Design, Capture and Evaluation of a VR Digital Twin Chemistry Laboratory for Undergraduate STEM Education

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Abstract: This paper presents the design, development, and pilot evaluation of a high-fidelity immersive virtual reality (IVR) digital twin of a university chemistry teaching laboratory, developed to support undergraduate students' transition into STEM laboratory work. The experience offers a private, low-stakes, repeatable environment for procedural familiarisation before time-constrained physical laboratory sessions. Developed collaboratively between the Department of Chemistry and a permanent institutional Creative Technology unit, the digital twin replicates the physical teaching laboratory in appearance, spatial layout, and logic. The technical workflow combined HDRI capture and manual 3D modelling, optimised for standalone VR headsets. The experience forms one component of a broader transmedia learning strategy incorporating video, web-based 3D exploration, and physical laboratory practice.

A pilot deployment with 40 first-year undergraduate Chemistry students yielded positive descriptive findings: 90% rated the experience as good or excellent, 75% reported increased confidence, and 77.5% identified it as extremely or very helpful for students with little or no prior laboratory exposure. Consistent with prior research indicating that immersive VR most reliably influences affective dimensions such as confidence and perceived preparedness, these findings are interpreted as descriptive indicators of learner perception rather than evidence of learning gains or direct skill transfer.

Keywords: digital twin; immersive virtual reality; chemistry education; immersive learning; pre-laboratory preparation

1. Introduction

1.1 Opportunity

The transition from secondary education to undergraduate study presents well-documented challenges for students entering STEM disciplines, particularly in relation to confidence, orientation, and familiarity with laboratory environments. Research in chemistry education shows that students arrive at university with highly variable exposure to laboratory practice, shaped by differences in school facilities, curricula, and educational cultures (Leong *et al*., 2021). These disparities are often intensified for students from under-resourced educational backgrounds and for international students navigating unfamiliar laboratory conventions. Within time-constrained undergraduate laboratory sessions, such differences can compound anxiety and reduce opportunities for exploratory learning, independent practice, and error-based reflection.

Immersive virtual reality (IVR) has emerged as one potential response to these challenges, offering immersive environments in which learners can rehearse procedures, make mistakes safely and more privately, and engage in repeated practice prior to higher-stakes physical laboratory work. Systematic reviews of immersive VR in STEM education report positive effects in the majority of studies, particularly when combining spatial presence with guided instruction (Tene *et al*., 2024; Hamilton *et al*., 2021). Research on immersive VR chemistry environments specifically suggests that its strongest and most consistent benefits lie in reducing anxiety and building learner confidence, particularly for novices entering unfamiliar laboratory contexts (Gungor *et al*., 2022). However, evidence from secondary education cautions that while virtual conceptual gains can rival physical ones, safe laboratory behaviours do not always translate directly to the bench (Hu-Au & Okita, 2021). In response to this literature, the present work deliberately avoids positioning VR as a substitute for physical laboratory practice.

Instead, immersive VR is framed as a pre-laboratory familiarisation intervention, intended to support orientation, reduce anxiety, and scaffold procedural understanding before students encounter real materials, risks, and time pressures, as part of wider, transmedia learning design. The digital twin prioritises spatial and contextual fidelity to the specific laboratory in which students will later conduct physical experiments, enabling rehearsal within a matched environment. This contrasts with platform-based virtual laboratories such as Labster, which are explicitly designed to provide institution-agnostic simulations aligned to curricular outcomes and therefore emphasise transferability over site-specific spatial replication (Essoe *et al*, 2022).

While the term “digital twin” is often associated with data-coupled industrial systems, it is used here in a pedagogical sense to denote a high-fidelity virtual representation of a specific laboratory space without live operational linkage. Functionally, the intervention corresponds to what the literature more commonly describes as a Virtual Reality Laboratory or Virtual Training Environment, intended to reduce the immersion gap in laboratory education rather than enable remote experimentation or bidirectional real-time coupling (Silva et al., 2023; Kritzinger et al., 2018). High spatial fidelity is prioritised not for photorealism *per se*, but to support learner orientation and familiarity during initial laboratory encounters. This design rationale is consistent with evidence that immersive presence improves affective outcomes such as motivation and perceived learning value in Immersive VR-based education (Makransky & Petersen, 2018).

The work is also informed by postdigital scholarship that rejects simplistic distinctions between technology-led and pedagogy-led innovation (Fawns, 2022). Rather than treating VR as an isolated intervention, the digital twin is conceived as one component within a broader transmedia learning strategy—understood here, following Jenkins (2006), as the intentional distribution of learning activities across multiple platforms and modalities. This understanding is consistent with multimodal theories of communication that emphasise how meaning emerges differently across visual, spatial, linguistic, and material modes (Kress & van Leeuwen, 2001), and with a view of learning as arising from the interaction of technologies, teaching practices, institutional infrastructures, and learner agency.

This paper presents the design, development, and pilot evaluation of a IVR digital twin of a university chemistry teaching laboratory, developed through sustained collaboration between the Department of Chemistry and Digital Media Lab (DML), a permanent institutional Creative Technology unit at Imperial College London. The study documents a replicable workflow for creating high-fidelity, interactive laboratory digital twins optimised for standalone VR headsets, and reports descriptive findings from a pilot deployment with first-year undergraduate Chemistry students focusing on perceived usability, engagement, confidence, and preparedness.

1.2 Institutional Context: DML as University CreaTech Infrastructure

Viewed through a postdigital lens, the intervention is not an isolated technological solution but part of an entangled constellation of pedagogy, infrastructure, institutional values, and design practice (Fawns, 2022). The presence of a permanent, in-house Creative Technology unit enables this entanglement to be sustained over time, supporting iterative refinement, asset reuse, and pedagogical alignment in ways that short-term or externally procured interventions typically cannot. Insight from pilot evaluation (see Section 3, Results & Analysis) has informed ongoing interaction design reiteration work within the unit in anticipation of subsequent cohort deployment and further evaluation. Assets, interaction logic, and audio developed for the VR digital twin can be repurposed across learning objects, theatre-scale visualisations, and other institutional platforms, positioning the project within wider strategic i educational technology infrastructure, rather than a standalone build. This approach aligns with research that frames educational technologies in higher education not as discrete tools, but as components of broader institutional infrastructures whose value is realised through sustained integration, stakeholder alignment, and long-term reuse (Chugh et al., 2023).

2. Project Description

A highly collaborative project was undertaken by a joint team from the Department of Chemistry and the Digital Media Lab. Following agreement on the requirements for the initial experience, the teaching laboratory was sampled as a collection of discrete assets and parameters, which were then reconstructed using the 3D modelling software Blender and the Unity game engine. Asset development was informed by detailed dimensional measurements, HDRI capture and lightmapping, photographic references for geometry and textures, and audio recordings capturing object interactions, impacts, actions, and ambient room tone. Video documentation of the target experiment was also recorded to guide early interaction design decisions within the game engine. To ensure that key apparatus — including the clamp stand and condenser — functioned digitally in ways consistent with their physical operation, each element was modelled as a distinct component and integrated into compound 3D assemblies. Situated within this digital twin of Imperial College London's Briscoe Chemistry teaching laboratory, a reflux setup was chosen as the focal activity, enabling students to rehearse procedural laboratory practices in advance of performing the same technique in the physical lab later.

2.1 Capturing the Environment

The Briscoe Lab is a large environment with objects that range in size from 1-2 cm (flask stirrers) to several meters (fume cupboards, desks). To create a digital twin of this environment, several capture methods and techniques were used. For the layout and dimensions of the floors, walls and windows, a floorplan of the building was used to ensure high accuracy measurements.

Measurement techniques. Techniques depend on the scale of the object being captured. Callipers can be used up to ~10cm and larger dimensions can be measured with tape, laser measures and LiDAR scans. While LiDAR scanning can accelerate the capture of large-scale environments and has been employed by the Digital Media Lab in other digital twin projects, manual modelling was preferred for this implementation. This decision reflected the need for models with components that move independently and for optimised polygon counts compatible with standalone VR headsets. Meshes produced by automated scanning techniques can require substantial optimisation to reduce the amount of graphical processing needed to render them (Webster, 2017; Pant *et al*, 2021).

Modelling Geometry. Hard surface modelling techniques in Blender and Maya were used to digitally reproduce man-made objects in the environment, and organic sculpting tools were used selectively for irregular forms. Models were subsequently optimised to reduce vertex count, balancing visual fidelity with the GPU limitations of standalone VR headsets (Meta Quest 3).

Material and textures. For colour and texture information, digital photography was used to capture representative material references. These were reproduced using a digital texturing workflow in Blender and Substance Painter, with Substance Designer used for procedural materials requiring repeating patterns. For objects requiring more intricate surface detail, such as scratches or fingerprints, detail layers were painted directly onto the model before baking down to a single texture.

Figure 1. Visual comparison of **(a)** the real-life Briscoe lab and **(b)** the virtual environment

Shaders and Lighting For some materials, such as glass and water, technical developers create shaders to visually approximate the effect of light refraction and reflection using the lighting information in the environment. For environment lighting, a grey and mirror ball were used to capture HDRI information — a high dynamic range image format that stores the full range of light and colour in the environment. This was digitised and used within the Unity game engine to simulate real-world lighting and reflections.

2.2 User Experience Design

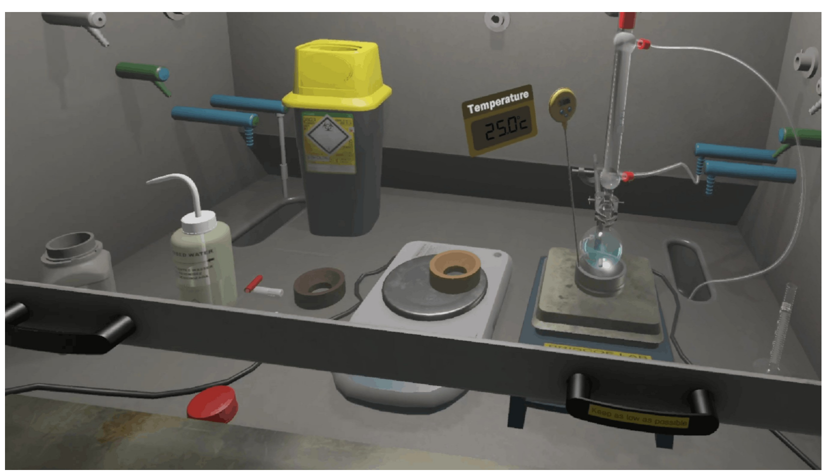

Figure 2. The virtual experimental setup within the fume cupboard in the main environment. Objects on display include distilled water bottle, weighing scales, sharps disposal, condenser tube, and round bottomed flask.

Prior to entering the virtual environment, students receive instruction on basic usage of the headset by teaching staff. Participants are initially placed within a dedicated virtual tutorial environment in which contextual User Interface (UI) prompts guide users through fundamental interaction mechanics, including locomotion, object manipulation, and trigger-based actions such as dispensing distilled water into a measuring cylinder. Participants who are already familiar with the interaction model may bypass the tutorial. Upon completing or skipping the tutorial, participants transition into the main environment: a high-fidelity digital twin of the physical Briscoe chemistry teaching laboratory. Here, users are guided through a complete reflux setup, comprising the following procedural stages: weighing and recording reagents; measuring and transferring distilled water; assembling the round-bottom flask, condenser, clamp stand, thermometer, and heating block; operating the fume cupboard water supply; and calibrating the magnetic stirrer and heater to initiate the reaction.

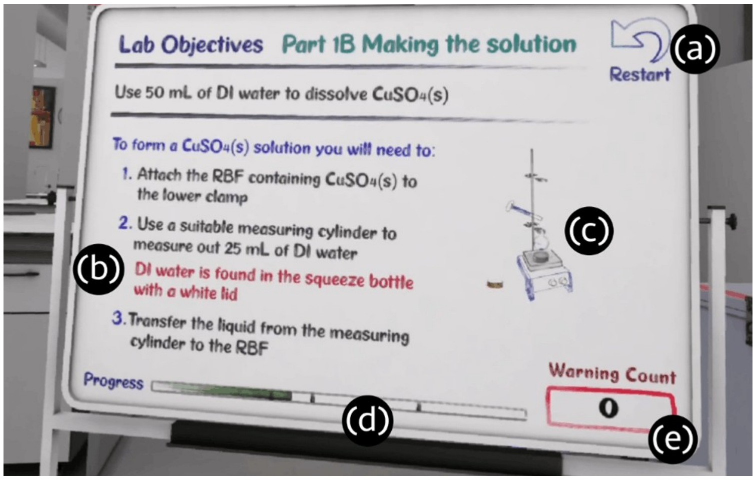

Figure 3. The digital whiteboard system **(a)** Button to manually restart the experiment **(b)** Detailed list of steps **(c)** Animated diagram of steps **(d)** Number of warnings**(e)** Progress bar to show how much of the experiment has been completed

The main environment is a digital twin of the real-life Briscoe lab at Imperial. Figure 1 compares the contents of the virtual environment to the real laboratory. The environment was designed to closely match the physical layout and the Briscoe lab to create a familiar environment for the user, that aims to improve retention of learning objectives (Essoe *et al*, 2022). Consequently, the digital twin is engineered to ensure that object behaviours remain predictable and consistent with their real-world counterparts. Figure 2 shows the layout of the virtual fume cupboard, directly mimicking the layout in the real-life lab. This alignment ensures that the technical knowledge, muscle memory, and intuitive skills developed within the simulation remain directly transferable to a physical laboratory setting. The virtual environment is centred on the fume cupboard, where all experimental procedures are conducted. Users are confined to the immediate vicinity of the fume cupboard, preventing deviation from the core tasks. This design means that participants may remain seated or standing in a fixed position throughout the simulation. Having a stationary play area simplifies logistical management for large-scale classroom implementation, accommodating up to 40 simultaneous users, each with an independent headset and designated play area.

Digital whiteboard. The digital whiteboard (shown in Figure 3) functions as a virtual pedagogical tool, providing students with learning objectives and procedural guidance at each stage of the experiment. Designed to facilitate an autonomous learning experience for up to 40 simultaneous users without direct instructor intervention, the whiteboard delivers all information required for independent completion. Technical diagrams are rendered in a hand-drawn aesthetic and animated into looping demonstrations of correct techniques. Furthermore, the interface utilizes diegetic controls—integrated directly into the virtual environment rather than a traditional UI overlay - to enhance immersion and minimize the cognitive load associated with complex controller mapping.

Pedagogical Feedback Mechanisms. The digital twin incorporates several logical systems to ensure that, upon completion, users have mastered the safe and correct procedures for the reflux experiment. Learner feedback is categorised as either 'Cautions' or 'Warnings.' Cautions serve as minor prompts to redirect students toward best practices, such as adding solid material to the round bottom flask while it is on the weighing scale, whereas ‘Warnings’ indicate more significant procedural errors, such as removing the copper sulfate from the fumehood without the lid on the container. Users are permitted up to three ‘Cautions’ before being redirected to the nearest checkpoint, while three Warnings necessitate a complete restart of the experiment. This tiered intervention system ensures that students cannot progress without adhering to the correct procedural sequence. Furthermore, it functions as a critical safety assessment; unlike a physical laboratory where an incorrect reflux setup might only be identified following equipment failure or fire, this virtual environment allows students to master safety protocols risk-free, ensuring these competencies translate directly to real-world practice.

2.3 Pilot and Co-Design Process

The pilot study was co-designed through a collaboration between the Department of Chemistry, which established the learning objectives, and the DML team, who focused on user interface (UI) design and the aesthetic fidelity of the digital twin. This co-design phase spanned approximately three months, characterized by an iterative feedback loop between the academic and development teams. Figure 4 shows the flow of how the pilot and co-design process occurred. Features were developed through rapid prototyping; the development team created functional models, which the academic team then evaluated to provide feedback for further refinement. This process culminated in a playable alpha version suitable for broader evaluation.

The methodology adhered to participatory design principles (Sanders & Stappers, 2008), with chemistry faculty serving as domain experts and DML staff providing technical expertise within structured workshops. Initial sessions were dedicated to defining core learning objectives and critical procedural milestones. Subsequent iterations involved faculty staff testing early prototypes to ensure scientific accuracy, pedagogical alignment, and the inclusion of necessary safety protocols. This approach ensured that technical implementation remained subservient to pedagogical requirements. During the subsequent evaluation phase, playtests were conducted with a small group of six Yr3 and Yr4 undergraduate Chemistry student participants unfamiliar with the system. The development team observed these sessions to identify possible cognitive friction or barriers to task completion. Informal participant feedback was collected and these valuable insights informed the final UI refinements prior to initial institutional rollout and evaluation.

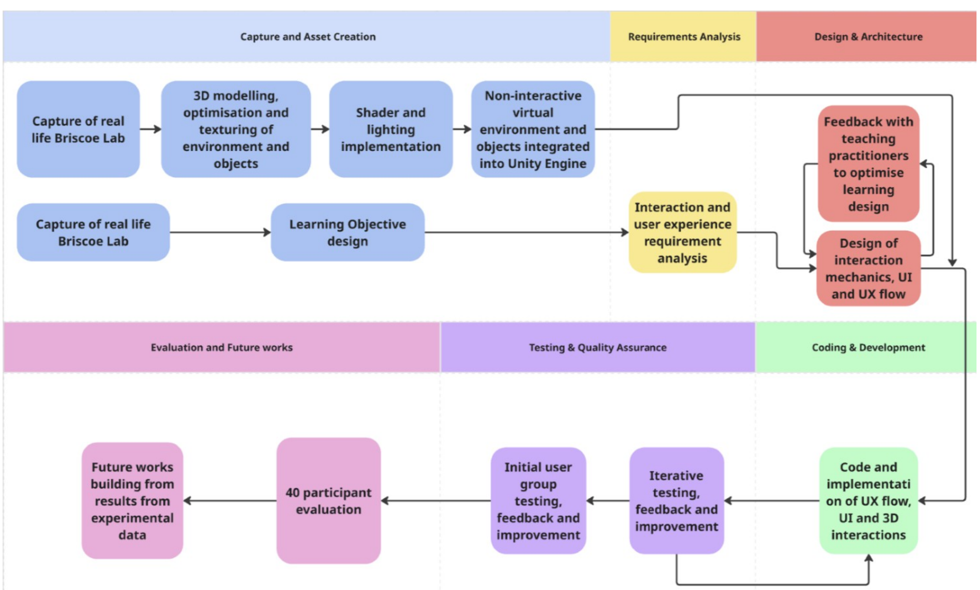

Figure 4. The Pilot and Co-Design Process carried out by the Digital Media Lab and Department of Chemistry at Imperial College London

3. Results and Analysis

First-year undergraduate students enrolled on any of the chemistry degree programmes at the institution were timetabled to attend this VR session. This was offered as a 90-minute session, with many students completing the entire task within 60 minutes. At the start of the session, a staff member explained the aim of the session, with respect to gathering feedback in an optional and anonymous feedback survey at the end of the VR experience. This was provided as a QR code in the room, along with participation information sheets for anyone wanting to complete the survey. It was made clear that this task had no bearing on their degree and the results are being used for evaluation methods. Students were given the option to leave the session at any point without any negative outcome. The survey was a mixture of open-ended questions and the use of a Likert scale. Based on the sessions, a total of 40 students responded to the survey. Their results are shown in this section. This study on the initial rollout had been granted ethical approval as per the Education Ethics Review Process at the university.

The post-survey was completed by 40 first-year undergraduate Chemistry students following their engagement with the Briscoe digital twin. Results indicate a strongly positive self-reported reception across confidence, enjoyment, usability, and perceived educational value. Given that the students were first-year undergraduates, they all had differing levels of practical experience at high school depending on where they studied. Constructivist theory was employed whereby there are elements of trivial constructivism (learning is an individual process, and teaching is to facilitate this process for the learner) and social constructivism (knowledge is a synergistic construction through interaction, language and culture, and scaffolding support learners to progress). Throughout the VR experience, these theories have been embedded since learners are the active participants, and the instructions/activities in the VR world are a vehicle to facilitate the learning process (Jordan *et al*., 2008). The students are actively ‘learning through doing’ and this engages them in active learning through this ‘tutorial-style’ scaffolding process (Vygotsky, 1978).

Results discussed in the following sub-sections are self-reported by the students who undertook the survey. There was no control group for this work. Following this initial evaluation, ongoing work is underway to measure the efficacy of the twin IVR training experience with actual physical lab performance. This aims to tie evaluation data between VR and “real life practice.” Ethical approval for this next phase has been granted and will be conducted during late spring/early summer of 2026.

3.1 Confidence and Perceived Learning Value

Survey question: "Do you feel more confident using VR following this experience?": Most students (75%, n=30) reported feeling more confident following the experience (rating 4 or 5 on a 5-point scale), with only 12.5% (n=5) reporting reduced confidence (rating 1 or 2; Figure 5). This aligns with the design intention of providing a low-stakes, repeatable rehearsal environment, supporting findings from Hamilton *et al*. (2021) that immersive VR may positively impact learner self-efficacy in laboratory contexts. The high confidence ratings are particularly noteworthy given that students may have had differing levels of prior VR experience, suggesting the tutorial environment and familiar lab replication were effective in reducing initial barriers. Whilst this was not a formal part of the evaluation, it was a question asked at the beginning of the session to engage discussion.

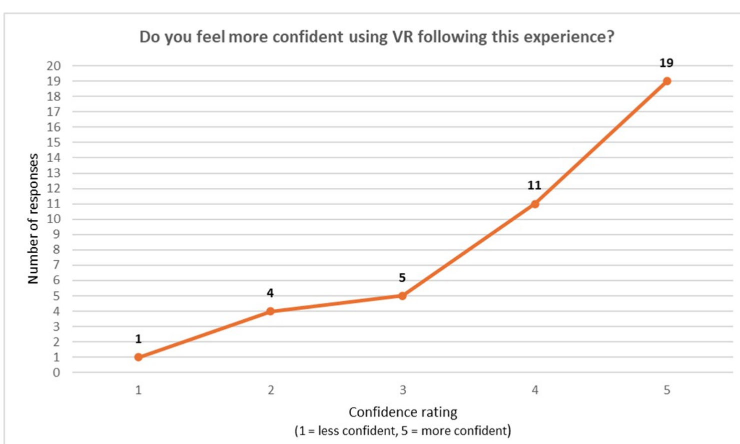

Figure 5. Student confidence ratings following engagement with the Briscoe VR digital twin (n=40).

Survey question: "How helpful do you think this app will be for students with little or no lab experience?": Of the 40 students, 31 (77.5%) rated the experience as extremely or very helpful for students with little or no prior lab experience (Figure 6), further supporting the intervention's intended role as a pre-lab familiarisation tool.

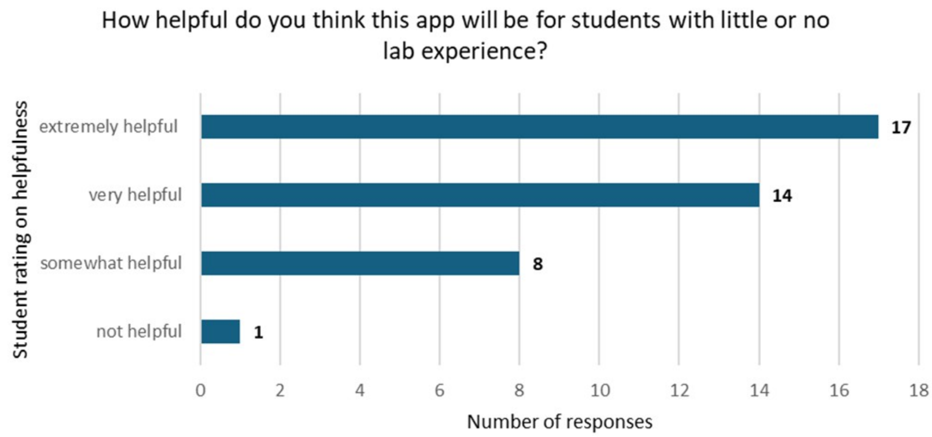

Figure 6. Student ratings of the helpfulness of the experience following engagement with the Briscoe VR digital twin (n=40).

3.2 Enjoyment and Engagement

Survey question: "Did you enjoy this experience? If so, what did you most enjoy?" (open ended): Open-ended responses revealed consistently positive language: 22.5% (n=9) used the word 'fun,' 27.5% (n=11) used 'enjoy' or 'enjoyable,' and 27.5% (n=11) referenced the words 'real' or 'realistic.' One student noted the "accuracy of the mechanics" when talking about the equipment and general handling. The same student commented that "a lot of effort has been put in to thinking about making the VR experience as similar to real life as possible and it shows."

Many students commented that they could "make mistakes" and "without any pressures" in a "safe environment" that was "low stakes" which might be present in a real lab setting. A VR simulation is not a replacement for real-life labs, and there are limitations, but one student commented that this "felt a bit different form the lab but I was still able to learn from it." These responses highlight the importance of the educational value of VR with another student commenting that this "seems pretty beneficial to practice before going into a real laboratory" suggesting value add to student training. A particularly noteworthy comment was from a student who responded that "gamified the experiment involving 5 lives which highlighted the common mistake which happens in the lab, so I will be taking these into considerations when doing the lab physically." This again shows how students can use this for training and consider what went wrong in the VR world to then be able to apply this in the real-world laboratory setting, indicating that scaffolded error feedback supported active learning (Kolb, 1984).

Survey question: "Any other comments about the learning experience?" (open-ended): From the responses, many students reiterated answers to previous questions (fun, cool, and difficult to measure). One of the responses highlighted the importance of exploring different modalities on learning: the student commented "I found it more helpful to virtually do the reflux instead of simply reading instructions prior to physically doing it in the lab." suggesting that VR-based rehearsal may be beneficial for students who engage more effectively with experiential, rather than text-based, instruction.

Survey question: How would you rate your overall experience with the app?: From the responses, 90% of the students (36 out of 40) rated this experience as either good or excellent. This was an exciting revelation, since it suggested that our aim with this experience correlated with student opinions (Figure 7).

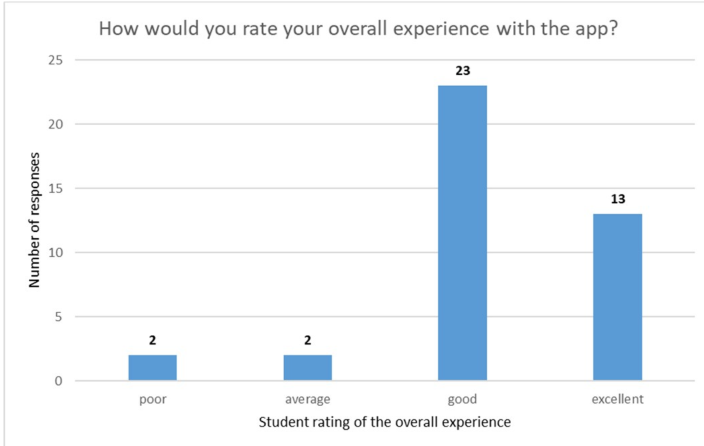

Figure 7. Student ratings of their overall experience following engagement with the Briscoe VR digital twin (n=40).

3.3 Usability and Technical Performance

Survey question: "How intuitive were the controls and navigation?": When asked about how intuitive the controls and navigations were, 32 students (80%) rated these as “easy” or “very easy” (Figure 8). It is noteworthy that students had differing levels of VR experience, however this was only discussed verbally at the start of the sessions.

Survey question: "Did you encounter any technical issues (*e.g.*, crashes, bugs, lag)?": Students were then asked whether they encountered any technical issues, and only 11 students (27.5%) commented that they did. They were then asked what these were. This ranged from glitching of the flask, copper sulfate sticking to the spatula, blurry images, headset screen sometimes going black (perhaps a hardware issue), boundary resetting partway through, the app “registering” when something was securely placed or not. These valuable insights, when deploying at a large scale, provide pointers for scheduled future reiteration work. Users were also asked how intuitive the content flow was. Of the 40 responses, 34 students (85%) rated this as “easy” or “very easy” which shows how the instructions have been designed to give a clear narrative. Each task builds on something that the student has done, as would be expected in the real world.

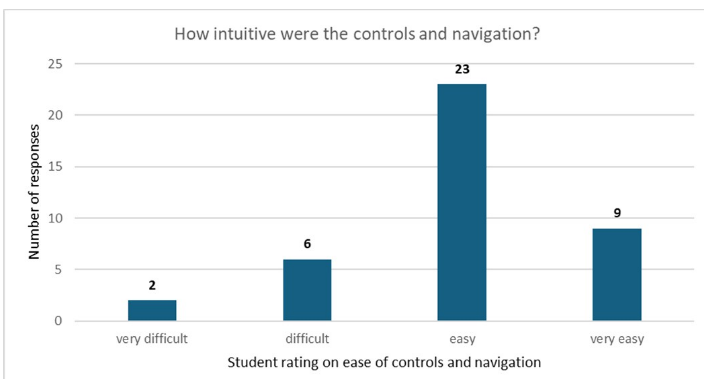

Figure 8. Student ratings of the ease of controls and navigation of the experience following engagement with the Briscoe VR digital twin (n=40).

3.4 Limitations and Areas for Development

Survey question: "What needs improving to help the learning experience?" (open-ended): Many students here commented on the functionalities built into the VR experience: blurriness of the measuring cylinder, hard to see the water level, hard to use turning mechanisms for knobs/dials, sensitivity of the controls, physics of the water bottle meant spillage was easy and resulted in "failure" of the task. These valuable insights allow further refinement of the experience in response to the student voice for future cohorts.

A few students noted feeling "dizzy" during the experience. This highlights one of the limitations since users can experience some disorientation owing to the immersive nature of the activity. Dizziness is a recognised limitation of immersive VR (Jensen & Konradsen, 2018). Students who reported dizziness were given the option to sit on a chair and see if they would prefer that, or to exit the experience. Some students found that being seated solved the dizziness, but some students still experienced dizziness so were told to not continue.

Considering the educational aspects, some students commented that the clarity of instructions could have been better. One student noted the experience was "missing the most important aspects of labs," citing (i) time management skills, (ii) note taking skills, (iii) understanding risks of real labs, and (iv) waste routes and disposal. These are valid observations; however, the experience is intentionally designed as a pre-lab familiarisation tool for students transitioning from secondary education, prioritising procedural confidence over comprehensive lab simulation. Health and safety aspects (points iii and iv) are subject to ongoing institutional discussion. Some students were also keen to choose different experiments or learn skills that are totally new to them. See Section 4.3 for details about future planned experiments.

4. Further and Future Work

A multi-year programme of work, of which two experiences and mediums have been developed (one rolled out) is intended to support wider Yr1 of Chemistry undergraduate curriculum with multimodal transmedia. The intent is to integrate this multimodal approach by October 2026.

4.1 Current state (May to October 2026)

Figure 9. Filming of Dr Ravi Singh (centre) at Imperial College London's Briscoe Chemistry lab for the preliminary video introduction by DML staff member Kieran Miller (left), August 2025 © Digital Media Lab, Imperial College London

Design. Specific actionable insight gained from initial pilot evaluation is used for interaction design reiteration on the Unity engine.

Evaluation. A post-physical lab self-reported survey has been granted ethics approval, with insights feeding onto the iterative evaluation and reiteration cycle. Following this initial evaluation, ongoing work is underway to measure the efficacy of IVR training with physical lab performance. This aims to tie evaluation data between IVR and physical lab practice.

Deployment. As part of the wider transmedia approach, a pre-VR video had been filmed in the physical

Briscoe Lab in August 2025. Setup for this deliverable is shown in Figure 9. This explains the aim of the VR training to the students, thereby replacing the in-person introduction done with this cohort. Timetabling constraints meant that this video was not used; the VR digital twin was deployed later in the year than anticipated. Subsequent cohorts will benefit from this preliminary video asset, due to optimised timetabling.

4.2 Next steps (AY2026-27)

Future development will expand the digital twin to additional experiments, complete the transmedia strategy with web-based and theatre-deployed components, and explore integration of AI-guided support for 24/7 availability following recent advances in conversational agents for laboratory digital twins (Taylor *et al*., 2025). Parallel deployment of the initial experience is also planned with students from Chemical Engineering department at Imperial College London, providing an initial opportunity to assess the transferability of the intervention across disciplinary contexts. This should also allow for evaluation of the experience when not used as a digital twin of a physical teaching lab students will then use (the departments operate separate labs), which would constitute a different pedagogical function despite deployment of same experience package and delivery devices.

Broader cross-institutional collaboration in discussion could further validate the replicability of the DML model and contribute to the establishment of best practices for high detail and / or digital twin development in higher education. As is the case with the cross-departmental deployment planned, across institutions the experience may serve as a more generalised introduction to chemistry laboratory practice, with transferable learning objectives around procedural familiarity and health and safety. The relative benefits and limitations of context-matched versus generalised VR laboratory environments represent a potential direction for future research.

4.3 Transmedia Strategy: Progressive Complexity and Varied Practice

The VR digital twin is designed as one component within a broader joint transmedia learning strategy in which different forms of engagement support distinct pedagogical purposes at different stages of the learning journey. Rather than extending a single narrative across platforms, the approach emphasises coordinated encounters with the same laboratory environment and procedures through multiple media, each contributing differently to learner preparation and understanding (Jenkins, 2006; Tombleson, 2024). Learning outcomes are understood as emerging from the interaction of these experiences rather than from any one medium alone, positioning VR within a wider learning ecology that resists technological determinism (Fawns, 2022). ‘

Within this framework, each mode of engagement plays a specific role. Video materials provide initial orientation and establish procedural expectations in context. Web-based 3D resources, delivered through the LMS (McKenna *et al*; 2024) and optimised for WebGL, enable asynchronous exploration of individual items of laboratory equipment on standard devices, supporting access for students unable to use VR headsets due to medical, physical, or logistical constraints. Immersive VR supports private, embodied rehearsal of complete experimental procedures within a spatially faithful representation of the laboratory. Theatre-scale visualisation enables instructor-led discussion and the establishment of shared reference points, while physical laboratory sessions remain the site of material manipulation, safety-critical practice, and expert feedback (Clewley *et al*; 2025). This layered design is consistent with evidence that varied practice across contexts supports the retention and transfer of procedural knowledge (Schmidt & Bjork, 1992; Rohrer & Taylor, 2007). At present, the web-based and theatre-scale components are presented as forward-looking elements of the overall design and have not yet been designed or evaluated in project context. Future work will examine the contribution of each component within the complete transmedia sequence, as well as wider learning objectives.

4.3 Expanded Content Development

Additional Experiments. It is the joint team's intention to develop yet more experiments for the Briscoe Lab VR Digital Twin, benefitting from the numerous existing, student-ready assets, code, environment, audio, user interface and interaction design, thus only developing or sampling/representing anew objects, actions or chemical reactions hitherto not used in the initial VR experience. Priority experiments for development in 2026-27 include: drug synthesis and serial dilution theory. The modular architecture of the digital twin allows new experiments to be added with approximately 60-70% asset reuse, significantly reducing development time and cost compared to the initial build. Each new experiment will undergo the same co-design and iterative testing process established for the reflux experiment. Recent advances in Gen-AI game engine integration - specifically Claude Code Opus 4.7 and Sonnet 4.6 integrated with Unity - should help expediting such consequent experiment design.

4.4 AI Integration

Beyond its current use for productivity gains in XR development, recent advances in conversational AI within laboratory digital twins suggest opportunities for 24/7 intelligent tutoring in immersive VR environments (Taylor *et al*., 2025). Future iterations could integrate AI agents capable of answering procedural questions, providing personalised hints, and adapting scaffolding in response to individual learner needs. Any such implementation would require careful pedagogical design to ensure that AI-mediated guidance complements, rather than displaces, the educational value of peer collaboration and instructor interaction.

5. Conclusion

This paper has presented a practice-based account of the design, development, and pilot evaluation of a VR digital twin of a university chemistry teaching laboratory, implemented as a pre-laboratory familiarisation intervention for first-year undergraduate students. The project illustrates how spatially faithful immersive environments can support confidence-building and procedural orientation prior to engagement with time-constrained physical laboratory sessions, without positioning VR as a replacement for authentic hands-on experimentation. The pilot evaluation, based on post-experience self-reported data, indicates that students perceived the experience as enjoyable, usable, and educationally valuable, with many reporting increased confidence and perceived preparedness, particularly for learners with limited prior laboratory exposure. Consistent with prior research indicating that immersive VR most reliably influences affective dimensions such as self-efficacy and perceived preparedness rather than directly demonstrating learning gains or performance transfer (Hamilton *et al*., 2021; Gungor *et al*., 2022), these findings are intentionally interpreted as descriptive and affective rather than as evidence of skill transfer.

Beyond the pilot results, the study's contribution lies in articulating a replicable design workflow, pedagogical principles for pre-laboratory VR use, and an institutional model that supports sustainable innovation through in-house expertise and asset reuse. Conceived as part of a wider transmedia learning framework, the VR digital twin functions as one modality within a coordinated learning ecology encompassing multiple forms of engagement and preparation. As immersive technologies become increasingly accessible within higher education, the critical question is not whether to adopt VR, but how to integrate it pedagogically, institutionally, and sustainably. This work illustrates one model through which context-specific digital twins, embedded within multi-modal teaching strategies and developed through collaborative co-design, can enhance undergraduate laboratory education while respecting the distinctive affordances of physical laboratory practice.

6. Contribution and Limitations

Contribution: This paper documents a practice-led workflow for developing interactive VR digital twins of teaching laboratories, combining HDRI capture, photogrammetry, and manual 3D modelling optimised for standalone VR headsets. It articulates pedagogical design principles for pre-laboratory VR experience, including low-stakes rehearsal, diegetic instructional interfaces, scaffolded error feedback, and spatial familiarity, grounded in experiential, constructivist, and multimodal learning theory. The study presents descriptive pilot evidence indicating positive student perceptions of usability, engagement, and confidence, and illustrates how permanent, in-house Creative Technology capabilities can support sustainable, iterative educational innovation through asset reuse and cross-project knowledge transfer.

Limitation: Findings are based on post-experience self-reported data from a single cohort (n=40) without control conditions, comparison groups, or direct measures of learning transfer to physical laboratory practice. The work is situated in a single institutional context, and the strong context-specific fidelity that characterises this intervention also limits straightforward transfer to institutions without access to the same physical laboratory configuration. A small number of participants reported VR-related discomfort. The transmedia components described in Section 4 have not yet been empirically evaluated.

6.1 Broader Implications

- Increase of practice and play-based learning without material increases to laboratory estate
- Potential for lower environmental and power utilisation footprint from usage of ~10W HMDs, as opposed to physical laboratories, with the associated HVAC (Heating, Ventilation and Air Conditioning) and aggregate operational carbon footprint
- Positioning of VR as one component within a transmedia strategy (e.g. VR + web-based 3D + video + physical lab) that provides progressive, accessible pathways for diverse learners while optimizing use of scarce physical resources and teaching staff time.
- Demonstration of how permanent CreaTech capabilities can enable scalable, sustainable educational innovation through asset and workflow reuse, in-house IP ownership, and cross-project knowledge transfer, contrasting with one-off projects, external partnerships or vendor lock-in.

As immersive technologies mature and become more accessible, the question for higher education institutions is not whether to adopt them, but how to do so sustainably and effectively. This project suggests that permanent institutional infrastructure (such as Creative Technology units), collaborative co-design processes, and multi-modal strategies offer a path toward meaningful integration of VR in STEM education, one that serves pedagogical goals and provides lasting value through iterative refinement and strategic asset reuse across projects and disciplines. The work contributes to the wider exploration of digital twins (specifically Virtual Training Environments) of physical spaces and their role within HEI teaching and learning and potential for a reimagination of the teaching estate, timetable and curriculum.

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