts, and VR practitioners. In Phase One, we established the core Deployment Needs (DNs) for VR adoption in post-primary schools through consultation with stakeholders. In Phase Two, we designed an initial prototype in collaboration with subject experts and invited co-designers to evaluate it, which resulted in the identification of the Design Requirements (DRs) for VR content and interaction design in post-primary settings. Finally, in Phase Three, we produced an advanced prototype that aligns with most DN and DRs, then invited co-designers for a final evaluation. Through this work, we aim to contribute to the HCI community by exploring stakeholders' perspectives on VR adoption in post-primary education and developing actionable DN and DRs to inform researchers and practitioners on the practical implementation of VR in these settings.

2. Related work

2.1. The pedagogical rationale behind immersive technologies

When considering the deployment of immersive technologies in education, it is crucial to identify the justifiable pedagogical value they can offer to teaching and learning. Educational theory, particularly constructivist practices, has long emphasized that learners attain knowledge most effectively when such knowledge is experienced actively, situated in meaningful contexts, and consolidated through reflection (Jonassen, 1991). The body of research within the HCI community has shown that immersive technologies such as VR and AR could afford precisely such conditions by providing a medium for experiential learning, where learners engage in a cyclical process of experience, reflection, conceptualization, and experimentation (Asad et al., 2021). Furthermore, leveraging embodied cognition in learning is a natural byproduct of immersive technologies; the heightened sense of presence, bodily gestures, and sensorimotor engagement can deepen learners' understanding of complex concepts (Al Hakim et al., 2024; Klingenberg et al., 2024; Yang et al., 2024b). From a social constructivist perspective, learning is mediated through collaboration and interaction (Makransky & Lilleholt, 2018; Scavarelli et al., 2021). In that respect, immersive technologies have been shown to support this approach by fostering socially mediated learning, where presence and co-presence enable collaboration, peer feedback, and co-construction of knowledge (Wei et al., 2025). Furthermore, immersive environments provide a unique capacity for reflection, iteration, and skill transfer. Since experiences can be paused, replayed, and revisited, learners are offered structured opportunities to reflect on their actions, explore alternatives, and construct knowledge through inquiry (Georgiou et al., 2021; Mahmoudi-Dehaki & Nasr-Esfahani, 2024). Finally, recent research indicates that VR does not inherently enhance inquiry learning; rather, its impact depends on

how well multimodal design elements are coordinated with the particular scientific reasoning processes learners must perform. When these elements are aligned, students produce more coherent explanations and interact more meaningfully with the content. (Chang et al., 2025).

This can provide learners with a space for safe, repeatable practice that enables experimentation without risk, thus supporting the transfer of procedural and conceptual skills from virtual to real-world contexts (Asad et al., 2021; Jones-Roberts & Bechtold, 2024). In addition, the integration of affective prompts, real-time feedback, and social scaffolds has been shown to enhance motivation, sustain engagement, and improve learning outcomes (Makransky & Petersen, 2021). As such, immersive technologies present compelling pedagogical opportunities, warranting deeper investigation into how these benefits can be realistically deployed to meet the needs of post-primary education. With that in mind, such technologies must be designed to be sensitive to the unique developmental attributes adolescents present with. For instance, research shows that adolescents differ cognitively, emotionally, and socially from older users, which directly affects how they experience presence and immersion, as well as how to design experiences that are age-appropriate, enjoyable, maintain their attention, and, of course, pedagogically valuable (Bailey & Bailenson, 2017; Hite et al., 2019). Furthermore, understanding the context in which such immersive technologies will be deployed is also essential and can impact “how” such technologies can be designed and deployed to naturally integrate into the institutional structure with minimized friction (Eccles & Roeser, 2011). Collectively, this indicates that deployment conditions for immersive technologies in education cannot be assumed to be uniform across age groups; rather, they must account for developmental stage, school context, and systematic factors to ensure equitable and safe adoption.

2.2. Immersive technologies in education

Within the broader landscape of immersive learning technologies, VR has emerged as the most extensively studied modality, valued for its ability to deliver fully immersive environments where learners can experiment, collaborate, and visualize abstract phenomena (M. Hamash et al., 2025; Pang et al., 2021; Samala et al., 2025). A recent meta-analysis further confirms the effectiveness of educational Virtual Environments (VEs), demonstrating that VR can significantly enhance knowledge retention in science education (G. Chen et al., 2025). Studies echoed the positive outcomes of VR in diverse contexts within education and learning, including healthcare and clinical contexts (Asoodar et al., 2024; Tabbaa et al., 2021), vocational and professional training in areas such as construction, automotive, and technical trades (Yadav, 2024), subject-focused learning in disciplines such as Science, Technology, Engineering, and Mathematics (STEM) (Abuhammad et al., 2021; Duca et al., 2024; Hamash et al., 2024; Pellas et al., 2020), computer science (Zhu et al., 2023), arts and history (Cecotti et al., 2024; Christopoulos et al., 2023), and cultural education (Christopoulos et al., 2024; Mercimek & Bulbul, 2026; Pellas et al., 2020). In addition to enjoyment, immersive engagement, self-efficacy, and motivation among learners (Baceviciute et al., 2020) VR can simulate risky, unsafe, or impossible scenarios (McIntosh, 2022; Soilis et al., 2024; Van Dinther et al., 2023). Furthermore, through designing experiences that can elicit a heightened sense of presence, VR can support teaching abstract concepts that are rich in spatial information, such as the Internet of Things (IoT) (Zhu et al., 2023), astronomical objects (Kersting et al., 2024), and molecular structures (Won et al., 2019). However, research suggests that these benefits are not inherent to VR itself, but depend on the extent to which learning experiences are designed in alignment with learners’ cognitive abilities, epistemic processes, and disciplinary reasoning, requiring careful attention to learners’ profiles and educational needs (G. Chen et al., 2025).

Whilst the use of VR has been widely investigated in education contexts, the vast majority of studies focus on adult learners in higher education (Jin et al., 2022, 2024b; Woźniak et al., 2020) or professional training (Sabrie et al., 2025; Yang et al., 2024a). Far fewer studies have examined how VR can support adolescent learning in educational contexts, despite critical differences from adult learners; engaging adolescents with VR introduces unique developmental, cognitive, emotional, and safeguarding considerations that shape how VR should be designed and used safely, ethically, and responsibly (Kaimara et al., 2022). Furthermore, the pedagogical realities of designing and delivering curricula for adolescents have distinct implications for the design and deployment of VR in this context. Unlike

adult education, which often assumes learner independence and minimal scaffolding, adolescent learning takes place in tightly structured classroom contexts where pacing, teacher facilitation, and Special Educational Needs (SEN) inclusivity are critical to learners' success (Southgate, 2022).

In that respect, some studies have explored the use and design of VR for adolescent learning in biology (Christopoulos et al., 2023), history and culture (Christopoulos et al., 2024), and earthquake escape training (Ye & Fan, 2025). Despite the reported advantages of VR in adolescent learning, including knowledge acquisition, spatial and structural understanding, better performance in high-stakes scenarios, as well as enhanced cognitive, behavioral, and affective engagement (Jin et al., 2022; Makransky & Petersen, 2021; Van Dinther et al., 2023), studies encompassing adolescent learning in VR remain underrepresented in the body of literature, leaving open questions about how such technologies translate into the realities of schools. Where the design of VR (Christopoulos et al., 2023; Ye & Fan, 2025) or AR (J. Chen et al., 2024; Moon et al., 2025; Woodward et al., 2022; Woźniak et al., 2020; Wu et al., 2023) has been explored specifically for adolescent learning, there has been limited engagement with stakeholders, including post-primary teachers and school leaders, whose perspectives on VR could be detrimental to its deployment, integration, and adoption into school curricula. As a result, perspectives on the pedagogical value, practical feasibility, and mitigating risks of VR in adolescent learning remain largely absent. There is, therefore, much to be learned about how VR can be designed and deployed in ways that are not only engaging for adolescent learners but also realistically adoptable by schools, if the technology is to move from experimental novelty toward sustainable integration in education.

2.3. The realist perspective on VR deployment in post-primary education

Alongside sustained interest in VR as a tool for learning, a substantial body of work highlights ethical and developmental concerns with a particular consideration to adolescent users. Current VR systems are capable of capturing extensive behavioral and physiological data, including gaze, bodily movement, and spatial interactions, creating privacy risks that are often opaque to adolescent users (Bailey et al., 2025). This is particularly concerning as research have found that that biometric content may be retrieved from behavioral data (Bozkir et al., 2021). In the case of social VR experiences, adolescents have reported difficulties managing their identity, discomfort when they are unable to protect their personal space, and exposure to harassment. As such, whilst VR may offer many benefits, if not designed appropriately, VR may pose ethical risks and privacy concerns to adolescent users. Furthermore, VR, if not designed appropriately, may present with health risks including nausea, dizziness, and visual fatigue (Hamash & Tiernan, 2024), symptoms that have been echoed across different user groups (including adults). Furthermore, research found that VR may present with behavioral risks as well. For instance, one study found that the use of VR may influence emotional regulation and behavioral responses, underscoring the need for developmentally sensitive design (Castaneda et al., 2017; Skulmowski, 2023). Parents have also reported these concerns; one study found that parents reported reduced family communication, and shared their concerns over the potential long term effects on their children's cognitive and physical development (Jin et al., 2024a).

In addition to health and safety concerns, there exist practical concerns over the financial implications of integrating VR in adolescent education remain a major barrier, as devices and software licensing are often priced beyond the budgets of schools (Chimbanga et al., 2024; Fransson et al., 2020). Beyond finances, many schools struggle with IT infrastructure, device management and connectivity, which can limit feasibility for routine classroom use (Mohamad Ali et al., 2024; Pellas et al., 2021). The body of research has also reported that school leaders are unclear about the implications of VR adoption in relation to timetabling, staff coordination and equity of access (Fransson et al., 2020; Kitzmann et al., 2024). Furthermore, the lack of health and safety guidelines (Southgate, 2020; Department for Business, Energy & Industrial Strategy, 2020), combined with insufficient training and teachers' immense workload, can erode their confidence in managing VR activities in classrooms, ultimately hindering the deployment of VR (Álvarez et al., 2024; Fransson et al., 2020). As such, whilst VR for adolescent learning holds great promise, there is a lot to be demystified about the needs and requirements of stakeholders for a realistic deployment and adoption of VR in schools. Specifically, we aim to understand the pragmatic needs, constraints, and opportunities of VR for adolescent learning. We also aim

to translate these into actionable guidance and design features, bridging the gap from promising prototypes to realistic deployment.

3. Methodology overview

3.1. Situating the research

To provide context for our investigation, we chose to explore the subject of chemistry in post-primary education as our use case for two key reasons. First, in recent systematic reviews, a study found that fewer than 1% of published VR education studies have examined post-primary settings, and even fewer targeted STEM-related topics, including chemistry (M. Hamash & Tiernan, 2024; Van Dinther et al., 2023). Secondly, schools are increasingly constrained by rising costs and shrinking budgets for chemical materials, forcing teachers to scale back laboratory work or replace it with simplified demonstrations (Burke, 2024). In the context of Ireland in particular, where this research is situated, a national report highlights widespread shortages of suitably equipped laboratories at schools and constrained opportunities for hands-on work (Association of Secondary Teachers, Ireland, 2025). Therefore, we believe that using chemistry as a vessel to explore the realistic deployment of VR may be more motivating for teachers and school leaders to engage with VR as a potential alternative for sustaining practical, hands-on learning. Finally, chemistry education is characterized by abstract and invisible processes, such as molecular geometry and sub-microscopic interactions, that traditional teaching methods often struggle to make accessible (Berg et al., 2019). In this respect, research has shown that VR could address these challenges in chemistry education for adults, where users can engage in abstract concepts and immerse themselves in molecular geometry (Saritaş, 2015; Van Dinther et al., 2023). As such, we hope to replicate these benefits by adopting these approaches to the design and deployment needs of adolescents in post-primary education.

3.2. Methodology approach & overview

This research adopts a multi-phase, iterative co-design approach that combines qualitative and quantitative methods to surface stakeholder needs progressively, translate these needs into design requirements, then ultimately, produce a realistically deployable prototype as presented in Figure 1. As such, adopting a mixed-methods approach allows us to capture a broad understanding of stakeholder attitudes and a deeper exploration of their lived experiences with VR. Given the multidisciplinary nature of this research, our approach was informed by design principles from both HCI and education disciplines, grounded in a shared ethos of sustained, collaborative engagement with stakeholders. In HCI research, Participatory Design (PD) (DiSalvo, 2016) emphasizes co-creation in authentic contexts, treating design as an active and ongoing dialogue with those who will shape and use the technology. PD has been widely used to understand the specific needs of unique users, such as children (Benton & Johnson, 2014), people with dementia (Hendriks et al., 2013), people on the autism spectrum (Maun et al., 2021), and those with visual impairment (Kim, 2024). Similarly, approaches in education research, such as the Design-Based Research (DBR) approach and its Educational Design Research (EDR) variant, are known for their dual focus on generating both theoretical insights and practical solutions in collaboration with practitioners. Drawing on this shared foundation, we implemented a three-phase design process in which co-designers ($n = 114$ unique co-designer), including post-primary chemistry teachers ($n = 47$), pre-service chemistry teachers ($n = 4$), post-primary students ($n = 10$), parents ($n = 2$), expert researchers in relevant subject fields ($n = 41$), post-primary school managerial staff ($n = 5$), and VR developers ($n = 5$), who we will refer to as co-designers in this study, have directly informed the design process. In Phase One, we collaborated with 63 unique co-designers to investigate the core stakeholder Deployment Needs (DNs) for the realistic deployment of VR in post-primary through surveys, interviews, and school consultations. In Phase Two, we used the Domain Needs (DNs) to guide design brainstorm sessions in collaboration with 9 co-designers that led to the development of an initial prototype, which was then evaluated with 27 co-designers (18 of whom had also participated in Phase One); the Design Requirements (DRs) were subsequently derived from this evaluation. Finally, an advanced prototype was developed in Phase Three based on the

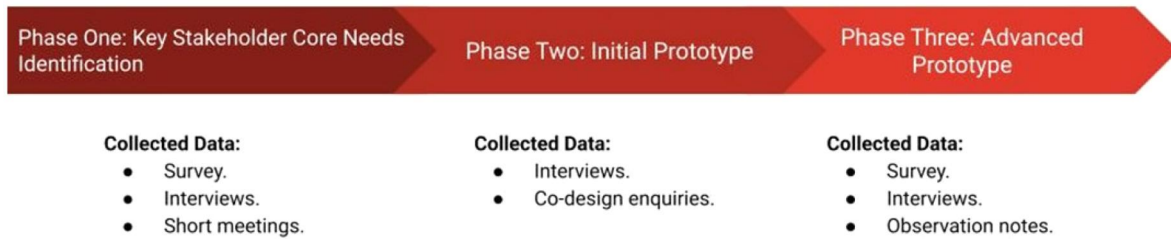


Figure 1. The three phases of co-design.

feedback we received, which was then evaluated by a cohort of stakeholders, which included 83 co-designers, of whom 42 were new co-designers who did not participate in previous Phases. This research work was conducted over a period of 10 months.

Figure 1 offers a visual presentation of the three-phase design process and the data captured in each phase.

3.3. Ethical considerations

This research was reviewed and approved by the Dublin City University Research Ethics Committee (DCUREC/2025/010) in Ireland. The study also complies with the ACM Code of Ethics and Research Integrity guidelines. While the ultimate end users of this research are teachers and post-primary students, we strictly involved adult stakeholders in the early phases. This decision reflected the prototype's initial immaturity and the potential safety risks associated with adolescents interacting with an unrefined VR experience. However, the teachers involved across all three phases had substantial post-primary teaching experience (seven years and above) and drew directly on that expertise to inform and shape each phase of the design process. As such, post-primary students engaged in Phase Three only after thorough testing, evaluation, and feedback by key stakeholders. In Phase Three, prior to engaging with students, the researcher who was due to have direct contact with students was vetted and approved by the Garda Police (Irish police). In addition, written approval and consent were collected from the school, as well as written consent from parents of the children who engaged in the study.

4. Phase one: Identifying stakeholder deployment needs

In this phase, we engaged multiple stakeholders to lay the groundwork for the co-design of VR tailored to post-primary education. Specifically, this included post-primary chemistry teachers, subject experts, and school managerial staff, aiming to explore the pedagogical, technical, institutional, and practical needs, barriers, and opportunities for VR deployment in post-primary schools. To achieve these, we administered a survey to 40 post-primary chemistry teachers in Ireland, capturing the attitudes, readiness, and potential barriers related to VR integration in post-primary schools in Ireland. We also invited 18 co-designers from a range of disciplines in HCI and education, as well as post-primary chemistry teachers and school staff, aiming to collect in-depth insights on the needs, barriers, and opportunities of deploying VR in post-primary education. Finally, to understand the practical deployment considerations, we conducted meetings with five schools, including those in management roles such as principals, vice principals, and education managers. The data from the survey, interviews, and meetings were then consolidated and used in design sessions with key stakeholder representatives to form and design the initial prototype (Phase Two).

4.1. Data collection & analysis

Because teachers are at the frontline of classroom practice, they hold unique insights into what works, what does not, and what is needed to make new technologies viable in post-primary settings. To capture these perspectives, forty post-primary chemistry teachers undertook the survey. The survey explored the following eight aspects in relation to the utilization of VR in post-primary education. The

Table 1. Demographics & background information of teachers.

Parameter	Parameter
Sex	Female (65%), Male (35%)
Age group (in years)	21–30 (27.5%), 31–40 (27.5%), 41–50 (25%), 51–60 (17.5%), 61+ (2.5%)
Teaching experience	1–5 years (30%), 6–10 (22.5%), 11–15 (17.5%), 16–20 (5%), 21+(25%)
Qualifications	Bachelor's Degree (20%), Post-Graduate Diploma or Master's (75%), PhD (5%)

survey was adapted from (Al Breiki et al., 2023), comprising Likert-scale and open-ended questions on attitudes, behavioral intention, subjective norm, and perceived readiness for VR deployment in post-primary education. Table 1 describes the demographics and background information of teachers.

As there are different post-primary setups in Ireland, it was important to capture responses from those who work in varied post-primary settings. Of the survey responders, 55% of teachers teach in voluntary secondary schools, 25% teach at community colleges, 5% teach at schools that are run by the local Education and Training Boards (ETBs), 2.5% teach at private schools, and 12.5% teach at community schools.

In terms of teachers' familiarity with VR, 92.5% teachers mentioned they had never received professional training on using VR in education. Only 10% mentioned they had used VR in their teaching at least once, while the majority (87.5%) were interested in using VR in their teaching. We also aimed to obtain in-depth insights into the deployment needs of stakeholders. As such, we conducted eighteen semi-structured interviews with an academic expert in chemistry ($n=1$), lecturers in chemistry education ($n=4$), expert in computational chemistry ($n=1$), researcher in educational technology ($n=1$), researcher in STEM education ($n=1$), experts in computer science ($n=2$), researcher in HCI ($n=1$), VR developers ($n=2$) and experienced post-primary chemistry teachers ($n=5$) with at least seven years of experience. The interviews focused on pedagogical and practical considerations for integrating VR in chemistry lab teaching, exploring how VR affordances could support skill and knowledge acquisition. The interviews were audio-recorded and lasted between 40 and 60 min. The recordings were then transcribed verbatim by one researcher and corroborated by another researcher.

Finally, in order to capture more organizational and managerial insights of VR adoption in post-primary schools, we liaised and met with managerial teams from five post-primary schools to explore the nuances of realistically deploying VR at their schools. We met with the principal of a post-primary school ($n=1$), the vice principals of a post-primary school ($n=3$), and a post-primary school managerial staff member ($n=1$). Specifically, we discussed practical issues in VR deployment, including classroom layout and set-up, technical, ethical, and health and safety considerations. Meeting minutes were noted by one researcher.

4.2. Phase one findings: Stakeholders' deployment needs (DNs)

In this phase, we aimed to identify the core stakeholders' Deployment Needs (DNs) when considering the realistic deployment of VR in post-primary school settings. Taking the views of a total of 63 stakeholders, we collated the qualitative data from the survey, interview transcriptions, and meetings, then clustered stakeholders' deployment needs using affinity mapping; a synthesis technique used to distill qualitative data into coherent clusters (Lucero, 2015). The quantitative data from the survey are reported and embedded within the affinity map, and quotes were added to provide better context to the affinity clusters. Figure 2 provides a visual representation of the affinity map produced as a result of Phase One analysis.

4.2.1. Defining the "why" and "how"

4.2.1.1. DN1 – Finding the "why". Co-designers consistently stressed that VR must have a clear pedagogical purpose in post-primary education, emphasizing that VR would be most valuable when it addresses gaps that conventional teaching cannot. In the context of post-primary education in chemistry, co-designers highlighted the value of VR in visualizing abstract or invisible processes, simulating

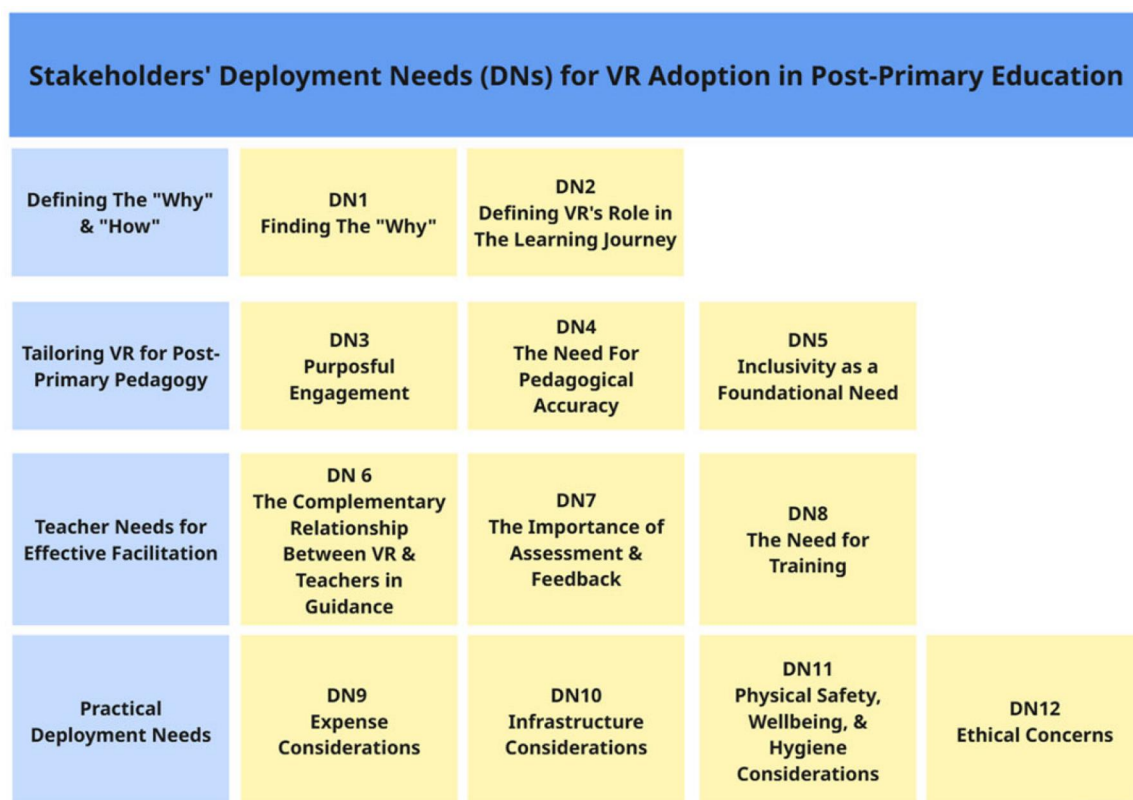


Figure 2. Affinity map of stakeholders' deployment needs (DNs).

hazardous scenarios, and enabling practice otherwise inaccessible in a classroom. These views were supported by survey responses, with 92.5% agreeing VR is valuable for visualizing abstract concepts and 90% highlighting its usefulness for pre-lab preparation. As one co-designer explained, *"If there's certain equipment they don't have ... then run it in this space [VR]"* [T07, Survey, Phase1].¹ Beyond subject-specific uses, participants also noted VR's potential to reduce student anxiety and build confidence: *"It can be great to build confidence before they go into the real lab"* [T09, Interview, Ph1]. Survey responders agreed with this view; with 92.5% agreeing VR may increase confidence in students and 87.5% indicating it may help reduce student anxiety through safe experimentation. As such, finding the "why" behind VR deployment in post-primary settings must demonstrate a compelling value proposition by offering meaningful benefits that cannot be achieved as effectively through existing methods.

4.2.1.2. DN2 – Defining VR's role in the learning journey. Through the data we collected, it was prevalent that co-designers highlighted the need to clearly define VR's pedagogical role, whether as a pre-lab exercise, a revision tool, a tool for formative assessment, or a scenario-based training tool, just to mention a few. As such, establishing this role is essential for meaningful integration into the students' learning journey. In the context of chemistry, most co-designers described VR being used as *"a good first step"* [E05, Interview, Ph1], where 92.5% of survey respondents agreed that VR should supplement rather than substitute traditional lab work, noting that *"It must not replace the real thing. Just support it"* [T05, Interview, Ph1]. This is especially when *"educational technology should not replace peer learning"* [M4, Managerial meetings, Ph1], adding that students' learning is not only about the subject-related skills but also about developing interpersonal and teamwork competencies. Furthermore, almost all co-designers who their expertise lay within the education discipline stressed the need for the VR activity to directly map onto existing curriculum standards and learning outcomes in order for its adoption to be meaningfully adopted, mentioning that *"We must align this [VR experience] with curriculum outcomes"* [T1, Survey, Ph1] and *"link[ing] simulations to learning goals is very important"* [E13, Interview, Ph1].

4.2.2. Tailoring VR for post-primary pedagogy

4.2.2.1. DN3 – Purposeful engagement. Co-designers frequently described VR as a tool that could transform learning into a purposefully engaging, motivating practice. One co-designer remarked, *“This might actually get some of the less interested students engaged”* [T1, Survey, Ph1], a view reflected in survey results, with 92.5% agreeing VR may make learning more engaging and 92.5% stating it may help maintain attention during procedural tasks. At the same time, several co-designers expressed their concern that students could trivialize VR and treat it as entertainment rather than a serious learning resource, particularly if the design lacked a clear instructional focus. Opinions also diverged on how VR activities should be structured. Some advocated tightly sequenced simulations that *“require correct step sequence before progression”* [T12, Survey, Ph1], while others preferred an open-ended exploration mode that encourages exploration and curiosity. Survey responses supported both perspectives, with 92.5% agreeing that VR should allow for both structured and exploratory modes. As such, a core need in designing VR for post-primary education must balance novelty with pedagogy, ensuring motivation is channeled into meaningful learning through experiences that are structured enough to support skill acquisition while remaining flexible enough to foster curiosity.

4.2.2.2. DN4 – The need for pedagogical accuracy. For co-designers, accuracy of content in VR was described as “non-negotiable” [E3, Interview, Ph1]. As one co-designer cautioned, *“students are very critical... if you spread some wrong information... they may remember it for their whole life”* [E6, Interview, Ph1]. As such, VR experiences must retain a level of fidelity and precision that ensures subject-specific correctness.

4.2.2.3. DN5 – Inclusivity as a foundational need. Co-designers emphasized that VR must be designed with inclusivity at its core, ensuring that students with SEN or those with disabilities are not excluded from learning. Teachers noted that some learners may be unable to engage fully due to visual impairments, motion sickness, or sensory sensitivities. One co-designer expressed the need to have other alternatives in the room when VR is being used, as VR would *“not [be] suitable for all students, [and therefore, there is a] need for inclusive alternatives”* [P7, Survey, Ph1]. These perspectives highlight that equitable adoption of VR in post-primary education requires designing beyond a one-size-fits-all approach; it demands flexible pathways, alternative formats, and accessibility features that position inclusivity as a foundational need rather than an afterthought.

4.2.3. Teacher needs for effective facilitation

4.2.3.1. DN6 – The complementary relationship between VR & teachers in guidance. Co-designers envisaged VR as a partner in guidance, supporting students from inside, while teachers guide from outside. Co-designers particularly valued built-in evaluation of progress that *“requires correct step sequence before progression”* [T12, Survey, Ph1] to ensure students will not just *“click through everything to get it over with”* [T5, Survey, Ph1]. Furthermore, teachers described their own role as framing the activity *“The teacher acts as a facilitator”* [T7, Interview, Ph1], provoking reflection *“... the students need to be provoked to think”* [E7, Interview, Ph1], and debriefing afterwards. As such, there is a need to define a coordinated model in which VR provides step-by-step scaffolding from within, while teachers mediate engagement from outside, ensuring the VR delivers a meaningful learning experience.

4.2.3.2. DN7 – The importance of assessment and feedback. Assessment and feedback are recognized as central components of the learning cycle, directly shaping both student progress and instructional practice. Co-designers emphasized that VR must be intentionally designed to capture both procedural and conceptual understanding. Such assessment feedback could vary in terms of style depending on the nature of the tasks and the learning objectives. Some suggested corrective feedback to incorrect actions *“It should alert them if they do something wrong. Like a virtual warning”* [T20, Survey, Ph1], while others envisaged *“By offering information through multiple channels—such as visual, auditory, and textual cues—students with different learning preferences or needs would be better supported in following procedures and mastering skills”* [E10, Interview, Ph1]. Echoing this sentiment from a leadership

perspective, a school vice principal stated, “*If we’re investing in immersive technologies like VR, we must also invest in meaningful assessment—otherwise, we’re just entertaining, not educating.*” [M21, Managerial meetings, Ph1].

4.2.3.3. DN8 – Need for training. Co-designers repeatedly stressed that effective use of VR depends less on the technology itself and more on the practicality of its implementation. As one co-designer explained, “*the main limitation here is the implementation*” [T19, Survey, Ph1]. Most co-designers highlighted the absence of clear guidance, with one noting, “*I have not had any kind of guidelines*” [E1, Interview, Ph1]. Survey findings reflected these concerns: 80% of respondents stated they lacked the skills to integrate VR into mainstream teaching in post-primary settings, 65% identified a lack of confidence in implementation, and 92.5% reported having received no official training on VR use in the context of education. Co-designers highlighted that both technical and pedagogical training are essential, with 80% calling for structured training before classroom use.

4.2.4. Practical deployment needs

4.2.4.1. DN9 – Expense considerations. Cost emerged as a double-edged factor in stakeholder discussions. On one hand, co-designers viewed VR as a way to compensate for limited resources; “*Even in schools with well-equipped laboratories, concerns around the potential loss or breakage of materials often limit student access to hands-on experiences. Teachers may hesitate to allow students to perform experiments themselves, given the cost and fragility of the equipment or the limited availability of materials*” [T02, Survey, Ph1]. Other co-designers cautioned that expenses related to hardware, software, and ongoing maintenance of VR could make adoption challenging: “*It [VR] holds great promise for education, but the financial demands, covering equipment, software, training, and upkeep, can be a major barrier. Schools need cost-effective models that still deliver strong learning outcomes.*” [M23, Managerial meetings, Ph1]. This ambivalence was reflected in survey results: while 87.5% of respondents agreed VR could reduce reliance on physical materials, yet 80% expressed concern over the affordability of VR. As such, in order for VR to gain traction in post-primary education, cost-effectiveness and long-term sustainability must be addressed alongside pedagogical value.

4.2.4.2. DN10 – Infrastructure considerations. Co-designers emphasized that even well-designed VR experiences cannot be meaningfully integrated without the necessary school infrastructure. Reliable Wi-Fi, adequate physical space, and sufficient hardware were all identified as prerequisites. As one co-designer explained, “*Not all schools have good Wi-Fi or enough VR devices*” [E9, Interview, Ph1], while another described chemistry labs as “*too restricted*” [E18, Interview, Ph1] for immersive use. Survey findings reflected these concerns, with 80% of respondents unsure whether their school’s current infrastructure could support regular VR implementation. As such, infrastructure considerations are a determinant of feasibility.

4.2.4.3. DN11 – Physical safety, wellbeing, & hygiene considerations. Co-designers stressed that VR adoption in schools must be grounded in safety, wellbeing, and hygiene considerations. Concerns ranged from physical risks such as nausea and dizziness: “*You have to keep these [side effects] in your mind*” [T16, Survey, Ph1], to the practical need for short sessions as a side effects preventive approach, and enforcing a seated mode whilst using VR for physical safety. Hygiene was another recurring issue, with “*disinfect between users*” cited frequently; yet 67.5% of survey respondents reported their schools lacked hygiene guidelines, despite 57.5% agreeing such policies are essential.

4.2.4.4. DN12 – Ethical concerns. Co-designers called for broader regulation to ensure VR in schools is both ethical and quality-controlled. Concerns centered on the accuracy of content, the safeguarding of student wellbeing, and the absence of formal oversight. As one co-designer commented on the “*need [for] regulations for the education [sector]*” [E19, Interview, Ph1]. Survey findings reflected this perspective, with 57.5% of respondents stating that official guidelines and regulations are necessary before

large-scale adoption. As such, the responsible integration of VR in post-primary education requires not only technical and pedagogical readiness but also clear ethical frameworks and regulatory standards.

5. Phase two: Initial prototype

In Phase Two, we aimed to synthesize the core DNs identified in Phase One by conducting co-design enquiry sessions in collaboration with 9 co-designers. Following the co-design enquiry sessions, we developed an initial prototype and invited 18 co-designers from relevant expertise who were also part of Phase One to evaluate the prototype, followed by interviews to obtain in-depth insights into the design requirements of VR for post-primary education.

5.1. Co-design enquiries sessions

In this stage, 9 co-designers participated in co-design enquiry sessions aimed at generating and refining design ideas, some of whom continued to contribute in subsequent stages, including: chemistry experts ($n=3$), an HCI researcher ($n=1$), a post-primary chemistry teacher ($n=1$), VR developers ($n=2$), and co-design researchers working with Irish schools ($n=2$) participated in eight design enquiry sessions, each lasting up to an hour with 1–3 participants in each session. In these structured one-on-one sessions, guided by Osborn's classical brainstorming principles (Smith, 1998) such as deferring judgment, encouraging idea fluency, and exploring multiple possibilities, co-designers reviewed the DNs identified in Phase One, brainstormed creative ideas, and explored design potentials and constraints relevant to deploying VR in post-primary settings. Sessions began with a presentation of Phase One findings, followed by expert identification of potential design implications, which were expanded and refined through facilitator prompts and iterative discussion. All sessions were audio-recorded, transcribed, and supplemented with researcher notes. To synthesize the outcomes, qualitative data were collated and clustered using affinity mapping, producing a systematic and thorough representation of the co-designers' Design Requirements (DRs).

5.2. Initial prototype design & development

The initial prototype was developed in Unity 6² using Meta's Building Blocks and the Meta SDK. The visuals for the initial prototype were designed using Unity's integrated tools alongside Meta's Building Blocks and Meta SDK. 3D models and assets were either custom-built within Unity or imported from external sources and then optimized for VR performance. The initial prototype comprised two VEs designed to support distinct yet complementary learning outcomes of the titration experiment. The titration experiment is a fundamental chemistry experiment used to determine the concentration of an unknown solution. We chose this experiment because it was consistently highlighted by the co-designers and mentioned in every teacher interview as an essential activity. As such, we decided to extract two experiences from the titration experiment concept. The first VE takes a procedural approach, where users are meant to follow specific steps, and the second VE takes a more abstract approach, allowing the user to zoom in and explore the molecular level. The design and structuring of these VEs were guided by the Cognitive-Affective Model of Immersive Learning (CAMIL) (Makransky & Petersen, 2021), which emphasizes how immersive learning experiences can simultaneously engage cognitive processes and affective responses to enhance understanding and retention. By aligning the VEs with CAMIL principles, the prototype aims to foster both procedural knowledge and deeper conceptual insight.

5.2.1. Titration training lab

The first VE (Figure 3) is a practical lab simulation that recreates a real-world acid-base titration experiment, emphasizing procedural skill development, an essential skill in chemistry lab practices. The simulation is designed to allow users to engage in the step-by-step titration process within a safe and controlled virtual setting. The VE was designed to allow users to interact with virtual lab equipment using handheld controllers, enabling them to pick up and manipulate items such as burets, flasks, and

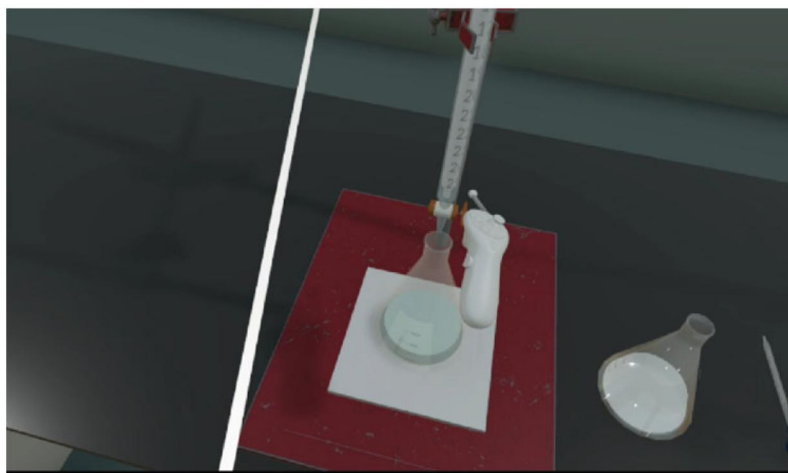


Figure 3. Snapshot of the titration training lab VE.

indicators. Clear visual instructions were presented through a screen within the VE, guiding learners through each procedural step. Users were expected to follow these textual prompts to complete the experiment accurately and safely.

5.2.2. Titration molecule exploration experience

The second VE (Figure 4) aimed to deepen learners' understanding of the chemical principles underlying the titration process by placing learners virtually inside the titration flask at a molecular level. In this, users were to observe dynamic, 3D molecular animations illustrating how acid and base molecules interact and react during titration. The VE was supported by rich visual detail and navigation controls, allowing learners to explore molecular interactions from multiple angles. A short video was integrated within the VE in the background as a secondary source of information.

5.3. Co-designer evaluation

Following the development of the initial prototype, it was evaluated by 18 co-designers, including some participants who had also contributed to the earlier co-design enquiry sessions, alongside newly recruited co-designers. We conducted interviews with 18 co-designers to explore the design requirements of VR experiences for post-primary education. Aiming to identify the Design Requirements (DRs) of VR for post-primary education, we engaged with co-designers to evaluate the prototype, followed by a semi-structured interview. We adapted our semi-structured interview structure from a similar study conducted by Makransky and Petersen (2021). As such, the initial prototype was evaluated by 18 co-designers, all of which have also participated in Phase One, including post-primary chemistry teachers ($n=5$), research expert in chemistry ($n=1$), researchers in chemistry education ($n=3$), expert in computational chemistry ($n=1$), researcher in educational technology ($n=1$), researcher in computational chemistry ($n=1$), researcher in STEM education ($n=1$), research experts in computer science ($n=2$), research expert in HCI ($n=1$), and VR developers ($n=2$). First, co-designers engaged with the VEs for 10–20 min, followed by a semi-structured interview. Interviews were 30 to 45 min long. All interviews were audio-recorded and transcribed by one researcher. The transcriptions were reviewed for accuracy and completeness by another researcher.

5.4. Phase two findings: Stakeholders' design requirements (DRs)

In this phase, we aimed to address the Design Requirements (DRs) for deploying VR in post-primary settings. We collated the qualitative data from the interview transcriptions and clustered co-designers' DRs using affinity mapping. Figure 5 provides a visual representation of the affinity map generated from the Phase Two analysis.

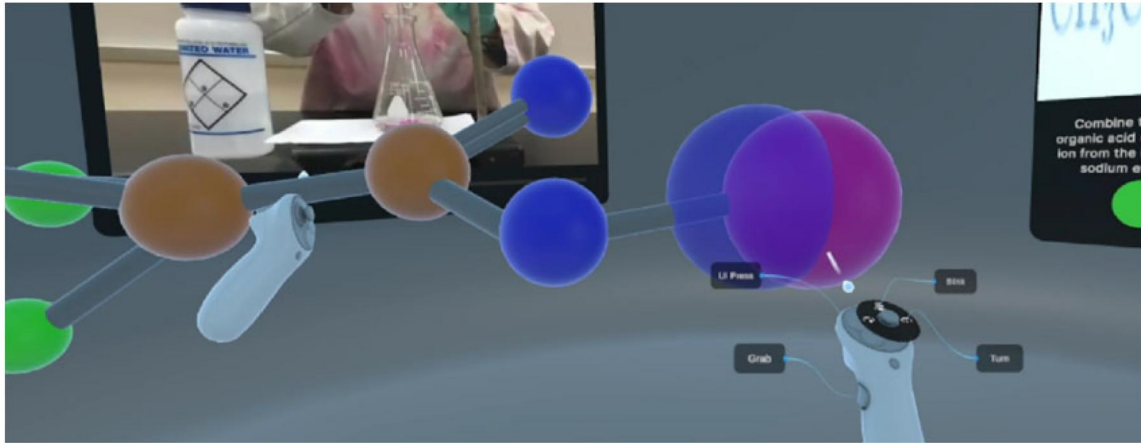


Figure 4. Snapshot of the molecule exploration VE featuring a conceptual design of the molecules inside the titration flask, illustrating acid-base interactions.

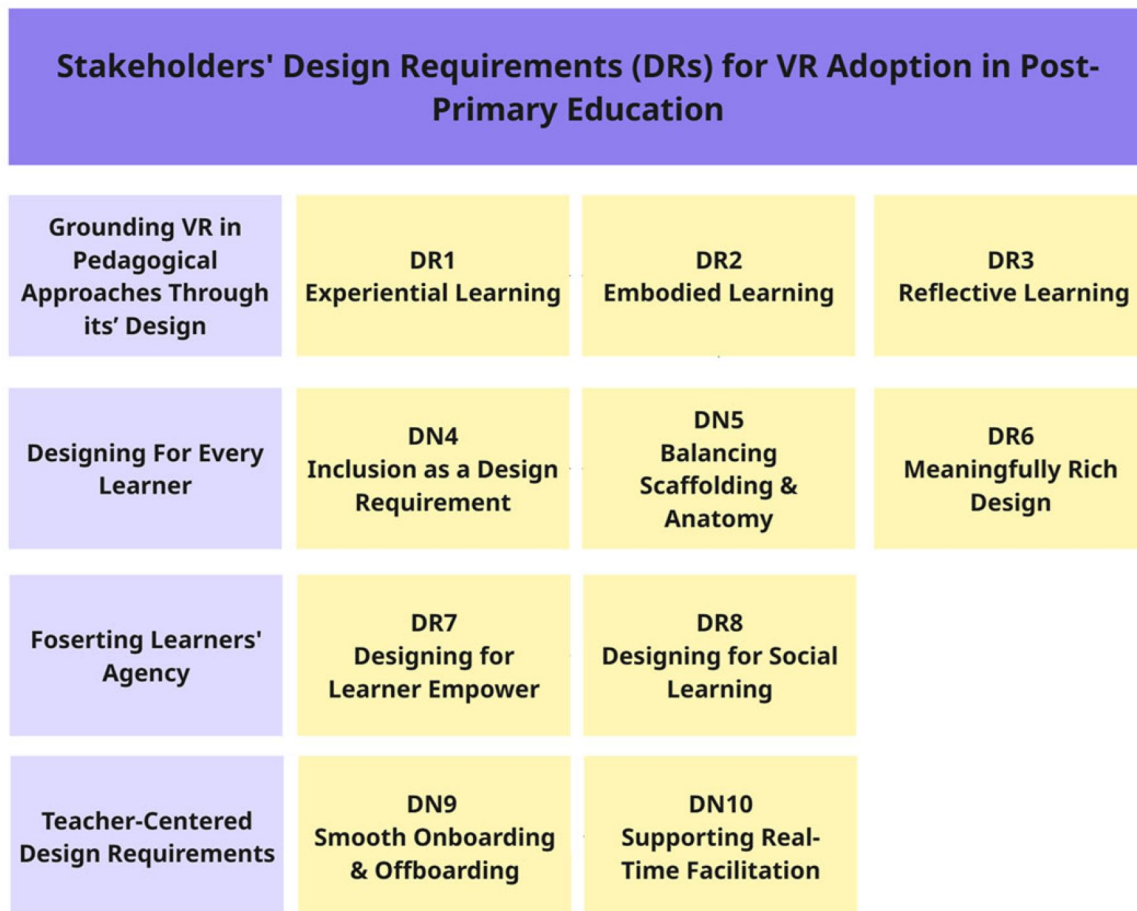


Figure 5. Affinity map of stakeholders design requirements (DRs).

5.4.1. Grounding VR in pedagogical approaches through its design

Throughout the interviews, co-designers stressed that VR can (and must) be grounded in robust pedagogical approaches. Crucially, co-designers emphasized that VR is not limited to a single learning theory; its affordances allow for the integration of multiple approaches within the same experience. As such, three pedagogical approaches emerged as key DRs to ensure that VR in post-primary education is sound on a pedagogical level.

5.4.1.1. DR1 – Experiential learning. Co-designers highlighted the benefit of VR (among other multi-media modalities) is its ability to focus on “doing” rather than simply “thinking” or “observing.” In such a way, co-designers emphasized the importance of designing VR experiences that mimic real-world interactions and approaches, thereby enhancing learners’ ability to transfer skills into real-world contexts. Particularly, experiences should be designed in a way that recreates the “*feeling of the real lab*” [E2, Interview, Ph2] experience, highlighting that interaction mechanisms (e.g., accurate hand movements, realistic resistance, etc.), sequence of actions (i.e., authentic processes) and feedback (including multi-sensory cues) in VR must mirror authentic laboratory practice.

5.4.1.2. DR2 – Embodied learning. Co-designers emphasized that VR’s strength lies in engaging the body directly in the learning process. One co-designer reflected, “*It’s amazing how you do an experiment without really thinking of the practical side of it. You’re just doing it*” [E11, Interview, Ph2]. In contrast to conventional instruction, where students must imagine invisible processes or recall step sequences, VR allows those concepts to be enacted through movement and feedback. Co-designers saw this as particularly valuable for adolescents, who often learn most effectively by combining motor activity with conceptual reasoning. Done well, embodied interaction not only could sustain engagement but also support deeper conceptual learning, ensuring that students remember processes as something they were actively part of.

5.4.1.3. DR3 – Reflective learning. Many co-designers emphasized that reflective learning is paramount in adolescent learning; yet, unlike experiential or embodied learning, where VR naturally excels, reflection does not emerge organically in immersive environments. As such, reflection must be deliberately designed within VR experiences for post-primary education. These could take different shapes in VR. Some co-designers advocated for a prediction–action–feedback loop, where learners could pause to predict “*what would happen next*” [E17, Interview, Ph2] and then carry on reflecting on “*what they noticed*,” encouraging learners to pause and make sense of their actions. Reviewability was also seen as an essential design requirement: the ability to replay key moments, compare attempts, and receive error-aware cues, turning mistakes into opportunities for deeper learning. As such, co-designers highlighted that reflection in VR should not be a postscript but an integral interaction mechanism, embedded within VR experiences for adolescent learning.

5.4.2. Designing for every learner

Co-designers repeatedly emphasized that VR for post-primary education must be inclusive by design, ensuring all students can participate meaningfully regardless of ability, pace, or learning style.

5.4.2.1. DR4 – Inclusion as a design requirement. This aspect of the VR experience had previously been identified as a stakeholder need (DN5) but was articulated more clearly here as a design requirement. Schools cater for diverse learners, and activities are expected to enable equal participation by all students, highlighting that it is “*crucial to include those who have additional needs or disabilities*” [E16, Interview, Ph2]. As such, co-designers repeatedly emphasized that inclusivity must be designed “*by default*” [E18, Interview, Ph2] if VR is to be successfully deployed in post-primary schools. The way co-designers conveyed this need into design requirements took many shapes. First, co-designers pointed out that the speed of movement of elements with VR experiences must be controllable, as co-designers criticized the prototype where “*students on the autism spectrum might find this nauseating*” [E1, Interview, Ph2]. Others described how “*the liquid’s change of color moved way too fast*” [E5, Interview, Ph2], leaving them feeling they “*didn’t have any control*” [E3, Interview, Ph2]. Adjustable pacing features (i.e., pausing, replaying, or skipping steps) were therefore seen as essential for supporting diverse learners. Finally, ensuring multi-platform access, for example, providing versions viewable on laptops or tablets, was seen as crucial for extending participation and enabling equitable classroom use.

5.4.2.2. DR5 – Balancing scaffolding & autonomy. Co-designers emphasized that the design of VR experiences should carefully balance guided instruction with opportunities for independent exploration.

As one co-designer explained, it should be *“like a mix of both. You give them some guidelines, you give them some instructions, but you also give them the freedom to explore and make their own mistakes”* [T14, Interview, Ph2]. This perspective reflects the dual need to scaffold novice learners while still fostering agency and curiosity. Co-designers also highlighted the value of differentiated learning pathways within the same experience to accommodate varying levels of prior knowledge. One expert suggested layered modes in which *“beginners show labels, [while] advanced removes them”* [E6, Interview, Ph2] with intermediate settings for learners consolidating earlier knowledge acquisition.

5.4.2.3. DR6 – Meaningfully rich design. Co-designers emphasized that while VR experiences should be engaging, richness must serve a clear pedagogical purpose rather than introduce distraction. One co-designer highlighted that developers *“cannot put in too much like stuff around your room, that [would] just ... draws attention away from the things that you really need to interact with”* [E13, Interview, Ph2]. Many co-designers commented that excessive visual or auditory detail risks overwhelming learners and diluting the learning goal. Instead, richness should be meaningful, adding contextual cues and interactive elements that reinforce core concepts. Whilst developers in this prototype iteration made every effort to break down steps and produce clear designs, co-designers highlighted the need for higher visual clarity, commenting that students would need clearer color transitions, atom labeling, more visible graduations, and larger text to ensure learners capture the visual cues they need to learn.

5.4.3. Fostering learners’ agency

Co-designers emphasized that VR should not only guide learners through tasks but also empower them to take ownership of their learning, both as independent problem-solvers and as collaborators engaging with peers.

5.4.3.1. DR7 – Designing for learner empowerment. Co-designers emphasized that VR should give learners a sense of empowerment by providing immediate and tangible feedback. Auditory, haptic, and visual cues were repeatedly highlighted as mechanisms for reassurance and motivation. Co-designers noted that controller vibrations would let students *“feel that they are touching elements”* [E18, Interview, Ph2], while confirmatory sounds or subtle effects would provide the feedback learners need to reinforce progress. Visual prompts were seen as equally vital, with arrows and on-screen indicators helping students stay oriented so students *“can’t feel lost”* [T14, Interview, Ph2], and tools like a *“little pH meter in the corner”* [E10, Interview, Ph2] offering real-time progress tracking. Encouraging phrases like *“Good job!”* or *“You’re almost there!”* [T8, Interview, Ph2] were suggested as lightweight but impactful motivators. Several co-designers advocated for gamified elements to transform routine repetitive tasks into meaningful engagement, for example, awarding recognition for accuracy and precision.

5.4.3.2. DR8 – Designing for social learning. Co-designers stressed that VR should not isolate learners but instead complement the inherently social nature of classroom practice. One suggested, *“Maybe you can do a multiplayer feature so that a group of students can experiment together, which will be a great way for them to collaborate and learn from each other”* [T15, Interview, Ph2]. Co-designers saw collaborative features as a way to support peer discussion, collective problem-solving, and reciprocal teaching, extending the benefits of the lab environment into the virtual space. Beyond synchronous multiplayer, asynchronous options were suggested. Such asynchronous collaboration may include activities such as sharing results, comparing outcomes, or annotating work.

5.4.4. Teacher-centered design requirements

While much research on educational VR focuses on designing for students (Hamash & Tiernan, 2024; Makransky & Petersen, 2021; Van Dinther et al., 2023), most co-designers stressed that teachers are the pivotal stakeholders who ultimately determine whether VR succeeds or fails in the classroom. Designing for teacher facilitation is therefore essential, not only to ease orchestration and classroom management, but also to ensure that VR integrates seamlessly into existing teaching practices.

5.4.4.1. DR9 – Smooth onboarding & offboarding. Throughout the interviews, co-designers emphasized the importance of clear guidance on how teachers could guide learners on entering and exiting the VR experience. One co-designer noted that learners may need “a 10–15 min snippet as a teaser” [E14, Interview, Ph2] before the VR activity commenced, to prepare learners appropriately before entering VR. Equally important, co-designers highlighted the need for structured debriefing, with a suggestion that after learners exit VR, teachers would “sit with them and ask them some questions about what they learned” [T18, Interview, Ph2]. These insights highlight that smooth onboarding and offboarding are not logistical details but pedagogical touchpoints: how students enter and exit VR determines whether the experience reinforces, rather than disrupts, classroom learning.

5.4.4.2. DR-10 – Supporting real-time facilitation. Co-designers stressed that VR must be designed to support teachers in actively guiding and evaluating student learning, rather than leaving them on the sidelines. They called for a variety of embedded assessment methods, including in-VR prompts for formative feedback and short quizzes at the end for summative checks. As one co-designer suggested, “I think having some kind of a test in the end would be good. Like, you know, ‘What’s the endpoint of the titration?’” [E2, Interview, Ph2]. Furthermore, the inclusion of real-time tracking tools could provide teachers with actionable data on student performance. Co-designers proposed metrics such as time taken to achieve the important tasks, mistakes, and the number of correct steps completed, which one teacher described as “a brilliant oversight for teachers because in terms of assessment, what we need is data” [T7, Interview, Ph2]. As such, VR should be designed not only to assess students directly, but also to equip teachers with the analytics and visibility they need to facilitate, intervene, and adapt instruction in real time.

6. Phase three: Advanced prototype

Following the feedback obtained from Phase Two, the advanced prototype (Phase Three) was developed, integrating improvements in interaction design, instructional flow (Figure 6), progress and guideline bars (Figure 7), and visual fidelity (Figure 8). The advanced prototype was evaluated by 83 co-designers (including 42 new co-designers who have not engaged in any of the previous Phases) who included: post-primary students ($n = 10$), post-primary chemistry teachers ($n = 4$), pre-service chemistry teachers ($n = 4$), chemistry lab technicians ($n = 1$), parents ($n = 2$), as well as subject experts from relevant disciplines, including HCI, education, and chemistry ($n = 21$). Data collected included a survey, interviews, in-app data metrics, and observational notes which were captured while users engaged with the prototype. These data provided insights into user experience, engagement, and the practical deployment of the advanced prototype.

6.1. Advanced prototype design & development

While Meta’s Building Blocks proved excellent for creating the initial prototype, as they allowed for rapid experimentation and early design validation, they no longer provided the necessary flexibility and control as the design requirements expanded. Therefore, a new prototype was developed from scratch using Unity 6 and the Unity XR Interaction Toolkit. Aiming to meet as many DNs and DRs as realistically possible, Table 2 presents the features embedded in the advanced prototype, and the DNs and DRs each feature aims to meet. At the end, the advanced prototype comprised four VEs, where co-designers engaged with these VEs in the following sequence: the Tutorial VE, the Titration Training Lab VE, the Titration Molecule Exploration VE, and finally, the Free Exploration VE.

6.2. Co-designer demographic & background information

The advanced prototype was evaluated by 83 co-designers (male = 40 (48.20%), female = 43 (51.81%)) aged from 14 to 61 years ($M = 28.43$, $SD = 9.12$), with the following breakdown:

Post-primary chemistry teachers ($n = 2$, who participated in Phases One and Two) and pre-service chemistry teachers ($n = 4$).

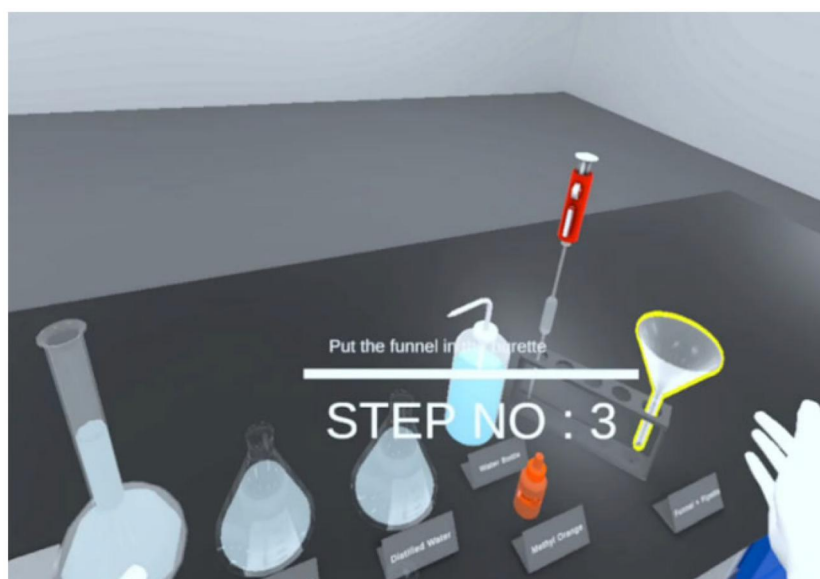


Figure 6. Snapshot of the titration training lab VE featuring the multimodal feedback (visual cues (highlight effect, text prompts), audio guidance).



Figure 7. Snapshot of the free exploration VE featuring progress bar and guideline bar.

Subject experts, researchers and practitioners ($n = 63$): HCI experts ($n = 18$), education experts and academics ($n = 24$), chemistry laboratory senior technical officer ($n = 1$), VR developers ($n = 3$), and VR and computer science practitioners ($n = 10$), and chemistry education experts ($n = 7$).

Post-primary students ($n = 10$): ages ranged from 14 to 18 years (male = 6 (60%), female = 3 (30%), preferred not to disclose = 1). Of which, three students reported having no prior experience using VR, and 7 have used VR before (at least once). On a 5-point Likert Scale, most students reported themselves as “Somewhat Confident” with no one choosing “Very Confident.”

Parents ($n = 2$, male = 1, female = 1): One parent reported having no prior experience with VR, and the other reported having good experience using VR.

6.3. Evaluation procedure & data collected

Considering the unique cohort of key stakeholders (i.e., students, parents, teachers, and subject experts), we needed to adapt the evaluation procedure (and tools used) to best capture their feedback and evaluation.

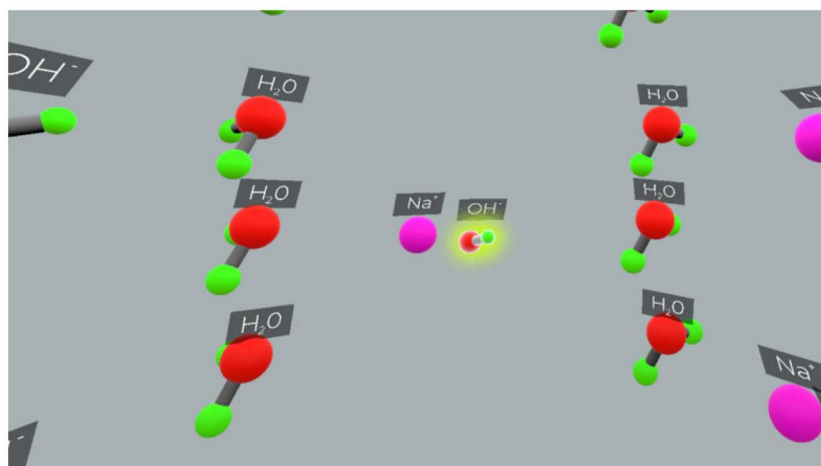


Figure 8. Snapshot of the molecule exploration VE featuring a conceptual design of the molecules inside the titration flask, illustrating user interactions with chemical molecules.

6.3.1. Procedure & data collection – Teachers & subject experts

Teachers and subject expert co-designers were invited to engage with the advanced prototype. Co-designers were asked to take a break after engaging with two VEs to minimize the risk of any adverse effects such as motion sickness and disorientation (Szpak et al., 2022). Furthermore, one researcher with a background in education and experience in VR design and development recorded qualitative observatory notes during co-designers' prototype evaluation sessions focusing on participants' behaviors, interaction patterns, any technical notes related to hardware issues or software issues, and any notable moments of confusion, engagement, or hesitation whilst interacting with the advanced prototype. On average, each testing session generated approximately one to two pages of notes, depending on the length and complexity of the user interaction. After co-designers concluded the evaluation session, they were invited to fill out a survey covering the following dimensions of their experience:

- The User Experience Questionnaire (UEQ) (Schrepp et al., 2017) explores 26 adjective pairs using a 7-point semantic differential, focusing on attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty.
- The NASA Task Load Index (NASA-TLX) (Hart & Staveland, 1988) evaluates cognitive load over five dimensions using a 7-point Likert scale.
- The Health and Safety scale, adapted from (Southgate, 2023), is a questionnaire designed to measure awareness of health and safety practices. In this study, it was modified to a 7-point Likert scale to assess co-designers' familiarity with VR-related health and safety procedures.
- The User Engagement Scale (UES) (O'Brien et al., 2018) was adapted to measure co-designers' ratings of enjoyment, immersion, curiosity, and perceived control using a 7-point Likert scale.
- The Sense of Presence was also captured by adapting 2 questions from the literature (Witmer & Singer, 1998). Co-designers responded using a 7-point Likert scale.
- The Simulation Effectiveness Tool – Modified (SET-M) (Leighton et al., 2015) was adapted to measure co-designers' views on the usefulness and contextual relevance of the advanced prototype.

Finally, co-designers were invited to engage in a semi-structured interview after they had filled out the survey. These interviews aimed to gain rich contextual insights into VR design and the realistic deployment of VR within post-primary settings.

6.3.2. Procedure & data collection – Students

Students were invited to engage with the advanced prototype. Aiming to minimize potential adverse effects of interacting with VR [73], students were asked to take frequent breaks between VEs. Similarly to the approach we undertook with teachers and subject experts, one researcher with a background in education and experience in VR design and development recorded qualitative observatory notes during

Table 2. Advanced prototype features mapped against aligned DNs & DRs.

Area of application	Prototype feature	Aligned DNs	Aligned DRs	Details
Enhancements That Support VR Experience Management	Health, Safety & Hygiene Protocol (New)	DN11, DN12	DR4, DR9, DR10	We introduced a written health, safety, and hygiene protocol (to be deployed for teachers' use) that covers practices before, during, and after VR use, aiming to include this as a practical aid for real-world classroom rollout.
	Teacher Data Dashboard (New)	DN7, DN6,	DR5, DR7, DR10	Generated from learners' interactions, the dashboard captured time spent per titration stage and frequency of the "help" feature usage. This was incorporated in the aims of allowing teachers to monitor their learners' progress and offer tailored guidance and feedback.
Enhancements That Directly Measure or Add Feedback on Student Progress	Progress Bar (New) Quizzes (New)	DN3, DN6 DN4, DN7	DR5, DR7 DR3, DR5, DR6	The progress bar demonstrates to learners where they are in the process. Short interactive quizzes were added to the VEs as a form of formative assessment, providing immediate feedback on students' learning.
	Student Data Dashboard (New)	DN7, DN6, DN5	DR5, DR3, DR5, DR7, DR10	Generated from learners' interactions, the dashboard provides them with feedback on the time spent on each stage and the number of times the "help" feature was used at each stage.
VE-Specific Enhancements	Tutorial VE (New)	DN6, DN8,	DR9	A new VE was developed to introduce users (teachers and learners) to essential VR interactions, addressing varying levels of prior VR experience and reducing barriers that had previously disrupted engagement.
	Titration Procedure VE (Revised)	DN1, DN2, DN4, DN6, DN8, DN9, DN10	DR1, DR2, DR5, DR6, DR7	In response to co-designers' feedback in Phase Two, the VE experience was redesigned to precisely match the Professional Development Service for Teachers (PDST) Chemistry Laboratory Manual for Teachers (Professional Development Service for Teachers, 2025). Additionally, we enhanced the 360° visualization of the NaOH solution in water to help learners visually see the subsequent effects of chemical interactions.
	Molecule Exploration VE (Revised)	DN1, DN3	DR2, DR6	Replaced passive molecule observation in this VE with interactive molecules to encourage active exploration.
	Free Titration Exploration VE (New)	DN2, DN5, DN6, DN8, DN9	DR1, DR5, DR7, DR4	This new VE allows learners to practise performing acid-base titrations independently, following the procedure learned in the Titration Training Lab VE. No guidance is provided by default; however, learners can access help via a "help" button.
Enhancements That Affect The Entire VR Experience	Optimisation & Interaction Refinement (Revised)	DN4, DN5, DN11, DN12	DR3, DR4, DR6, DR9	We revised VE content to minimize adverse effects such as eye strain, lag, and delay. Interaction mechanisms were also revised so that it is consistent and intuitive across the entire experience. All simulations of chemical liquids were redesigned to help learners observe the changes better.
	Scaffolding & Guidance (Revised & New)	DN6, DN7, DN1, DN2, DN3	DR1, DR2, DR3, DR4, DR6, DR7, DR5	Added a more structured, step-by-step guidance with multimodal feedback, including atom labeling, visual cues, scaffolded prompts, and audio guidance. We also added guideline UI panels, audio descriptions, pH progress bars, and an expanded introduction to explain laboratory instruments and their purposes.
	VE Content Richness & Design (Revised)	DN1, DN3,	DR2, DR6,	Refined the VE content design by removing distracting elements. Aiming to produce an experience closer to the real-world one, the graphics were redesigned to be more realistic (i.e., true-looking glassware).
	Spatial Awareness (New)	DN5, DN11	DR4, DR6	Incorporated spatial sound within VEs, aiming to enhance users' immersion and spatial awareness.

co-designers' prototype evaluation sessions, aiming to analyze students' behaviors, reactions, and interactions with the prototype. On average, each testing session generated approximately one to two pages of notes, depending on the length and complexity of the user interaction. In addition, the prototype captured in-app interaction metrics as students engaged with the prototype, including the time spent in each stage and the number of times the "help" feature was used.

Once students completed the VR session, they were asked to fill out a survey. The survey was adapted from the teachers and subject expert survey so that the terminology is made simpler for students. The survey included the measures mentioned in Section 6.3.1, including the UEQ for user experience, NASA-TLX for cognitive load, UES for user engagement and enjoyment, and sense of presence. Following completion of the survey, students took part in a semi-structured interview intended to gather their perspectives on the advanced prototype, focusing on their experiences of its use and their perceptions of its role in relation to subject-related knowledge and skills. On average, students took around 50 min to engage with the prototype and the short survey, while interviews lasted between 15–35 min.

6.3.3. Procedure & data collection – Parents

Parents first watched their children engage with the advanced prototype. Afterwards, parents were welcome to experiment with the prototype to obtain a direct experience with VR. Finally, parents participated in semi-structured interviews to capture their perspectives on the use of VR for their children's learning, including perceived benefits, concerns, and expectations regarding its use in schools. On average, interviews lasted between 10–15 min.

6.4. Data analysis

In total, we analyzed the survey data, interview transcripts, and observation notes. As for interviews, we were only able to conduct interviews with 28 co-designers due to their time constraints and availability. Those who took part in interviews included chemistry teachers in post-primary education ($n = 2$), pre-service chemistry teachers ($n = 4$), post-primary students ($n = 10$), Parents ($n = 2$), researchers in chemistry education ($n = 6$), researchers in education ($n = 9$), and researchers within the HCI discipline ($n = 4$). All interviews were transcribed by one researcher verbatim then corroborated by another researcher.

Quantitative (survey) and qualitative (interviews and observation notes) data were analyzed using a deductive framework aligned with the five survey domains (i.e., user experience, user engagement, enjoyment and presence, cognitive load, perceived usefulness and alignment to context, and health, safety and hygiene protocol (Gale et al., 2013)). We took a deductive approach to the thematic analysis. One researcher coded the raw data, and a second researcher interrogated the initial codes, ensuring that the codes were appropriately reflective of the data. Then, the two researchers reviewed and critically discussed the themes and underlying codes until an agreement was reached. Data were coded to these domains and synthesized to identify convergences, divergences, and explanatory context for the survey results. Representative excerpts are presented to illustrate domain-specific patterns and exceptions.

6.5. Phase three: Advanced prototype evaluation

The results from the survey, interviews, and the researcher's observation notes were organized to address the following themes: (i) User Experience, (ii) User Engagement, Enjoyment & Presence, (iii) Cognitive Load, iv. Perceived Usefulness & Alignment to Context, and v.

6.5.1. User experience

The UEQ (Schrepp et al., 2014) captures the users' experience on a -3 to $+3$ Likert scale. Across the board, almost all ratings report a benchmarking of "excellent" (i.e., mean value above 2.00) with a few exceptions where co-designers reported a benchmarking of "good" (i.e., mean value between 1.50 and 2.00), specifically: subject experts' ratings on dependability, teachers rating on stimulation and novelty.

Table 3. UEQ mean (M) and standard deviation (SD) of teachers, subject experts and student ratings.

Category	Item	Teachers' ratings (−3 to +3 Likert scale)	Subject experts' ratings (−3 to +3 Likert scale)
Task-related (pragmatic) qualities	Perspicuity	M = 2.07 (SD = 0.43)*	M = 2.10 (SD = 0.86)*
	Dependability	M = 2.18 (SD = 0.20)*	M = 1.98 (SD = 0.65)
	Attractiveness	M = 2.71 (SD = 0.18)*	M = 2.53 (SD = 0.64)*
	Efficiency	M = 2.25 (SD = 0.27)*	M = 2.12 (SD = 0.66)*
Non-task-related (hedonic qualities)	Stimulation	M = 1.82 (SD = 2.29)	M = 2.44 (SD = 0.77)*
	Novelty	M = 1.79 (SD = 1.20)	M = 2.34 (SD = 0.79)*
	Students' ratings (4-point Likert scale)		
Task-related (pragmatic) qualities	Ease of understanding the activity	M = 3.7 (SD = 0.42)	
	Ease of use	M = 3.8 (SD = 0.42)	
	Clarity of instructions	M = 3.9 (SD = 0.32)	

Items marked with “*” to indicate a benchmark of “excellent” in accordance with the questionnaire.

Table 3 presents the mean ratings of UEQ sub-items per user group (i.e., teachers, subject experts, and students). Overall, these results indicate that co-designers found the final prototype usable, appealing, efficient, and generally, well-received.

Qualitative data aligned with the quantitative user-experience indicators; several co-designers described the experience in terms that speak to a high level of environmental coherence, for example characterizing it as “*realistic ... it didn't feel like in a virtual environment*” [E2, Interview, Ph3]. This suggests more than surface fidelity; it indicates a reduction in “interface awareness,” where attention is allocated to the activity itself rather than to managing the mediation of VR. This was highlighted by a student who mentioned they prototype helped them stay (“*focused on completing the tasks fully and correctly*” [S4, Interview, Ph3]), a comment from one of the parents supported this concept “*my son was very focused on learning the titration skill throughout this VR experience*” [P1, Interview, Ph3]. Observational data supports this reading, noting that the workflow was readily navigable and that “*it seemed very easy for the user to follow the instructions and complete all required tasks*” [T26, Observations, Ph3]. Such ease of navigational flow allows users to engage with VR seamlessly and sustain momentum of engagement.

At the same time, in some interviews, co-designers highlighted usability frictions and why they matter for VR-based instructional experiences. In tasks requiring repeated actions, one co-designer pointed to the absence of progress feedback, while the VE instructed users to add five drops, the lack of a drop counter left users uncertain about completion status “*we don't know how many times we still need to add*” [E4, Interview, Ph3]. Without a visual representation of the task counter, users relied on working memory to track counts, increasing cognitive overload and creating avoidable ambiguity at precisely the moments when the experience is meant to reinforce procedural understanding. Co-designers also raised ergonomics concerns with seated interaction, noting difficulty reaching certain materials (“*found it difficult to reach some of the materials ... you need to make them lower*” [E7, Interview, Ph3] “*placing the items was annoying at times*” [S3, Interview, Ph3]). When key objects sit outside a comfortable reach radius, it introduces a physical access constraint that may disrupt task flow, undermine perceived control, and divert attention from the learning activity toward compensatory posture and reach adjustments.

6.5.2. User engagement, enjoyment & presence

To assess the co-designers' overall enjoyment and engagement, we utilized an adapted version of the User Engagement Scale (UES) (O'Brien et al., 2018), which measured co-designers' ratings of Enjoyment, Curiosity, Immersion, Presence, and Perceived Control Satisfaction using a 7-point Likert scale (and an adapted 4-point scale for students). Across all stakeholder groups, the data reveal a strong pattern of high engagement, enjoyment, and sense of presence when interacting with the prototype (see Table 4).

Qualitative accounts and observational notes converged with the survey results, adding important texture about how engagement was produced in situ. Many co-designers expressed their enjoyment interacting with the VEs, including teachers “*I really thought that was excellent, and I did enjoy it a lot*” [T2, Interview, Ph3] students (“*it was very fun and enjoyable*” [S7, Interview, Ph3]), and parents who watched their children engage with VR and tried the prototype themselves as well, describing the

experience as “really cool” [P2, Interview, Ph3] and “a great experience” [P1, Interview, Ph3]. However, some co-designers highlighted how engagement moved the users’ mindset from simple task completion to enjoyable, natural exploratory play (e.g., “The user enjoyed the process of searching for ions” [T36, Observations, Ph3]). Interview data suggests that this enjoyment was closely tied to perceived interactional fluency: co-designers framed the interface as self-evident “so intuitive! I see a colorful highlight” [E10, Interview, Ph3], indicating that perceptual cues supported rapid action–feedback loops. Co-designers also articulated design ideas aimed at sustaining engagement by shifting them from passive witnessing to active prediction, for example proposing prompts that encourage hypothesis formation (“students could then be predicting the color of the solution before it happens” [E1, Interview, Ph3]). As such, engagement was not merely a reaction to use of VR in its own right but was scaffolded by features that enabled co-designers to anticipate, test, and confirm outcomes, aligning enjoyment with epistemic agency.

Across the stakeholder groups, co-designers expressed their heightened sense of presence and immersion with many quotes in the interviews along the lines of “very interesting; immersive and engaging” [E22, Interview, Ph3] and “it’s like being in the lab” [T4, Interview, Ph3]. Some co-designers explicitly linked engagement to the unusual standpoint of being “inside the flask” [E22, Interview, Ph3]. This was also highlighted by parents where they valued that their child was able to “see what’s happening in the flask,” justifying that it helped them “intuitively know what to do” [P2, Interview, Ph3] during the titration. In this context, immersion functions as a perceptual reconfiguration that renders microscopic or otherwise abstract chemical processes experientially accessible, amplifying attention and curiosity in ways that conventional laboratory settings rarely afford. Co-designers’ accounts indicate that presence was experienced as actionable and agentic: co-designers described an orientation toward directing, probing, and iterating the experimental process rather than watching outcomes unfold. This was not only observed by the researcher; students have also noticed this stating “When I looked at my friends during my breaks, everyone seemed very interested” [S4, Interview, Ph3].

6.5.3. Cognitive load

The Raw NASA Task Load Index (Raw TLX) (Hart & Staveland, 1988) was used to assess users’ perceived workload over five dimensions, calculated as a sum on a 0–100 scale (0 = no cognitive load, 100 = significant cognitive load). Overall, the findings indicate that the advanced prototype imposed a manageable cognitive overload across all stakeholder groups (see Table 5).

The results indicate that co-designers were able to complete the activity without substantial overload. As such, the prototype appears to distribute effort away from continuous cognitive “problem-solving about the interface” and toward the pedagogical task at hand, suggesting a workable balance between instructional complexity and interactional burden. In other words, the system seems to support productive effort, engagement with the chemistry procedure, without escalating into extraneous load driven by interaction friction. The qualitative data help explain the mechanisms through which workload was kept low. Co-designers attributed ease to the prototype’s perceptual and representational affordances: visually salient cues (“the visuals were very attractive and helped me focus” [E8, Interview, Ph3]), sequential scaffolding (“it made it easier to go like this to here, this to here, this to here” [T2, Interview, Ph3]), and environmental coherence (“...because it felt like a real lab... I forgot I was in VR” [E11, Interview, Ph3]). Furthermore, students appreciated the “safe to experiment” approach, as (“being able

Table 4. UES mean (M) and standard deviation (SD) of teachers, subject experts and student ratings.

Item	Teachers’ ratings (7-point Likert scale)	Subject experts’ ratings (7-point Likert scale)
Enjoyment	M = 6.57 (SD = 0.79)	M = 6.56 (SD = 0.78)
Curiosity	M = 6.86 (SD = 0.38)	M = 6.62 (SD = 0.79)
Immersion	M = 6.71 (SD = 0.60)	M = 6.49 (SD = 0.78)
Presence	M = 6.86 (SD = 0.38)	M = 6.81 (SD = 0.38)
Perceived control satisfaction	M = 6.00 (SD = 1.15)	M = 6.46 (SD = 0.93)
Item	Students’ ratings (7-point Likert scale)	
Enjoyment	M = 3.8 (SD = 0.42)	
Interest	M = 3.9 (SD = 0.32)	
Realism	M = 3.2 (SD = 0.63)	

Table 5. Mean (M) and standard deviation (SD) of teachers, subject experts and student ratings of cognitive load.

Item	Teachers' ratings (0–100 scale)	Subject experts' ratings (0–100 scale)
Overall cognitive load	M = 44.6 (SD = 4.0)	M = 23.60 (SD = 16.50)
Item	Students' ratings (on a 1–4 Likert scale)	
Thinking required	M = 2.2 (SD = 0.63)	
Mental tiredness	M = 1.3 (SD = 0.48)	
Instructions were clear	M = 1.1 (SD = 0.32)	
Easy to understand	M = 1.3 (SD = 0.48)	

to mess around safely helped me understand the titration better" [S1, Interview, Ph3]). In here, the ability to make mistakes without consequence and iterative exploration techniques seemed to help students reduce performance pressure; a contributor to cognitive load (Sevcenko et al., 2023). Parents framed VR as a mechanism for redistributing learners' limited attentional resources: by offloading the demands of procedural coordination, the simulation was perceived to create capacity for conceptual reasoning ("when they [students] are less focused on "the technique," VR gives them "more space to think about" the conceptual understanding behind the experiment" [P2, Interview, Ph3]), and that using VR before "real" lab experiments could "remove the mental load of focusing on the procedure" [P1, Interview, Ph3], enabling both teachers and students to prioritize conceptual learning.

However, we identified moments where extraneous load reenters via visual and temporal constraints. In one case, the researcher notes comments on how one teacher expressed their exhaustion as the VE "tired their sight" [T4, Observations, Ph3] when reading instructions in VR. This suggests that legibility is not simply a matter of providing information, but providing it at an appropriate scale, contrast, and reading distance for prolonged use in head-mounted displays. Other causes for strain and load were attributed to tracking and sequencing; recalling steps ("To remember what we did in the first one" [T4, Interview, Ph3]) and coping with uncertainty under time pressure ("Even I was kind of like, wait!" [T2, Interview, Ph3]). While co-designers reported low cognitive load scores in the survey, these remarks suggest that workload may be episodic: most steps are manageable, but specific transition points (e.g., between sub-tasks) can create brief spikes when users must reconstruct the procedure's current state.

6.5.4. Perceived usefulness & alignment to context

To assess the perceived usefulness and contextual fit of the advanced prototype, we administered an adapted version of the Simulation Effectiveness Tool–Modified (SET-M) (Leighton et al., 2015) using a 7-point Likert scale. Co-designers (teachers and subject experts) rated the prototype as highly useful and closely aligned with the post-primary chemistry laboratory curriculum (subject experts (M = 6.47 (SD = 1.47)), teachers (M = 6.32 (SD = 1.20))). Students were also asked to self-assess their understanding of the titration process after using the prototype on a 4-point Likert scale, reporting strong perceived understanding (M = 3.60 (SD = 0.96)). Finally, students indicated their interest in using VR for learning in school; responses were uniformly positive (M = 4.00, SD = 0.00), suggesting high receptivity to classroom integration.

In addition to self-report measures, we analyzed in-app interactions to characterize students' engagement across the titration workflow. Two indicators were extracted for each stage: (a) time spent per stage (completion time), and (b) help-seeking frequency (number of help-button presses, which surfaced contextual hints) (see Table 6). Stage one "Safety Set-Up" was completed rapidly with minimal reliance on help, suggesting that core safety actions were readily interpretable and routinized. Stage two "Apparatus Cleaning" exhibited the greatest between-student variability in completion time, with the highest rate of help requests, indicating that this stage posed the most procedural uncertainty. The subsequent stages, "Titration Preparation" (Stage three) and "Titration (Stage four)," showed comparatively stable completion times alongside low use of the help button, implying more consistent execution once students had transitioned into the main experimental sequence.

Interviews across stakeholder groups converged on a coherent message: the prototype was valued not simply as an engaging VR experience, but as a pedagogically accountable learning environment whose legitimacy depends on making curricular intent, procedural structure, and support mechanisms explicit to learners. Co-designers repeatedly oriented to the importance of curricular grounding as a condition for classroom uptake, emphasizing that alignment should be legible not only to teachers but

Table 6. Students' average completion time across titration stages and frequency of "help" button use.

Stage	Average time spent to complete tasks (in seconds)	Average number of times the "help" button use
Safety set up	M = 27.63 (SD = 24.63)	M = 0.30 (SD = 0.67)
Apparatus cleaning	M = 213.60 (SD = 83.32)	M = 4.60 (SD = 5.70)
Titration preparation	M = 110.65 (SD = 30.28)	M = 2.50 (SD = 2.99)
Titration	M = 78.99 (SD = 28.53)	M = 1.10 (SD = 2.51)

also to learners. One co-designer noted, that the value of VR is particularly useful when a complex topic is first introduced *"VR is good idea to explain [to students] at the beginning..."* [E3, Interview, Ph3]. Similarly, parents commented that *"it would be brilliant if you could go into a virtual lab... and do the techniques"* [P1, Interview, Ph3] before proceeding to the "real" experimentation, providing learners who are underprepared with an opportunity to rehearse procedures in a safe setting. Furthermore, parents saw VR as an opportunity beyond its use as a pedagogical tool, and more into what the use of advanced technologies may offer students in the future (*"a great opportunity that helps [their child] learn better and opens future doors for [their child]"* [P2, Interview, Ph3]), framing the use of VR as a resource with longer-horizon benefits.

This emphasis on interpretability was mirrored in students' accounts of clarity and structure, where the value of VR was articulated through the system's capacity to render a complex procedure learnable through guided sequencing and self-paced enactment. Students described the experience as directly supporting conceptual understanding (*"it helped me understand the acid-base titration"* [S2, Interview, Ph3]), making abstract representations meaningful (*"...made me understand the chemical equation better"* [S5, Interview, Ph3]), and supporting procedural memory (*"helped me remember the order you do everything better"* [S3, Interview, Ph3]).

Additionally, stakeholders valued help features that preserve learner agency while maintaining safety and correctness. Teachers explicitly endorsed an on-demand assistance model, labeling it as a *"fantastic resource for developing those independent learning skills"* [Pre-T2, Interview, Ph3], highlighting that *"they only accessed the help if they needed it"* [T1, Interview, Ph3]. Students not only valued the space of independent completion, but they also highlighted a sense of self-pride when empowering students' learning autonomy (*"it took me through the steps while I did it all by myself"* [S10, Interview, Ph3]). As such, scaffolding seems to have been available without becoming intrusive: support is positioned as a resource for recovery and confidence rather than a constant overlay that can deskill learners or dampen exploration.

7. Discussion & future work

Despite the consistently positive outcomes reported in research on the use of VR in the context of education (Asad et al., 2021; M. Hamash & Tiernan, 2024; Pellas et al., 2020, 2021; Van Dinther et al., 2023), the majority of this work has been situated in higher education and adult vocational and technical training, furthermore, the lack of a practical, realistic bridge between small-scale VR experiments and mainstream adoption of VR in post-primary schools is scarce (Radianti et al., 2020). In this study, we captured the perspectives of 114 co-designers, including post-primary chemistry teachers, pre-service chemistry teachers, post-primary chemistry students, parents, subject experts, and VR developers, across a three-phase process that surfaced Deployment Needs (DNs), articulated Design Requirements (DRs), and evaluated their interaction with an advanced prototype. Echoing the results from other studies, our findings reinforce the efficacy of VR in delivering experiences that support knowledge acquisition, autonomous exploration, and increased engagement and enjoyment (Makransky & Petersen, 2021; Van Dinther et al., 2023). Furthermore, in the context of chemistry, which aligns with prior evidence showing that VEs can significantly improve knowledge retention in science education (G. Chen et al., 2025). Most importantly, VR design can be tailored to adolescent learning needs, for example, by balancing autonomy with guidance, avoiding cognitive overload (Albus et al., 2021; Makransky & Petersen, 2021), in line with cognitive load guidance (Sweller et al., 2019), and designing experiences that are inclusive "by default" to meet the needs of diverse learners across the developmental spectrum (John et al.,

2022), and foster first-person experiential learning and enhance students' ability to understand and explain scientific phenomena through embodied perspectives (Pang et al., 2021).

Yet, deployment remains treated peripherally within the body of research; few studies explicitly involve diverse stakeholders such as teachers, school leaders, and practitioners, despite their pivotal role in determining whether VR can be adopted at scale. Where infrastructural or curricular constraints are mentioned (e.g., Christopoulos et al., 2023; Moon et al., 2025; Ye & Fan, 2025), they are often framed as barriers rather than designable conditions for adoption. By contrast, our findings shift the focus from what VR can do to what VR must have in order to become a mainstream educational tool. We foreground stakeholders' perspectives and systematically translate them into DNs and DRs, offering a concrete pathway for operationalizing VR in schools. In here, we found that "deployability" is not separate from design; it is partly produced by design choices that make VR teachable and governable in classrooms, with minimal inertia and friction in a natural classroom environment. Specifically, our findings underscore a central condition for sustained deployment of VR in post-primary schools: designing for students' learning experiences is necessary but insufficient unless teachers' practical and professional needs are addressed through design. These findings reinforce the view that the impact of VR depends on how its multimodal features are structured to support specific reasoning processes within inquiry-based learning (Chang et al., 2025).

Prior work on classroom VR adoption has documented teacher-facing barriers, including maintaining classroom control, designing and sequencing activities, developing technical competence, and adapting to facilitative, student-centered pedagogies (Hamash et al., 2024; Hamash & Tiernan, 2024; Jiang et al., 2025). This was also echoed in Phase One of our study; teachers' reluctance to implement VR was strongly shaped by the absence of reliable technical guidance and a concrete, school-appropriate protocol addressing health, safety, and hygiene practices—an absence that directly undermined confidence in delivering VR activities under typical classroom conditions. Consistent with this, teachers and other stakeholders evaluated "classroom-ready" VR in terms of the supports that enable professional accountability and orchestration: embedded analytics and assessment methods were positioned as what differentiates a learning VR experience from entertainment; health and hygiene procedures and safety considerations were framed as prerequisites for legitimate use with young learners; and onboarding, offboarding, and debrief were described as pedagogical touchpoints that structure the learning episode rather than as ancillary logistics.

A key insight across all phases of the study was the repeated emphasis on scaffolding, guidance, assessment, and feedback. Even when content was paced and scaffolded through multiple modalities (i.e., auditory narration, text-based prompts, interactive cues, and color-based feedback), co-designers stressed the need for further support. This distinction highlights a critical difference between adolescent learning and prior studies of VR in higher education and adult training (Bacca-Acosta et al., 2022; Chernikova et al., 2020; Huang, 2024), where scaffolding and feedback are often assumed to be minimal or unnecessary. Furthermore, we found that workload is another component that directly affect the success of the VR deployment, particularly for adolescent learning. While co-designers experienced a manageable workload when interacting with VR, small breakdowns can reintroduce extraneous load and undermine flow. This corresponds with recent work showing that signaling and cueing can support recall and aspects of cognitive load in VR, while not automatically reducing extraneous demand (Albus et al., 2021). This explains why micro-level state feedback and perceptual clarity matter for sustained use.

Perhaps the most cited barrier in the context of VR and education is attributed to the cost. However, our findings suggest that this perception deserves nuance. Co-designers pointed out that the cost of consumables and equipment for subjects such as chemistry is already substantial, often pushing teachers to rely on demonstrations rather than allowing students to experiment directly. In the longer term, VR could offer a financially sustainable alternative by enabling repeated, hands-on practice without draining physical resources. Having that said, while low-cost solutions such as Google Cardboard or mobile VR may appeal to schools with constrained budgets, our findings identified DRs such as embodied learning, predictive checks, complex interactions, multimodal feedback, and teacher-facing analytics, cannot be delivered with such low-cost devices.

Finally, across all three phases, ethics and safety operate as the legitimacy threshold for VR with minors. Stakeholders' calls for hygiene procedures, supervision, age appropriateness, and regulation are consistent with prior HCI work documenting that families evaluate children's VR through governance concerns (who controls boundaries, content, and accountability) as well as experiential risks (Jin et al., 2024a). The same holds for privacy: new HMDs can generate sensitive behavioral/sensor traces, and recent peer-reviewed network-level analyses show that children's VR accounts can be exposed to distinct privacy risks, strengthening stakeholders' demand for oversight and policy rather than ad hoc practice (Skulmowski, 2023). In our study, we took a conservative approach on the type of data the app was allowed to collect (i.e., number of times students used the click button, amount of time spent per titration stage). Nonetheless, we recognize that such conservative approach might be disadvantageous in some learning contexts, where further behavioral and interaction insights might be beneficial. As such, privacy, anonymity, and safeguarding must be thoroughly examined before introducing to adolescents, while recognizing that such design decisions may shape whether schools and families will permit the use of VR, and thus whether any learning mechanisms can operate at the scale and duration required for curricular integration.

Looking ahead, Artificial Intelligence (AI) could be embedded to support the deployment of VR in post-primary education by addressing some of the DNs and DRs identified in the study. AI-driven adaptivity could personalize pacing, scaffolding, and feedback in real time, improving inclusivity for diverse learners. Automated analytics could transform raw VR interaction logs into actionable dashboards for teachers, highlighting where students struggle and guiding post-class interventions.

Finally, another reflection based on our findings is the need for "plug-and-teach" authoring VR tool-kit. It is neither realistic nor sustainable for teachers to depend entirely on external VR developers to create each activity. Teachers already operate under heavy workloads, and the time required to co-develop bespoke VR content for every lesson is prohibitive. For VR to become mainstream, teachers need lightweight authoring tools that allow them to assemble labs and activities from pre-built components and deploy them directly to students. Such tools would democratize content creation, reduce reliance on specialist expertise, and accelerate the integration of VR into everyday school practice.

8. Conclusion

This study investigated the realistic adoption of VR in post-primary education through a three-phase, stakeholder-driven process involving 114 co-designers. We identified key Deployment Needs (DNs) and Design Requirements (DRs), and demonstrated their integration in an advanced prototype, showing that effective use of VR depends on multiple intersecting factors, including pedagogical alignment, inclusive design, appropriate scaffolding, meaningful richness of virtual environments, and a shared model of guidance and support between teachers and the technology. By articulating both deployment conditions and design requirements, this work contributes a structured design space that bridges the gap between experimental VR applications and their practical, scalable use in realistic school settings. In doing so, it positions VR not as a standalone novelty, but as a complementary tool embedded within broader teaching and learning processes within a wider socio-technical ecosystem involving pedagogy, teacher facilitation, and institutional constraints.

Despite these contributions, several limitations should be acknowledged. The study is situated within post-primary chemistry education in Ireland, which may limit transferability to other subjects and educational systems. While multiple stakeholders were engaged, student involvement was more limited in earlier phases due to ethical and design constraints. In addition, the evaluation reflects short-term interactions with a research prototype rather than sustained classroom "in-the-wild" integration, and the sample size of student participants remains relatively small. Future work should extend this research through longitudinal classroom deployments and validate the proposed DNs and DRs across diverse subjects, educational contexts, and cultural settings. Further research is also needed to explore scalable implementation pathways, including teacher training, institutional readiness, and infrastructure support, to enable sustainable adoption of VR in schools. Nonetheless, we hope to have contributed to HCI community by providing a multi-stakeholder investigation of VR for adolescent learning and by advancing an integrated understanding of deployment needs and design requirements for realistic

classroom adoption. We offer actionable DNs and DRs that can inform the design of immersive learning environments and support more grounded and scalable VR integration in education.

Notes

1. [co-designer type (T = Teacher, E = Expert, S = Student, P = Parent, M = Managerial team) and Number, Source, Phase Number].
2. <https://unity.com/>.

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Authors' contributions

CRedit: **Mahmoud Hamash**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing; **Peter Tiernan**: Project administration, Supervision, Validation; **Luma Tabbaa**: Validation, Visualization, Writing – original draft, Writing – review & editing; **Gareth W. Young**: Supervision.

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No public data available.

References

- Abuhammad, A., Falah, J., Alfalah, S. F. M., Abu-Tarboush, M., Tarawneh, R. T., Drikakis, D., & Charissis, V. (2021). "MedChemVR": A virtual reality game to enhance medicinal chemistry education. *Multimodal Technologies and Interaction*, 5(3), 10. <https://doi.org/10.3390/mti5030010>
- Al Breiki, M., Al Abri, A., Al Moosawi, A. M., & Alburaiqi, A. (2023). Investigating science teachers' intention to adopt virtual reality through the integration of diffusion of innovation theory and theory of planned behaviour: The moderating role of perceived skills readiness. *Education and Information Technologies*, 28(5), 6165–6187. <https://doi.org/10.1007/s10639-022-11367-z>
- Al Hakim, V. G., Chen, Y.-E., Lin, M.-H., Chang, C.-Y., Wang, J.-H., Chang, C.-K., Zhuang, Y., Yang, S.-H., & Chen, G.-D. (2024). Marrying physical and virtual realms: An embodied, multi-modal approach to situational learning in digital reality. *International Conference on Computers in Education*. <https://doi.org/10.58459/icce.2024.4882>

- Al-Ansi, A. M., Jaboob, M., Garad, A., & Al-Ansi, A. (2023). Analyzing augmented reality (AR) and virtual reality (VR) recent development in education. *Social Sciences & Humanities Open*, 8(1), 100532. <https://doi.org/10.1016/j.ssaho.2023.100532>
- Albus, P., Vogt, A., & Seufert, T. (2021). Signaling in virtual reality influences learning outcome and cognitive load. *Computers & Education*, 166, 104154. <https://doi.org/10.1016/j.compedu.2021.104154>
- Álvarez, I. M., Manero, B., Romero-Hernández, A., Cárdenas, M., & Masó, I. (2024). Virtual reality platform for teacher training on classroom climate management: Evaluating user acceptance. *Virtual Reality*, 28(2), 78. <https://doi.org/10.1007/s10055-024-00973-6>
- Asad, M. M., Naz, A., Churi, P., & Tahanzadeh, M. M. (2021). Virtual reality as pedagogical tool to enhance experiential learning: A systematic literature review. *Education Research International*, 2021, 1–17. <https://doi.org/10.1155/2021/7061623>
- Asoodar, M., Janesarvatan, F., Yu, H., & De Jong, N. (2024). Theoretical foundations and implications of augmented reality, virtual reality, and mixed reality for immersive learning in health professions education. *Advances in Simulation (London, England)*, 9(1), 36. <https://doi.org/10.1186/s41077-024-00311-5>
- Association of Secondary Teachers, Ireland. (2025). *School leaders: Workload, wellbeing and curriculum change*.
- Atabek, O. (2019). *Challenges in integrating technology into education*. <https://doi.org/10.48550/ARXIV.1904.06518>
- Bacca-Acosta, J., Tejada, J., Fabregat, R., Guevara, J., & Kinshuk. (2022). Scaffolding in immersive virtual reality environments for learning English: An eye tracking study. *Educational Technology Research and Development*, 70(1), 339–362. <https://doi.org/10.1007/s11423-021-10068-7>
- Baceviciute, S., Mottelson, A., Terkildsen, T., & Makransky, G. (2020). *Investigating representation of text and audio in educational VR using learning outcomes and EEG* [Paper presentation]. Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (pp. 1–13). Association for Computing Machinery. <https://doi.org/10.1145/3313831.3376872>
- Bailey, J. O., & Bailenson, J. N. (2017). Immersive virtual reality and the developing child. In *Cognitive development in digital contexts* (pp. 181–200). Elsevier. <https://doi.org/10.1016/B978-0-12-809481-5.00009-2>
- Bailey, J. O., You, X., Won, A. S., Ahn, S. J., & MacIntyre, B. (2025). Students' privacy and ethical concerns of using social virtual worlds for online learning. *Proceedings of the ACM on Human-Computer Interaction*, 9(7), 1–22. <https://doi.org/10.1145/3757428>
- Benton, L., & Johnson, H. (2014). Structured approaches to participatory design for children: Can targeting the needs of children with autism provide benefits for a broader child population? *Instructional Science*, 42(1), 47–65. <https://doi.org/10.1007/s11251-013-9297-y>
- Berg, A., Orraryd, D., Pettersson, A. J., & Hultén, M. (2019). Representational challenges in animated chemistry: Self-generated animations as a means to encourage students' reflections on sub-micro processes in laboratory exercises. *Chemistry Education Research and Practice*, 20(4), 710–737. <https://doi.org/10.1039/C8RP00288F>
- Bozkir, E., Günlü, O., Fuhl, W., Schaefer, R. F., & Kasneci, E. (2021). Differential privacy for eye tracking with temporal correlations. *PloS One*, 16(8), e0255979. <https://doi.org/10.1371/journal.pone.0255979>
- Burke, M. (2024). *The chemicals cost crisis*. RSC Education. <https://edu.rsc.org/analysis/the-chemicals-cost-crisis/4018689.article>
- Castaneda, L. M., Bindman, S. W., Cechony, A., & Sidhu, M. (2017). The disconnect between real and virtually real worlds: The challenges of using VR with adolescents. *Presence: Teleoperators and Virtual Environments*, 26(4), 453–453. https://doi.org/10.1162/PRES_a_00310
- Cecotti, H., Huisinga, L., & Peláez, L. G. (2024). Fully immersive learning with virtual reality for assessing students in art history. *Virtual Reality*, 28(1), 33. <https://doi.org/10.1007/s10055-023-00920-x>
- Chang, J., Tang, K.-S., & Park, J. (2025). Epistemic design features of virtual reality-based scientific inquiry across different types of reasoning: A multimodal perspective. *Research in Science Education*. <https://doi.org/10.1007/s11165-025-10309-2>
- Chen, G., Oubibi, M., Zhou, Y., Li, Y., Wang, H., & Gao, Y. (2025). The potential of human-machine collaborative learning in educational virtual environments for knowledge retention in science learners: A decade-long meta-analysis. *Interactive Learning Environments*. Advance online publication. <https://doi.org/10.1080/10494820.2025.2570495>
- Chen, J., Zhao, L., Li, Y., Xie, Z., Wilensky, U., & Horn, M. (2024). “Oh My God! It's Recreating Our Room!” *Understanding children's experiences with a room-scale augmented reality authoring toolkit* [Paper presentation]. Proceedings of the CHI Conference on Human Factors in Computing Systems (pp. 1–17). Association for Computing Machinery. <https://doi.org/10.1145/3613904.3642043>
- Chernikova, O., Heitzmann, N., Stadler, M., Holzberger, D., Seidel, T., & Fischer, F. (2020). Simulation-based learning in higher education: A meta-analysis. *Review of Educational Research*, 90(4), 499–541. <https://doi.org/10.3102/0034654320933544>
- Chimbganda, S., Moyo, T., Moyo, C., Musonda, I., Mwanaumo, E., Onososen, A., & Kalaoane, R. (2024). Barriers to virtual reality implementation for health and safety training of construction workers in Zimbabwe. In *Development and infrastructure in developing countries: A 10-year reflection* (1st ed., pp. 526–536). CRC Press. <https://doi.org/10.1201/9781003483519-57>

- Christopoulos, A., Mystakidis, S., Cachafeiro, E., & Laakso, M.-J. (2023). Escaping the cell: Virtual reality escape rooms in biology education. *Behaviour & Information Technology*, 42(9), 1434–1451. <https://doi.org/10.1080/0144929X.2022.2079560>
- Christopoulos, A., Styliou, M., Ntalas, N., & Stylios, C. (2024). The impact of immersive virtual reality on knowledge acquisition and adolescent perceptions in cultural education. *Information*, 15(5), 261. <https://doi.org/10.3390/info15050261>
- Chua, W. L., Tan, R. X. R., Liaw, S. Y., Koh, Y., Chan, G. W. H., Mikkonen, K., Neo, N. W. S., & Seah, B. (2025). Blending of virtual reality with high-fidelity simulation for interprofessional team training: A mixed methods study. *Nurse Education Today*, 155, 106857. <https://doi.org/10.1016/j.nedt.2025.106857>
- Department for Business, Energy & Industrial Strategy. (2020). *The safety of domestic virtual reality systems (BEIS Research Paper Number 2020/038)*. GOV.UK. <https://www.gov.uk/government/publications/safety-of-domestic-virtual-reality-systems>
- DiSalvo, B. (2016). *Participatory design through a learning science lens* [Paper presentation]. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (pp. 4459–4463). Association for Computing Machinery. <https://doi.org/10.1145/2858036.2858405>
- Duca, A., Constantinescu, G.-G., & Iftene, A. (2024). *Future education: Experimenting with chemical reactions in virtual reality* [Paper presentation]. 2024 International Conference on INnovations in Intelligent SysTems and Applications (INISTA) (pp. 1–6). Association for Computing Machinery. <https://doi.org/10.1109/INISTA62901.2024.10683861>
- Eccles, J. S., & Roeser, R. W. (2011). Schools as developmental contexts during adolescence. *Journal of Research on Adolescence*, 21(1), 225–241. <https://doi.org/10.1111/j.1532-7795.2010.00725.x>
- Fransson, G., Holmberg, J., & Westelius, C. (2020). The challenges of using head mounted virtual reality in K-12 schools from a teacher perspective. *Education and Information Technologies*, 25(4), 3383–3404. <https://doi.org/10.1007/s10639-020-10119-1>
- Gale, N. K., Heath, G., Cameron, E., Rashid, S., & Redwood, S. (2013). Using the framework method for the analysis of qualitative data in multi-disciplinary health research. *BMC Medical Research Methodology*, 13(1), 117. <https://doi.org/10.1186/1471-2288-13-117>
- Georgiou, Y., Tsivitanidou, O., & Ioannou, A. (2021). Learning experience design with immersive virtual reality in physics education. *Educational Technology Research and Development*, 69(6), 3051–3080. <https://doi.org/10.1007/s11423-021-10055-y>
- Hamash, M. A., Mohamed, H., & Tiernan, P. (2024). Developing a new model for achieving flow state in STEAM education: A mixed-method investigation. *Sains Humanika*, 16(3), 101–111. <https://doi.org/10.11113/sh.v16n3.2163>
- Hamash, M., & Tiernan, P. (2024). *Trends in virtual reality research for post-primary education (2013–2024)* [Paper presentation]. 2024 IEEE 13th International Conference on Engineering Education (ICEED) (pp. 1–6). IEEE. <https://doi.org/10.1109/ICEED62316.2024.10923821>
- Hamash, M., Tiernan, P., & Young, G. (2025). Virtual reality in post-primary education research trends from 2013 to 2024: A systematic-narrative review. *Computers & Education: X Reality*, 7, 100123. <https://doi.org/10.1016/j.cexr.2025.100123>
- Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Advances in psychology* (Vol. 52, pp.139–183). Elsevier. [https://doi.org/10.1016/S0166-4115\(08\)62386-9](https://doi.org/10.1016/S0166-4115(08)62386-9)
- Hendriks, N., Truyen, F., & Duval, E. (2013). Designing with dementia: guidelines for participatory design together with persons with dementia. In P. Kotzé, G. Marsden, G. Lindgaard, J. Wesson, & M. Winckler (Eds.), *Human-computer interaction – INTERACT 2013* (Vol. 8117, pp. 649–666). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-40483-2_46
- Hite, R. L., Jones, M. G., Childers, G. M., Ennes, M., Chesnutt, K., Pereyra, M., & Cayton, E. (2019). Investigating potential relationships between adolescents’ cognitive development and perceptions of presence in 3-D, haptic-enabled, virtual reality science instruction. *Journal of Science Education and Technology*, 28(3), 265–284. <https://doi.org/10.1007/s10956-018-9764-y>
- Hobbiss, M. H., & Lavie, N. (2024). Sustained selective attention in adolescence: Cognitive development and predictors of distractibility at school. *Journal of Experimental Child Psychology*, 238, 105784. <https://doi.org/10.1016/j.jecp.2023.105784>
- Huang, H. L. (2024). Exploring the impact of VR scaffolding on EFL teaching and learning: Anxiety reduction, perceptions, and influencing factors. *Multimodal Technologies and Interaction*, 8(10), 85. <https://doi.org/10.3390/mti8100085>
- Jiang, H., Zhu, D., Chugh, R., Turnbull, D., & Jin, W. (2025). Virtual reality and augmented reality-supported K-12 STEM learning: Trends, advantages and challenges. *Education and Information Technologies*, 30(9), 12827–12863. <https://doi.org/10.1007/s10639-024-13210-z>
- Jin, Q., Kawas, S., Arora, S., Yuan, Y., & Yarosh, S. (2024a). *Is your family ready for VR? Ethical concerns and considerations in children’s VR usage* [Paper presentation]. Proceedings of the 23rd Annual ACM Interaction

- Design and Children Conference (pp. 436–454). Association for Computing Machinery. <https://doi.org/10.1145/3628516.3655804>
- Jin, Q., Liu, Y., Yarosh, S., Han, B., & Qian, F. (2022). *How will VR enter university classrooms? Multi-stakeholders investigation of VR in higher education* [Paper presentation]. CHI Conference on Human Factors in Computing Systems (pp. 1–17). Association for Computing Machinery. <https://doi.org/10.1145/3491102.3517542>
- Jin, Q., Liu, Y., Yuan, Y., Han, B., Qian, F., & Yarosh, S. (2024b). *Virtual reality, real pedagogy: A contextual inquiry of instructor practices with VR video* [Paper presentation]. Proceedings of the CHI Conference on Human Factors in Computing Systems (pp. 1–21). Association for Computing Machinery. <https://doi.org/10.1145/3613904.3642510>
- John, A. R., Singh, A. K., Do, T.-T. N., Eidels, A., Nalivaiko, E., Gavvani, A. M., Brown, S., Bennett, M., Lal, S., Simpson, A. M., Gustin, S. M., Double, K., Walker, F. R., Kleitman, S., Morley, J., & Lin, C.-T. (2022). Unraveling the physiological correlates of mental workload variations in tracking and collision prediction tasks. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 30, 770–781. <https://doi.org/10.1109/TNSRE.2022.3157446>
- Jonassen, D. H. (1991). Objectivism versus constructivism: Do we need a new philosophical paradigm? *Educational Technology Research and Development*, 39(3), 5–14. <https://doi.org/10.1007/BF02296434>
- Jones-Roberts, C., & Bechtold, C. (2024). Experiential learning in higher education. *Journal of Technology-Integrated Lessons and Teaching*, 3(2), 53–63. <https://doi.org/10.13001/jtilt.v3i2.8587>
- Kaimara, P., Oikonomou, A., & Deliyannis, I. (2022). Could virtual reality applications pose real risks to children and adolescents? A systematic review of ethical issues and concerns. *Virtual Reality*, 26(2), 697–735. <https://doi.org/10.1007/s10055-021-00563-w>
- Kersting, M., Bondell, J., Steier, R., & Myers, M. (2024). Virtual reality in astronomy education: Reflecting on design principles through a dialogue between researchers and practitioners. *International Journal of Science Education, Part B*, 14(2), 157–176. <https://doi.org/10.1080/21548455.2023.2238871>
- Kim, H. N. (2024). Guidance for best practices in participatory design involving people with visual impairment. *Ergonomics in Design: The Quarterly of Human Factors Applications*, 32(2), 48–54. <https://doi.org/10.1177/10648046211058248>
- Kitson, A., Antle, A. N., Kenny, S., Adhikari, A., Karthik, K., Cimensel, A., & Chan, M. (2024). *I call upon a friend”: Virtual reality-based supports for cognitive reappraisal identified through co-designing with adolescents* [Paper presentation]. Proceedings of the CHI Conference on Human Factors in Computing Systems (pp. 1–18). Association for Computing Machinery. <https://doi.org/10.1145/3613904.3642723>
- Kitzmann, H., Norbistrath, U., Kaivo, A., Sandre, M., & Toomsalu, P. (2024). *VR as a tool in the educational process: requirements and implementation process* [Paper presentation]. 2024 2nd International Conference on Intelligent Metaverse Technologies & Applications (iMETA) (pp. 127–133). Association for Computing Machinery. <https://doi.org/10.1109/iMETA62882.2024.10808100>
- Klingenberg, S., Bosse, R., Mayer, R. E., & Makransky, G. (2024). Does embodiment in virtual reality boost learning transfer? Testing an immersion-interactivity framework. *Educational Psychology Review*, 36(4), 116. <https://doi.org/10.1007/s10648-024-09956-0>
- Leighton, K., Ravert, P., Mudra, V., & Macintosh, C. (2015). Updating the simulation effectiveness tool: Item modifications and reevaluation of psychometric properties. *Nursing Education Perspectives*, 36(5), 317–323. <https://doi.org/10.5480/15-1671>
- Lucero, A. (2015). Using affinity diagrams to evaluate interactive prototypes. In J. Abascal, S. Barbosa, M. Fetter, T. Gross, P. Palanque, & M. Winckler (Eds.), *Human-computer interaction – INTERACT 2015* (Vol. 9297, pp. 231–248). Springer International Publishing. https://doi.org/10.1007/978-3-319-22668-2_19
- Mahmoudi-Dehaki, M., & Nasr-Esfahani, N. (2024). Educational virtual reality (VR): Revolutionizing future academic practices. In S. Mazhar Hussain & A. Nawaz Hakro (Eds.), *Advances in educational technologies and instructional design* (pp. 105–128). IGI Global. <https://doi.org/10.4018/979-8-3693-6407-9.ch005>
- 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., & 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>
- Maloney, D., Freeman, G., & Robb, A. (2021). *Social virtual reality: Ethical considerations and future directions for an emerging research space (version 1)*. arXiv. <https://doi.org/10.48550/ARXIV.2104.05030>
- Maun, R., Fabri, M., & Trevorrow, P. (2021). Adapting participatory design activities for autistic adults: A review. In M. M. Soares, E. Rosenzweig, & A. Marcus (Eds.), *Design, user experience, and usability: Design for diversity, well-being, and social development* (Vol. 12780, pp. 300–314). Springer International Publishing. https://doi.org/10.1007/978-3-030-78224-5_21
- McIntosh, V. (2022). Dialing up the danger: Virtual reality for the simulation of risk. *Frontiers in Virtual Reality*, 3, 909984. <https://doi.org/10.3389/frvir.2022.909984>

- Mercimek, N., & Bulbul, A. (2026). Virtual reality for cultural heritage: A systematic review and the proposal of the AMUX-VR framework. *International Journal of Human-Computer Interaction*, 42(10), 6844–6869. <https://doi.org/10.1080/10447318.2025.2562962>
- Mills, K. A., Scholes, L., & Brown, A. (2022). Virtual reality and embodiment in multimodal meaning making. *Written Communication*, 39(3), 335–369. <https://doi.org/10.1177/07410883221083517>
- Mohamad Ali, N., Mat Nayan, N., Mhd Salim, M. H., & Yakob, Z. (2024). Exploring the awareness of immersive technology: Potential and challenges. *Journal of Information System and Technology Management*, 9(37), 98–108. <https://doi.org/10.35631/JISTM.937008>
- Moon, H., Bautista Isaza, C. A., Gallagher, M., McDaniel, C., Vernier, A., Ican, L., Springer, K., Cohn, M., Bennett, S., Nair, P., Ricard, A., Pochiraju, N., Enriquez, D., Lee, S. W., Ogle, J. T., Newbill, P., & Jeon, M. (2025). “Look at my planet!”: How handheld virtual reality shapes informal learning experiences [Paper presentation]. Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems, 1–8. Association for Computing Machinery. <https://doi.org/10.1145/3706599.3720020>
- O’Brien, H. L., Cairns, P., & Hall, M. (2018). A practical approach to measuring user engagement with the refined user engagement scale (UES) and new UES short form. *International Journal of Human-Computer Studies*, 112, 28–39. <https://doi.org/10.1016/j.ijhcs.2018.01.004>
- Pang, C. G., Devi, S., Wong, D., Cai, Y., & Ba, R. (2021). The use of immersive virtual reality technology to deepen learning in Singapore schools. In Y. Cai, W. Van Joolingen, & K. Veermans (Eds.), *Virtual and augmented reality, simulation and serious games for education* (pp. 45–59). Springer Singapore. https://doi.org/10.1007/978-981-16-1361-6_5
- Pellas, N., Kazanidis, I., & Palaigeorgiou, G. (2020). A systematic literature review of mixed reality environments in K-12 education. *Education and Information Technologies*, 25(4), 2481–2520. <https://doi.org/10.1007/s10639-019-10076-4>
- Pellas, N., Mystakidis, S., & Kazanidis, I. (2021). Immersive virtual reality in K-12 and higher education: A systematic review of the last decade scientific literature. *Virtual Reality*, 25(3), 835–861. <https://doi.org/10.1007/s10055-020-00489-9>
- Professional Development Service for Teachers. (2025). *Senior cycle chemistry – Curriculum resources*. PDST. <https://www.pdst.ie/node/4381>
- Radiani, 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>
- Röwer, H. A. A., Skvortsova, A., Saab, M. M., Hartigan, I., Bausewein, C., Pereira, S. M., Hernández-Marrero, P., Hrdlička, J., Rusinová, K., Loučka, M., Hrdličková, L., Zielina, M., Payne, C., Van Vliet, L. M., Klemmt, M., Afshar, K., & Stiel, S. (2025). Innovations in communication training for medical and nursing students: Virtual reality communication tool for application and evaluation with key stakeholders and students (VR-TALKS) – A study protocol. *PEC Innovation*, 7, 100426. <https://doi.org/10.1016/j.pecinn.2025.100426>
- Sabrie, N., Khan, R., Plahouras, J., Johnston, B. C., Scaffidi, M. A., Grover, S. C., & Walsh, C. M. (2025). Virtual reality simulation training for health professions trainees in gastrointestinal endoscopy. *Cochrane Database of Systematic Reviews*, 9(9), CD008237. <https://doi.org/10.1002/14651858.CD008237.pub4>
- Samala, A. D., Rawas, S., Rahmadika, S., Criollo-C, S., Fikri, R., & Sandra, R. P. (2025). Virtual reality in education: Global trends, challenges, and impacts—game changer or passing trend? *Discover Education*, 4(1), 229. <https://doi.org/10.1007/s44217-025-00650-z>
- Sarıtaş, M. T. (2015). Chemistry teacher candidates acceptance and opinions about virtual reality technology for molecular geometry. *Educational Research and Reviews*, 10(20), 2745–2757. <https://doi.org/10.5897/ERR2015.2525>
- Scavarelli, A., Arya, A., & Teather, R. J. (2021). Virtual reality and augmented reality in social learning spaces: A literature review. *Virtual Reality*, 25(1), 257–277. <https://doi.org/10.1007/s10055-020-00444-8>
- Schrepp, M., Hinderks, A., & Thomaschewski, J. (2014). Applying the User Experience Questionnaire (UEQ) in different evaluation scenarios. In A. Marcus (Ed.), *Design, user experience, and usability. Theories, methods, and tools for designing the user experience* (Vol. 8517, pp. 383–392). Springer International Publishing. https://doi.org/10.1007/978-3-319-07668-3_37
- Schrepp, M., Hinderks, A., & Thomaschewski, J. (2017). Construction of a benchmark for the User Experience Questionnaire (UEQ). *International Journal of Interactive Multimedia and Artificial Intelligence*, 4(4), 40–44. <https://doi.org/10.9781/ijimai.2017.445>
- Sevcenko, N., Appel, T., Ninaus, M., Moeller, K., & Gerjets, P. (2023). Theory-based approach for assessing cognitive load during time-critical resource-managing human–computer interactions: An eye-tracking study. *Journal on Multimodal User Interfaces*, 17(1), 1–19. <https://doi.org/10.1007/s12193-022-00398-y>
- Singh, S., Kaur, A., & Gulzar, Y. (2024). The impact of augmented reality on education: A bibliometric exploration. *Frontiers in Education*, 9, 1458695. <https://doi.org/10.3389/feduc.2024.1458695>
- Skulmowski, A. (2023). Ethical issues of educational virtual reality. *Computers & Education: X Reality*, 2, 100023. <https://doi.org/10.1016/j.cexr.2023.100023>

- Smith, G. F. (1998). Idea-generation techniques: A formulary of active ingredients. *Journal of Creative Behavior*, 32(2), 107–134. <https://doi.org/10.1002/j.2162-6057.1998.tb00810.x>
- Soilis, N., Bhanji, F., & Kinsella, E. A. (2024). Virtual reality simulation for facilitating critical reflection and transformative learning: Pedagogical, practical, and ethical considerations. *Advances in Simulation (London, England)*, 9(1), 49. <https://doi.org/10.1186/s41077-024-00319-x>
- Southgate, E. (2020). *Virtual reality in curriculum and pedagogy: Evidence from secondary classrooms*. Routledge, Taylor & Francis Group.
- Southgate, E. (2022). Teachers facilitating student virtual reality content creation: Conceptual, curriculum, and pedagogical insights. In P. MacDowell & J. Lock (Eds.), *Immersive education* (pp. 189–204). Springer International Publishing. https://doi.org/10.1007/978-3-031-18138-2_12
- Southgate, E. (2023). *Children's evaluation of a virtual reality boating safety education resource* [Paper presentation]. 2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW) (pp. 508–512). IEEE. <https://doi.org/10.1109/VRW58643.2023.00111>
- Stracke, C. M., Bothe, P., Adler, S., Heller, E. S., Deuchler, J., Pomino, J., & Wölfel, M. (2025). Immersive virtual reality in higher education: A systematic review of the scientific literature. *Virtual Reality*, 29(2), 64. <https://doi.org/10.1007/s10055-025-01136-x>
- Sweller, J., Van Merriënboer, J. J. G., & Paas, F. (2019). Cognitive architecture and instructional design: 20 years later. *Educational Psychology Review*, 31(2), 261–292. <https://doi.org/10.1007/s10648-019-09465-5>
- Szpak, A., Richards, A., Michalski, S. C., & Loetscher, T. (2022). *Getting the most out of virtual reality: Evaluating short breaks to reduce cybersickness and cognitive aftereffects* [Paper presentation]. 2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW) (pp. 533–537). IEEE. <https://doi.org/10.1109/VRW55335.2022.00119>
- Tabbaa, L., Ang, C. S., Siriaraya, P., She, W. J., & Prigerson, H. G. (2021). A reflection on virtual reality design for psychological, cognitive and behavioral interventions: Design needs, opportunities and challenges. *International Journal of Human–Computer Interaction*, 37(9), 851–866. <https://doi.org/10.1080/10447318.2020.1848161>
- Thulin, E. J., Stilwell, S., Bitar, M. E., & Heinze, J. E. (2025). Landscape and design considerations for statewide technology-facilitated anonymous or confidential reporting systems in schools to mitigate youth firearm harms. *Journal of Threat Assessment and Management*. Advance online publication. <https://doi.org/10.1037/tam0000254>
- Van Dinther, R., De Putter, L., & Pepin, B. (2023). Features of immersive virtual reality to support meaningful chemistry education. *Journal of Chemical Education*, 100(4), 1537–1546. <https://doi.org/10.1021/acs.jchemed.2c01069>
- Walsh, A., O'Brien, R., McGuire, K., & Power, D. (2025). Exploring virtual reality as a tool for enhancing teaching and learning anatomy to medical students: A feasibility and acceptability study. *Clinical Teacher*, 22(5), e70191. <https://doi.org/10.1111/tct.70191>
- Wei, Z., Liao, J., Lee, L.-H., Qu, H., & Xu, X. (2025). *Towards enhanced learning through presence: A systematic review of presence in virtual reality across tasks and disciplines (version 1)*. arXiv. <https://doi.org/10.48550/ARXIV.2504.13845>
- 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>
- Won, M., Mocerino, M., Tang, K.-S., Treagust, D. F., & Tasker, R. (2019). Interactive immersive virtual reality to enhance students' visualisation of complex molecules. In M. Schultz, S. Schmid, & G. A. Lawrie (Eds.), *Research and practice in chemistry education* (pp. 51–64). Springer Singapore. https://doi.org/10.1007/978-981-13-6998-8_4
- Woodward, J., Alemu, F., E. López Adames, N., Anthony, L., C. Yip, J., & Ruiz, J. (2022). “It Would Be Cool to Get Stamped by Dinosaurs”: Analyzing children's conceptual model of AR headsets through co-design [Paper presentation]. CHI Conference on Human Factors in Computing Systems (pp. 1–13). Association for Computing Machinery. <https://doi.org/10.1145/3491102.3501979>
- Woźniak, M. P., Lewczuk, A., Adamkiewicz, K., Józiewicz, J., Malaya, M., & Ladonski, P. (2020). *ARchemist: Aiding experimental chemistry education using augmented reality technology* [Paper presentation]. Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (pp. 1–6). Association for Computing Machinery. <https://doi.org/10.1145/3334480.3381441>
- Wu, Y., You, S., Guo, Z., Li, X., Zhou, G., & Gong, J. (2023). *MR.Brick: Designing a remote mixed-reality educational game system for promoting children's social & collaborative skills* [Paper presentation]. Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (pp. 1–18). Association for Computing Machinery. <https://doi.org/10.1145/3544548.3581041>
- Yadav, S. (2024). Navigating the virtual classroom with virtual reality: revolutionizing education through immersive experiences. In S. Gökoğlu & F. Erdoğan (Eds.), *Advances in educational technologies and instructional design* (pp. 29–54). IGI Global. <https://doi.org/10.4018/979-8-3693-6030-9.ch002>
- Yahya, L. B., Radid, M., Yaagoubi, M. E., Elmoumou, L., Abouri, O., Naciri, A., & Chems, G. (2025). The effect of immersive simulation-based learning on an anatomy program in nursing education: A quasi-experimental study. *Korean Journal of Medical Education*, 37(3), 281–291. <https://doi.org/10.3946/kjme.2025.341>

- Yang, C., Zhang, J., Hu, Y., Yang, X., Chen, M., Shan, M., & Li, L. (2024a). The impact of virtual reality on practical skills for students in science and engineering education: A meta-analysis. *International Journal of STEM Education*, 11(1), 28. <https://doi.org/10.1186/s40594-024-00487-2>
- Yang, Z., Zhang, Z., Wu, W., & Xia, Z. (2024b). *A study on user's cognitive needs in virtual reality training systems from an embodied cognition perspective* [Paper presentation]. 2024 30th International Conference on Mechatronics and Machine Vision in Practice (M2VIP) (pp. 1–5). Association for Computing Machinery. <https://doi.org/10.1109/M2VIP62491.2024.10746113>
- Ye, R., & Fan, M. (2025). *Exploring the design of a multimodal head-mounted virtual reality for earthquake escape education for primary school students* [Paper presentation]. Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (pp. 1–6). Association for Computing Machinery. <https://doi.org/10.1145/3706599.3719919>
- Zhu, Z., Liu, Z., Zhang, Y., Zhu, L., Huang, J., Villanueva, A. M., Qian, X., Pepler, K., & Ramani, K. (2023). *LearnIoTVR: An end-to-end virtual reality environment providing authentic learning experiences for internet of things* [Paper presentation]. Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (pp. 1–17). Association for Computing Machinery. <https://doi.org/10.1145/3544548.3581396>

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