School of Chemistry

An Immersive Virtual Laboratory: Effects on Procedural Understanding

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1. Abstract

Immersive virtual reality (iVR) is becoming increasingly widespread as an entertainment medium due to its ability to immerse the user in an interactable life-like environment. Recently, research has explored its viability as a novel educational technology. However, the precise learning benefits that iVR affords are currently unclear. This article, therefore, assesses the potential of iVR to promote procedural understanding of chemistry laboratory techniques in higher education students.

To investigate this, an iVR chemistry laboratory simulation was used to teach participants the reflux experiment and they were then assessed on their ability to assemble the reflux apparatus in the real laboratory. The results were compared with a group of students who learnt via a non-immersive 2D web-based application. The iVR group assembled the apparatus with fewer mistakes, and reported themselves as feeling more confident, indicating a greater level of procedural understanding. These results suggest that iVR may be suitable for the learning of simple chemistry experiments. Further research is needed to determine if these benefits extend to more complex experiments and non-chemistry procedures.

2. Literature Review

2.1. Virtual Reality: The Ultimate Display

In his 1965 essay, Ivan Sutherland envisioned the 'Ultimate Display': a physically transcendent virtual environment indistinguishable from reality. He writes, "A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal."[1] This, in essence, is the ultimate aspiration of Virtual Reality (VR).

In principle, VR is a medium that synthesises a sense of *realness* or *presence* using modern technology. Bown *et al.* define *presence* as 'the felt sense of authentic reality that would result from engagement with sophisticated media'.[2] To achieve this, technology is utilised to trick the senses so that a virtual world is perceived as real; the ability to intuit virtual stimuli as artificial is suppressed, creating a sense of *presence*.[3] This is what makes VR wholly unique: the feeling that one is really 'there' in the virtual world, allowing one to overcome the limits of time and space, opening up countless possibilities in entertainment, art, education, training, business, communication, science, and more.

The potential of a VR system to provide this experience is a function of its *vividness* and *interactivity*.[4] The former can be described as a measure of the quality of the virtual multisensory environment, particularly its visual richness. Interactivity, on the other hand, measures the ability of the user to manipulate and influence the virtual environment.[2] As these components improve, a VR device incrementally approaches Sutherland's 'Ultimate Display'.

2.2. Virtual Reality: The Beginning

Although VR technology has grown rapidly in recent years, the concept has taken many forms throughout the last few centuries. Arguably, the first instance of a 'virtual reality' occurred in the late 18th century: the panoramic painting.[5] These were painted landscapes, often vastly proportioned, that curved to surround the observer's entire horizontal vision. The public became quickly fascinated with their power to cast the viewer into another world and they grew hugely popular.[2] However, panoramic paintings were only stimulating in the visual sense, and it was not until the 1950s that the idea of a multisensory experience was explored.

Morton Heilig, an early pioneer of VR, envisioned a revolutionary theatre experience that could stimulate not only visually, but with sound, touch, and taste. The idea led to the creation of the *Sensorama* in 1962 (Fig. 1), a multisensory theatre cabinet which included a stereoscopic 3D display, stereo speakers, wind and scent generators, and a vibrating chair.[6] Although primitive, the components of the *Sensorama* foreshadowed the VR head-mounted display that would arrive over half a century later. Heilig was a visionary, and often considered the father of VR, but was widely unrecognised in his time. It was innovators like Heilig that propelled VR forwards in its early stages.

Figure 1: Morton Heilig's Sensorama in use.[7]

During the 1960s, the next significant innovation in VR arrived. Graphics technology and computational power were rapidly improving, and in 1968 Ivan Sutherland created the '*Sword of Damocles*'. This was a prototypical head-mounted display (HMD) that could interface with a computer to transpose a wireframe cube over the user's vision and incorporated head-tracking so that the user could observe the virtual cube from multiple angles. This marked a huge step forward for VR technology. While other primitive HMDs had been developed before this,[2] the *Sword of Damocles* was the first to use a computer for graphics output instead of a camera. Furthermore, for the first time, this demonstrated that we could enhance our perception of reality with the help of computer graphics, a technology that would later become known as *augmented reality*.[8]

While VR had not yet been commercially adopted, over the following years and decades it played a crucial role as a training tool. By the 1970s, advances in computer graphics technology allowed for virtual environments to be used in place of videos or physical models, and so military pilots began to be trained in interactive VR cockpits. This provided a safer and more cost-effective alternative to prior training methods.[9] In 1990, NASA's Johnson Space Centre created a VR laboratory to prepare astronauts for spacewalks. The simulation was sufficiently advanced that several astronauts described that their real experience was "just like the VR lab".[10] That these early implementations found success, even with limited hardware, is evidence that VR is hugely promising for education and training purposes.

However, by this point, VR technology was highly specialised, largely unaffordable, and practically unobtainable to the general public. Furthermore, VR hardware was still in its infancy. Providing a high level of presence would require innovations in VR display technology and motion tracking along with significant computational power. It was not until the 21st century that advancements in VR and computer technology allowed for the full potential of VR to be realized.

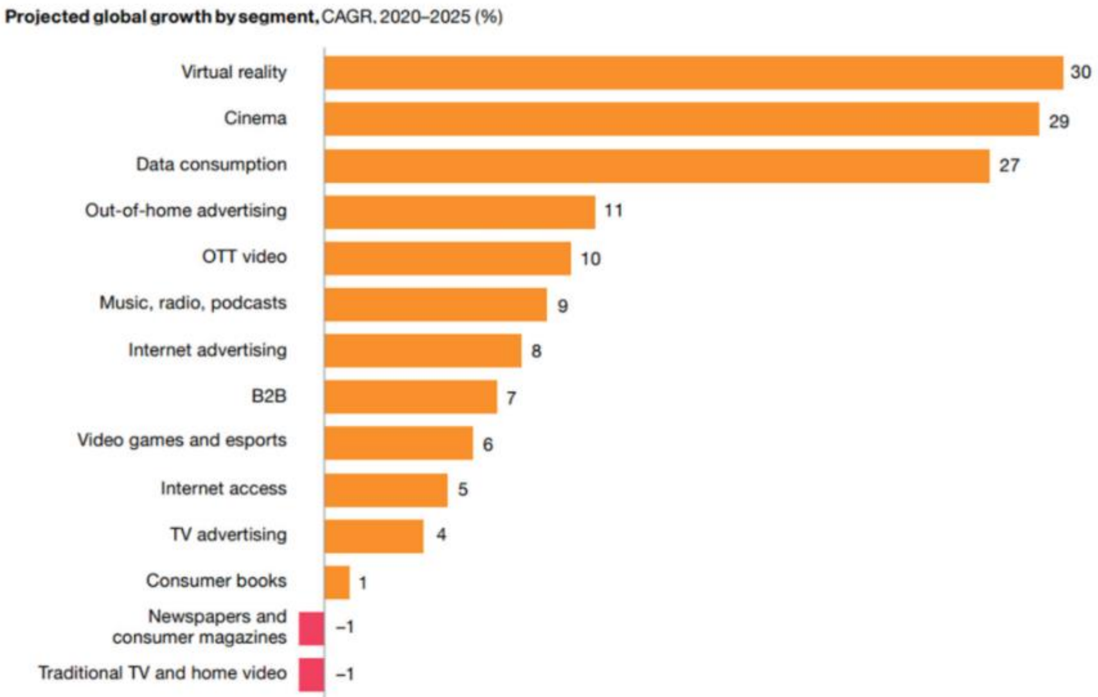

Figure 2: Projected growth of VR compared to other media, from 2020 until 2025.[11]

2.3. VR and computer hardware in the present day

Today, the VR industry is expanding rapidly, with global revenues projected to rise by 30% annually until 2025 (Fig. 2).[11] One of the key factors driving the growth of VR is the immense increase in computing power since the 1960s. In 1965, Gordon Moore, co-founder of Intel, predicted that the transistor count in an integrated circuit would double every year, and later revised this to doubling every two years;[12] this would become known as 'Moore's Law'. Over the years, this has largely held true (Fig. 3), with the number of transistors in a microchip growing by a factor of around 25 million from 1970 to 2019.[13] With this growth has followed improvements in processing speed and memory capacity along with a reduction in the size and cost of computer components among other advances.[14] However, the rapid growth predicted by Moore's Law may soon decline as transistors become increasingly smaller to increase density. As the size decreases, quantum effects become more prominent, resulting in unintended behaviour. This is particularly likely to occur as transistor gates approach 2 nanometres, which is only one order of magnitude greater than the silicon atoms that make up the gates.[15] Hence, the growth in computing power seen in previous decades which facilitated the emergence of VR is likely unsustainable, so that, henceforth, the rate of growth of computational power may decline.

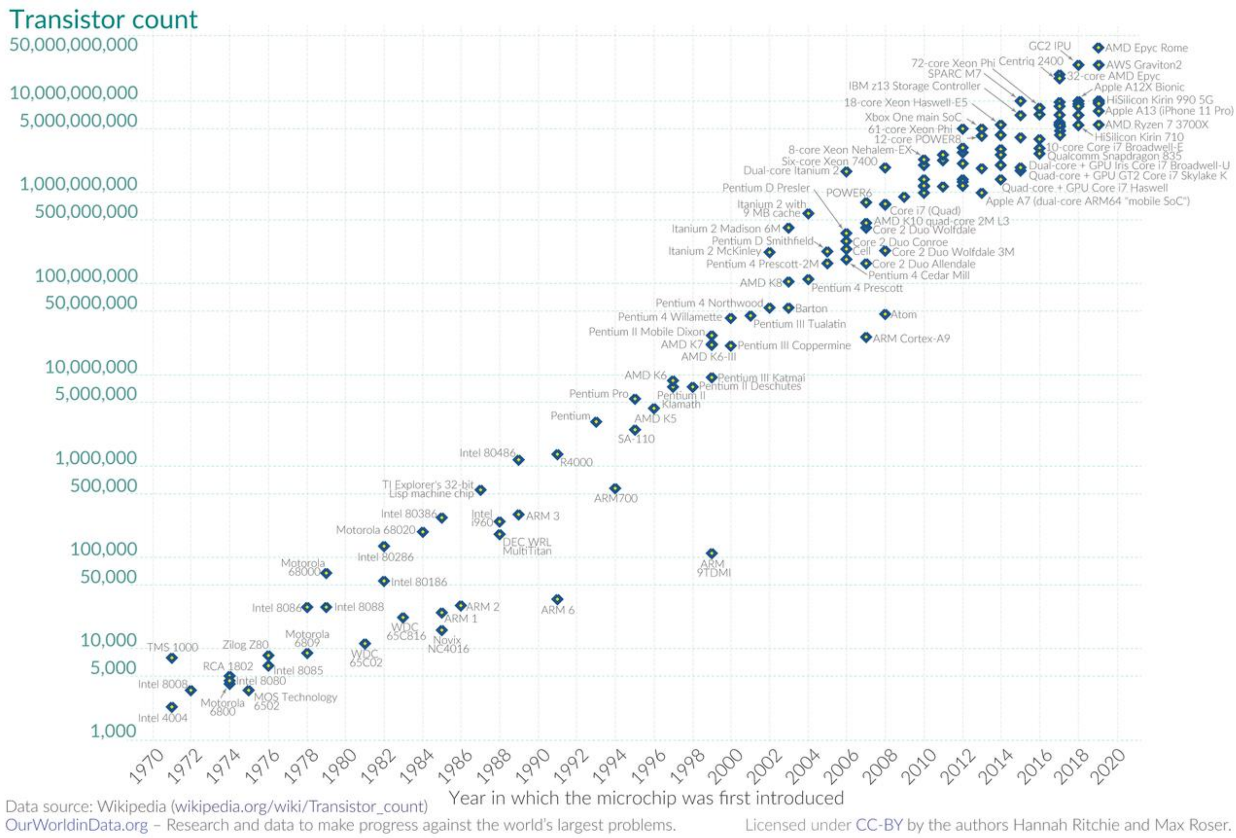

Figure 3: Growth of transistor counts on a microchip since 1970.[13]

Modern VR devices have made significant progress in resolution, refresh rate, and field of view. A high resolution improves visual detail and clarity and minimises visual artefacts, such as the screen-door effect and aliasing artefacts.[16] These are especially noticeable in HMDs due to the close proximity of the user's eyes to the display. A high refresh rate is important as it provides a smooth sense of motion. At low refresh rates, motion can seem unrealistic and latency is introduced which prevents head motion from synchronizing with the rendered environment.[17] This can induce feelings of discomfort.[18]

With VR display technology rapidly advancing, more powerful graphics processors are required to render VR environments at a high resolution and frame rate. Modern Graphics Processing Units (GPUs) are built and marketed with VR in mind.[19] In particular, the Nvidia RTX 4090 is easily capable of running the most computationally demanding VR applications currently available. Furthermore, Nvidia has also explored combining raw processing power with AI frame interpolation technology to achieve high performance at a more accessible price.[20] At the cost of some degree of graphical fidelity, older generation GPUs with a cheaper price tag such as the Nvidia GTX 1080Ti are capable of competently running most VR games.[21] With advances in memory capacity and Central Processing Unit (CPU) core count and speed, VR-capable computers are now readily available and relatively affordable.

In 2010, a VR system consisting of an HMD and various peripherals attached to a tablet computer cost $45,000 and weighed almost 11 kg. By 2013, a comparable system cost $1,300 and weighed only 2 kg.[22] This rapid cost reduction is largely owed to the release of the Oculus Rift, the first consumer-grade HMD capable of providing a modern level of presence; this is often referred to as immersive VR (iVR). Following the release of the Rift, the industry has grown rapidly, with major technology companies such as Meta (formerly Facebook), Valve and Sony becoming involved in the development of new HMDs. According to the 2022 Steam Hardware Survey, the Meta Quest 2 made up 42% of VR headsets used with the Steam video game distributor, followed by the Valve Index (18%) and the Oculus Rift S (14%)[23]. The prevalence of the Quest 2 is likely due to it being a standalone system that does not require a VR-capable computer and instead has the option of running VR software natively. Along with its relatively cheap price, this makes the Quest 2 more accessible than its PC-VR competitors.[24] However, while standalone options compromise performance for portability and accessibility, tethered HMDs such as the Valve Index can offer a higher level of vividness.[25]

Pose tracking is a crucial aspect of VR hardware. Pose tracking refers to the ability to track the position as well as the orientation – pitch, roll and yaw – of the HMD. There are two pose tracking methods used in VR: outside-in tracking and inside-out tracking. In outside-in tracking, cameras are positioned around the environment which detect infrared waves emitted by the HMD to determine the user's pose. Conversely, in inside-out tracking, 'markers' situated around the environment emit infrared waves which are detected by cameras on the HMD itself. While outside-in tracking was used by the Oculus Rift,[26] newer HMDs such as the Valve Index tend to use inside-out tracking.

The Oculus Quest uses a modified inside-out approach called *markerless* tracking. It uses the HMD's cameras to build a 3D map of the surrounding environment in real-time and a machine learning algorithm determines the pose of the user within the map.[27] This makes the Quest more accessible by removing the need for markers to track pose, which means that smaller environments such as a personal office can be used for VR. Furthermore, methods that use external cameras or markers suffer from occlusion: if the line of sight between the marker/camera and the user is obstructed, the pose cannot be tracked. Markerless tracking sidesteps this problem. However, markerless tracking is less precise than other methods and introduces latency. Further, it is more computationally expensive than the other methods, due to the need to synthesise a map of the environment in real-time, and because of limitations in current machine learning implementations.[28] Despite this, these problems may be overcome as mobile processor technology and machine learning algorithms improve over time.

Interactivity is also a vital aspect of VR hardware as it allows the user to manipulate and influence a virtual environment, which contributes to presence.[4] A key benefit that interactivity provides is that it opens new avenues of communication between the user and the VR application. For example, hand-held controllers allow the user to directly manipulate virtual objects, and, in response, the controllers vibrate to provide information about the interaction; this is known as 'haptic feedback'. Haptic feedback plays a significant role in VR: it communicates force and physical sensation, helping the virtual interaction to feel more life-like.[29] Alongside haptics, intuitiveness is an important consideration for VR interactivity. A virtual action should aim to mimic its real-world counterpart as closely as possible so that the user can use intuition instead of learning and recalling an abstract action.[4] This helps to impart greater presence as users can focus on the experience itself rather than learning how to interact with it.[30]

Typically, interaction with a VR environment is performed with hand-held controllers, although a wide variety of input devices exist, including haptic gloves and eye-tracking.[31,32] In general, hand-held controllers detect input via button and joystick interactions, and can track the position and orientation of the controller, allowing for a virtual representation of the user's hands. They often feature a 'trigger' button which can be used, for instance, to intuitively represent pulling the trigger of a gun or grabbing an object. Also, 'point and click' interaction, similar to clicking a computer mouse, enables the ability to manipulate far-away objects and interact with user interfaces.[33]

Body-based interaction is a novel alternative which allows users to interact in VR without holding controllers. This has the advantage of being highly intuitive and allows for gesture-based communication, as seen in the social virtual world platform VRChat.[34] However, while hand-tracking could increase presence and presents new ways to communicate, limitations such as the lack of haptic feedback and poor tracking prevent its adoption outside social applications.[35]

Haptic gloves may be a viable solution to this as they introduce force feedback while also being capable of natural and intuitive interaction. However, current commercial options are too bulky to feel natural and are prohibitively expensive.[31] Further, current haptic devices can provide some degree of tactile stimuli, whereas truly simulating the body's full range of motion and haptic sensation will require force and thermal feedback and the ability to track each finger in multiple degrees of freedom.[36] This remains an area of active research, with 'soft' haptics that utilize extendable and flexible materials being suggested as a potential avenue forward.[29]

2.4. VR Software Design

2.4.1. Optimisation

To provide a satisfactory experience, VR applications must be carefully designed to ensure that the VR experience runs at a high refresh rate with minimal stuttering for a given HMD. This process is called *optimisation* and is crucial in avoiding negative effects such as motion sickness,[37] which would prevent users from feeling present. The Meta Quest documentation thus advises a minimum frame rate of 72 FPS for a comfortable experience.[38]

In the process of optimization, various techniques are used to reduce the computational load placed on the computer hardware, two of which will be briefly explored. One of these techniques is limiting the polygon count of 3D models. 3D models are composed of edges, faces and vertices that make up a polygon mesh. The greater the number of polygons, the more detailed the mesh will appear, but the greater the computational cost. To balance computational cost and visual clarity, the Meta Quest documentation recommends a maximum polygon count of one million per rendered frame.[38] Polygon count can be further reduced using a technique called level of detail. In this technique, 3D models are assigned multiple meshes that range from low to high polygon count. Models far away from the player cannot be made out clearly which means that they can use a lower detail mesh to reduce polygon count. This allows the polygon budget to be allocated mainly for nearby objects, providing an overall increase in visual quality.[39] Some game engines also supply (either natively or as an add-on) an automatic level of detail tool which procedurally generates simplified meshes, making this a quick process.[40-41]

Figure 4: Mipmapping without anisotropic filtering (left) and mipmapping with anisotropic filtering (right).[45]

Mipmapping is another technique which applies a similar process to textures. The visual clarity of a texture will increase with its resolution, but this will also take up more space in memory.[42] Mipmapping, improves performance by reducing the resolution of distant textures. However, this creates noticeable visual artefacts, particularly when a plane is viewed at an oblique angle, due to the jarring transition from one mipmap level to another. To counteract this, a technique called texture filtering is used which reduces the blurring that mipmapping causes.[43] Anisotropic filtering (Fig. 4) is the most advanced of the texture filtering techniques and is supported by many game engines, such as Unity.[44]

2.4.2. Locomotion

VR locomotion can be classified into four distinct methods: motion-based, room scale-based, controller-based, and teleportation-based. Motion-based locomotion involves physical actions such as swinging the arms or walking in place to represent virtual movement while keeping the user in the same physical location. Room scale-based locomotion maps the physical room to the virtual environment, allowing the user to move in the virtual world by walking in the real world. Controller-based locomotion uses an input device such as a joystick to move the user in the VR environment. Teleportation-based locomotion uses the 'point-and-click' action to teleport the user to the desired location; this is commonly performed with a controller but is also possible through hand-tracking.[46,47]

The ideal method of locomotion is dependent on the desired level of realism and accessibility among other factors. For example, a VR training simulation may utilize room scale-based locomotion for greater realism, while a VR video game may use teleportation-based locomotion as it is likely to be played at a desk. Methods that employ physical actions may be more intuitive and less cognitively demanding, but interaction through a controller is more accessible and less physically demanding.[46] A study comparing controller-based and teleport-based locomotion with redirected walking (a motion-based technique) found that redirected walking enhanced the user's spatial awareness over other methods, but the sense of presence was unaffected.[48] One advantage of motion-based, controller-based, and room scale-based locomotion is that movement is continuous, which can feel more natural and engaging than non-continuous methods such as teleportation.[49] However, room scale-based locomotion is limited by the size of the physical space. In addition, the mismatch between virtual and physical self-motion in controller-based locomotion can feel unnatural and contribute to cybersickness.[49] Kyungmin *et al.* addressed this issue and found a significant reduction in cybersickness by dynamically limiting the user's field of view during virtual motion with controller-based locomotion.[50] In conclusion, each method of locomotion has its unique advantages and disadvantages; determining the right method is a vital part of creating VR software design.

2.4.3. Sound Design

Sound design has been shown to largely contribute to the feeling of presence in VR.[51] Unlike traditional media, audio in VR is spatialized, allowing the user to accurately locate audio sources in 3D space. Auditory output is thus able to provide spatial information in all directions, whereas visual output is limited by the field of view of the HMD and the occlusion of objects in the virtual world. In addition, audio manipulation techniques such as reverberation can be used to impart the feeling of “being surrounded by a spatial scene”, which contributes to the feeling of presence.[52] Spatialized audio also helps to reduce cybersickness as visual and audio information is synchronised, reducing sensory mismatch.[53]

To achieve effective sound design, it is important for the application to provide audio feedback for key interactions, which will provide greater information to the user.[54] For instance, placing an object on a surface should play a sound effect to indicate that the object has collided; this could be difficult to determine by visual input alone. One study researched the effect of using movement-triggered step sounds and found that although the technique is difficult to implement accurately with current technology, a significant improvement in presence was experienced by users.[51] In summary, sound design is crucial to an effective VR application and its contribution to presence should not be underestimated.

2.4.4. Inclusivity

The goal of inclusivity in VR can be summarised by the principles of Universal Design: “the design and composition of an environment so that it can be accessed, understood and used to the greatest extent possible by all people regardless of their age, size, ability or disability”.[55]

Cybersickness is a significant barrier to inclusive VR and is frequently experienced by its users.[56] It is characterized by symptoms of disorientation, nausea, and oculomotor symptoms (such as headaches and eyestrain).[57] Along with negatively impacting feelings of presence,[58] this also can present a safety hazard, particularly in the case of disorientation. As such, cybersickness is an area of priority for VR research. The most prevalent theory for the cause of cybersickness is sensory mismatch, where the body’s sensory systems provide conflicting information in response to a stimulus.[56]

Several techniques exist for combating cybersickness. Some of these have been discussed previously, such as reducing latency, maintaining a high frame rate, and dynamically limiting the Field of View during virtual motion. The method of locomotion is also important in preventing cybersickness. Stationary methods of locomotion are likely to cause a sensory mismatch, particularly controller-based locomotion, as the user remains still while experiencing virtual motion. Motion-based locomotion, such as walking in place, may alleviate some sensory mismatch by providing proprioceptive cues during physical movement. Despite being stationary, teleportation-based locomotion is unaffected by sensory mismatch as it is non-continuous, so the user does not experience virtual motion.[59] Other factors that increase cybersickness include long duration of use, gradual changes in acceleration, and a high field of view. Field of view can be decreased to reduce cybersickness, but this comes at the cost of presence.[60]

For individuals with mobility impairments, the physical demands of interaction can present a significant barrier. Common mobility impairments that can impact VR use include fatigue from standing for long periods, limited vertical range of motion (such as crouching and reaching up), and poor balance.[32] These problems can be alleviated through various techniques. For instance, the need for vertical movement can be limited, instead utilizing space on the horizontal plane of the user's arms. Some games such as 'Vacation Simulator' utilize a mechanic that allows players to pick up items on the floor without reaching down, by hovering their hand above the item and holding the trigger on the controller.[61] Another game, 'Arca's Path VR', utilizes simple head movements to move the player, avoiding physically demanding interaction and reducing the cognitive demands compared to controller-based input schemes.[62] To support users who are limited to a wheelchair, WalkinVR allows users to gain greater control by using a controller to virtually walk, crouch, and raise their hands rather than using physical movement.[63]

In conclusion, VR applications can become more inclusive by considering the needs of the individual and implementing design solutions to meet these needs. It is important to mitigate cybersickness as this impacts many users of VR and may prevent its widespread adoption.

2.5. The Gamification of Education

Today's students are well acquainted with video games; the majority of 8-17 year-olds consider them an important aspect of their life.[64] Gaming has rapidly captured the attention and motivation of young people over the past five decades, which contrasts with the lack of motivation they often display towards curriculum content;[65] this dissonance is a constant source of frustration for parents and teachers alike. To rectify this, the motivational and engaging design elements of games could be combined with teaching to improve the learning experience, a process called *gamification*.[65] Gamification is becoming increasingly accepted as an instructional method and efforts to integrate game elements into school curricula are well documented.[66]

According to Nah *et al.*, some of the potential elements of gamification include leaderboards, rewards, game fiction, feedback, points, levels and stages, and achievements.[66] A 2020 meta-analysis by Sailer and Homner found small but statistically significant improvements in behavioural, cognitive, and motivational learning outcomes when gamification was used. The study suggests that social elements such as collaboration and competition are key contributors to the improvement in behavioural learning outcomes. However, the precise game elements that empower learning remain unclear.[67] In line with a 2017 meta-analysis by Dichev and Dicheva,[68] Sailer and Homner note that despite many publications in the field, the general quality of research is low. Dichev and Dicheva argue that to improve research quality, there is a need for more focused research; studies should examine specific game elements rather than gamification as a whole, which excessively broadens the scope of research. As a result of the poor research quality, there are no practical guidelines to aid the implementation of gamification into educational activities. Hence, current implementations are largely empirical rather than grounded in theory, which may limit their effectiveness.[67]

2.6. VR in Education

The importance of education calls for the development and integration of new technologies to provide more effective ways to learn, and hence further societal and private interests. The recent revival of VR and the rapid growth that ensued have diverted the attention of researchers to this novel technology and its effectiveness as an educational tool, although VR as a tool for education is far from a new concept, having been used in pilot training since the early 1970s.[9] However, while the idea of utilizing VR in education is generally favourable among teachers,[69] it has not yet seen widespread adoption in educational institutions.[70,71]

Much of the optimism and interest surrounding VR has been due to its supposed ability to increase learner motivation and focus and to enable the easily repeatable practice of challenging situations in a safe environment.[70,72] This was especially the case before 2016 when the amount of research was relatively scarce – the quantity of research grew tenfold from 2015-2020, expedited by the COVID-19 pandemic[71] – and the recency of the VR revival caused great excitement. However, these purported advantages are generally untrue. Kavanaugh *et al*. argue that learner motivation is likely to increase due to the novelty of the experience and is thus only a short-term effect which should not be relied upon. As the majority of educational VR studies only examined short-term outcomes, it is particularly difficult to conclude any lasting effects.[70] Further, Jensen and Konradsen emphasise that VR does not "automatically" cause learning to take place; as a medium, it is not necessarily more effective than other learning media in general, but with sufficiently designed software it can be more effective in specific applications.[72]

Along with the lack of long-term studies, as reported by Kavanaugh *et al*.,[70] several difficulties with the state of educational VR research itself have been identified. A 2020 review noted that educational VR research has not reached maturity and is still in its prototyping phase. Several key problems were recognised: firstly, articles often neglect to describe the technical development of the educational software that was used, limiting reproducibility; secondly, articles that do describe technical development tend to focus on the usability of the software rather than the learning outcomes; thirdly, most articles were not grounded in pedagogical theory,[73] which was in agreement with the findings of Kavanaugh *et al*.[70] Partly as a result of these factors, research is typically exploratory, rather than being built off existing experiments.[73,74] Radianti *et al*. highlight the need for future works to "take a holistic standpoint", meeting these criteria: (1) being grounded in pedagogical theory, (2) carefully designed in terms of software, building off of the successful design elements identified by previous works, (3) describing in detail the technical development, and (4) evaluating both software usability and learning outcomes. While difficult, meeting such criteria would greatly improve the quality of research and increase generalisability.[73] Another problem is the speed of technological progress of VR. Rapid advances in VR tech may make current research less relevant or even obsolete, which is problematic considering that most educational VR research is still exploratory. It also requires that researchers stay up to date with the current tech or risk falling behind. On the other hand, new improvements to VR tech could enhance learning and the growth of the industry could pave an easier path for educational researchers.[74]

Despite that educational VR may not live up to the ‘hype’ surrounding it, some studies have tentatively suggested key areas where it can be beneficial in its current state. While acknowledging a low quantity and quality of relevant research, Jensen and Konradsen used the Bloom taxonomy – which classifies learning outcomes into cognitive, psychomotor, and affective domains[75] – to identify in which contexts immersive VR (abbreviated as iVR; this usually refers to the use of an HMD) provides learning benefits over non-immersive technologies and traditional learning media.

Regarding the cognitive domain, skill acquisition was limited to recalling and understanding only visual and spatial information. This advantage follows from presence, which allows navigation in the virtual world to trigger the same brain mechanisms as navigation in the real world.[8] iVR has resultingly been used in cases such as treating PTSD associated with a particular place in soldiers, and spatial memory rehabilitation following traumatic brain injury.[8,76] iVR can also be used to visualise and understand spatial relationships that are imperceivable in real space, such as subatomic structures and exoplanets.[77] However, iVR performed worse for cognitive skills other than those of visual and spatial information. Cognitive Load Theory proposes that working memory is a limited resource and so unnecessary information should be avoided to prevent the overuse of these resources (a high cognitive load).[78] Using this theory, Makransky analysed EEG recordings during iVR learning and found that cognitive load was significantly higher and thus users learned less when compared to desktop-based learning. He suggests that the sensory fidelity of iVR adds an extraneous load that is distracting and irrelevant to the learning task.[79] This is in line with the results found by Huang *et al*.[80] as well as Moesgaard *et al*., the latter of whom described study participants as “too enthralled… to notice the information that was presented to them”.[81] Jensen and Konradsen also identified cybersickness and a lack of familiarity with iVR hardware as being problematic.[72] However, given that their review only looked at articles published between 2013 and 2017, this problem may be less relevant now as newer iterations of iVR hardware have successfully reduced cybersickness.[82] Makransky further suggests that high cognitive load may arise from the excitement users experience due to the novelty of the experience.[79] Thus, as iVR becomes more widespread and the public becomes more acquainted with the technology, cognitive load and technical unfamiliarity may diminish, and a greater variety of cognitive skills could be developed.

Psychomotor skill acquisition is best when specialised input devices are used that can accurately simulate the corresponding real action. Hence, specialised implementations in non-immersive VR such as surgery simulators show significant psychomotor skill transfer.[83] However, Jensen and Konradsen highlight that iVR peripheral devices have poor realism, perhaps due to being multi-purpose tools that can be used across different simulations/games, and therefore psychomotor skill acquisition is limited. To improve in this regard, immersive iVR peripherals need greater haptic and tactile feedback, which will improve the degree of realism and afford greater psychomotor learning.[72]

Jensen and Konradsen also suggest that iVR can evoke emotional responses, through presence, and thus could be useful for affective skill acquisition. This is in agreement with a 2022 review by Bolouki, who found that natural environments in VR can induce relaxed moods, promote mindfulness, and lower blood pressure and heart rate.[84] Overall, the quantity of research in this area remains small. Nevertheless, iVR shows promise for the acquisition of affective skills. For instance, controlled and repeated exposure to relevant stimuli could be used to treat phobias, which has already seen success with non-immersive VR.[85]

In a more recent review, Hamilton *et al*. further identified that iVR may be highly effective at teaching procedural skills. iVR is advantageous in this scenario as it allows one to practice a procedure before attempting it in the real world, which greatly reduces risk and improves performance. However, only two studies measured skill transfer from the virtual to the real world; while both reported positive results, more research is needed before a solid conclusion can be made.[86]

iVR is therefore a unique educational technology and can afford greater advantages over other learning technologies and traditional learning media in specific applications. However, given the fast technological progress of VR and the surge in research due to the COVID-19 pandemic, an up-to-date review of learning outcomes is needed so that the precise benefits that iVR affords can be identified. Furthermore, Hamilton *et al*. indicate that the evaluations of learning outcomes used in the reviewed educational iVR articles suffered from poor methodology.[86] If future studies can act upon the guidelines proposed by Radianti *et al*.,[73] the applications of iVR in education can be better understood and thus successfully implemented into educational institutions.

2.7. Immersive VR in Chemistry Laboratories

The laboratory is one of the most important components of the chemistry higher education curriculum. It provides a unique learning environment that promotes scientific inquiry and tests understanding of curriculum content while developing "higher-order learning skills that include planning an experiment, observing, asking relevant questions, hypothesizing, and analysing experimental results".[87] However, chemistry teaching laboratories are labour-intensive and highly expensive to run due to the cost of instruments, chemicals, staff, waste disposal, equipment, etc. Indeed, university budgets are at present highly strained, and chemistry departments in particular operate at a significant deficit.[88,89] Furthermore, the impact of the COVID-19 pandemic and concerns regarding the possibility of future pandemics have drawn attention to the limitations of practical teaching and indicate the need for a distance-based alternative. iVR may be able to alleviate these problems. An iVR laboratory simulation could reduce cost,[90] increase safety,[91] and overcome physical constraints such as the size of a laboratory and the infrastructure required to run it.[92] Further, it could improve flexibility and accessibility in cases where students cannot attend a physical laboratory due to illness, injury, or pregnancy.[90]

Further investigation into the role of iVR in chemistry teaching laboratories, and education in general, is needed to identify its pedagogical implications. Currently, a relatively large number of studies look at non-immersive (web/desktop-based) virtual chemical laboratories compared to immersive VR solutions.[93] Furthermore, studies that examine iVR in pedagogical applications often utilise mobile VR devices, which lack the interactivity of high-end devices such as the Meta Quest 2, and tend to neglect psychomotor, affective, and procedural skill acquisition in contrast to cognitive skill acquisition (Fig. 5).[86]

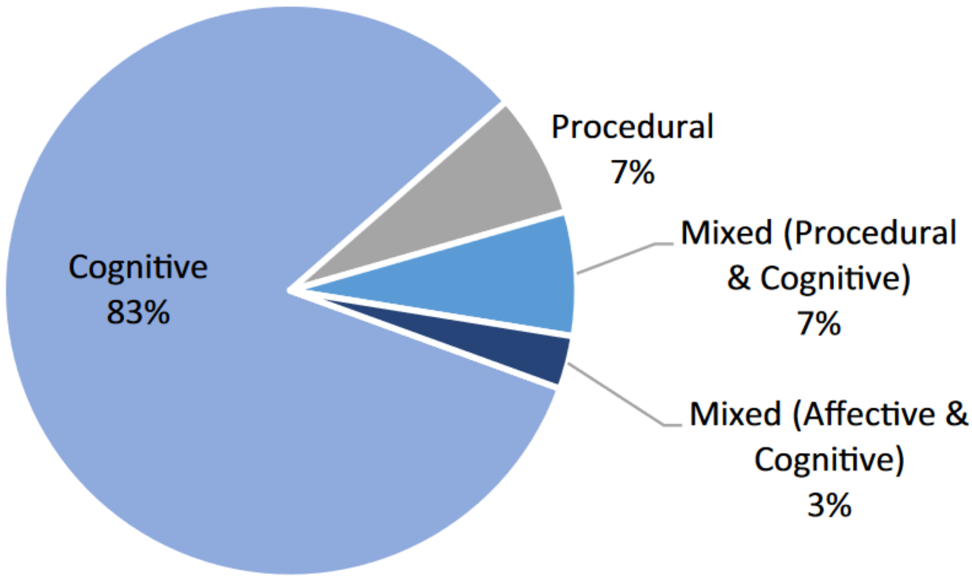

Figure 5: Distribution of assessed learning outcome domains in existing educational VR studies.

Hamilton *et al*. identified that iVR could be effective at teaching procedural skills,[86] exposing a potential area of focus for iVR laboratories. While the overall quantity of published studies in this area is small, the results so far have been encouraging.[94,95] Procedural knowledge is best understood as the ability to carry out a task ("know-how") and is distinct from conceptual knowledge which involves the understanding of the underlying theory ("know-why"). However, the two are linked and procedural understanding can promote the development of conceptual knowledge by reducing the cognitive load of the task, according to the Unified Learning Model.[96] A deep procedural understanding allows for adaptability, critical judgement and evaluation when carrying out a task.[97] An iVR laboratory could help in this regard by (1) allowing the repeated practice of an experiment, reinforcing the standard procedure in memory and thus providing shallow procedural skills, and (2) safely enabling free experimentation which allows one to test and evaluate different experimental outcomes and hence acquire deeper procedural skills. Therefore, the current approach of learning theory before applying it in the laboratory could be supplemented with an iVR simulation beforehand, improving conceptual and procedural understanding. With regards to practical chemistry, procedural skills may also be associated with psychomotor skills, the degree of which depends on the exact procedure.[86] As noted by Jensen and Konradsen, psychomotor skill development is inhibited in iVR and therefore some procedures may be unsuitable or must be adapted for iVR learning.[72]

One struggle that chemistry laboratories face is that students often experience significant cognitive load due to the lack of familiarity with the laboratory environment, which inhibits the attainment of conceptual knowledge.[98] An iVR laboratory could therefore provide the student with a greater spatial understanding of the laboratory beforehand,[72] as well as familiarity with the experimental procedure, which would reduce cognitive load and allow for greater conceptual and procedural understanding when performing in the real laboratory.

However, the ability of an iVR chemistry laboratory to provide learning benefits would significantly depend on the quality of its software design. This poses a challenge: designing an iVR laboratory that could adequately meet the learning outcomes of a physical laboratory in an educational institution would require the collaboration of experts from multiple disciplines, including software engineers, chemistry professors, and educational technologists,[93] informed by up-to-date instructional theory and VR design practices. Currently, there is a lack of content for iVR learning and the difficulty of developing a VR simulation is prohibitive to the adoption of educational iVR.

2.8. Research objectives

So far, the potential of iVR to provide procedural learning benefits is largely unexplored in literature. Therefore, the present study aims to test the hypothesis that learning via iVR simulations can afford greater procedural learning benefits than non-immersive learning material. In assessing the pedagogical potential of iVR, a VR simulation of a relatively simple chemical experiment – the reflux experiment – is developed.

Furthermore, the surrounding literature highlights the difficulty of developing high-quality iVR simulations, especially in terms of development time, technical expertise, and financial cost. As a VR simulation is developed within this study, the secondary research objective aims to show that the development of a high-quality VR simulation can proceed quickly while being inexpensive and technically accessible. As part of this, the user experience of the VR simulation will be investigated, allowing insight into factors such as presence, visual clarity, and ease of interaction to determine the quality of the simulation.

3. Materials and Methods

3.1. Participants

10 participants were recruited for the study, comprising four women and six men with ages ranging from 19 to 54 (mean = 26.3). The majority of participants were students of Humanities at the University of Bristol, but three participants outside the university and a researcher from the university's Psychology department were also recruited. All participants had a non-Chemistry background and had studied Chemistry as either a GCSE or an A-level. Participants were informed of the study through a recruitment letter and provided written consent. The study was approved by The Faculties of Life Sciences and Science Research Ethics Committee (FREC).

3.2. Study design

Participants were randomly assigned to the VR group (n = 6), which undertook the immersive VR simulation, and the control group (n = 4), which undertook a non-immersive 2D web-based simulation.

3.3. Materials

The materials used included: a non-immersive 2D web-based training simulation; a VR laboratory simulation; a participant questionnaire; a procedural understanding assessment; and a post-intervention questionnaire which assessed the participant's opinions regarding their VR experience.

3.3.1. DLM Web Application

A 2D web-based training simulation found on the University of Bristol's Digital Learning Manual (DLM) was used for this study.[99] The simulation is designed to teach procedural knowledge of the reflux experiment to undergraduate Chemistry students and is currently used for this purpose at the University of Bristol. It emphasises the exploration of procedural outcomes and encourages learning from the consequences of the user's choices with the provision of instant feedback. The reflux procedure used in this simulation proceeds via (1) adding anti-bumping granules to a round-bottom flask half-filled with liquid, (2) clamping the flask, (3) filling the condenser with water from the bottom and removing water from the top, (4) securing the tubing with wire, and (5) setting the heating temperature to a moderate heat. Potential mistakes include an omission of any of these steps, setting the temperature too high, using a flask that is too small, adding a stopper, and filling the condenser from the top.

The simulation begins with an introduction screen which provides a general guideline for the experiment and encourages the user to explore different procedural options (Fig. 6).

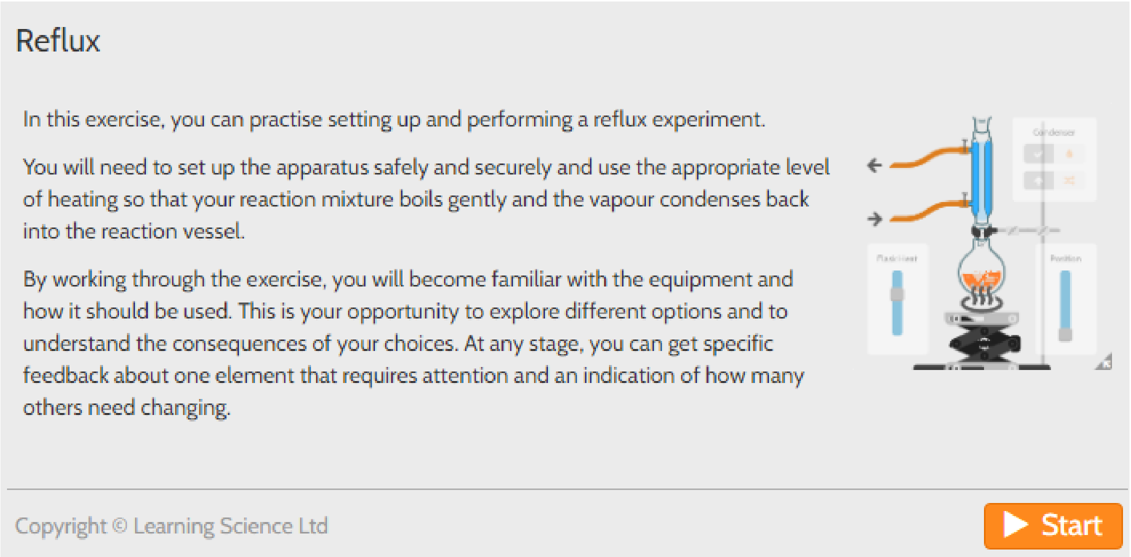

Figure 7: The introduction screen of the DLM's 2D simulation.[99]

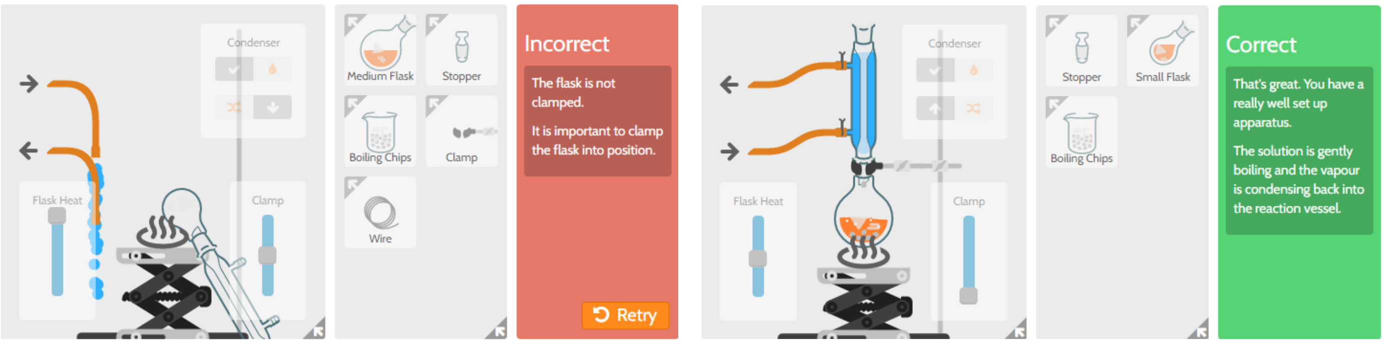

Figure 6: Examples of the error and success screens of the DLM's 2D simulation.[96]

When the user starts the simulation, a new screen containing a 2D representation of an incorrectly assembled reflux apparatus appears. An animation shows the apparatus disassemble, and then the user is asked to assemble it correctly. The user can interact with web elements to add and remove paraphernalia and adjust various properties of the equipment. A click-and-drag motion can be used, for instance, to add boiling chips to the flask or clamp the glassware. Sliders can be dragged to control the temperature and the height of the clamp. A button allows the user to enable and disable water flow while another switches the input and output of water into the condenser. At any time, the user can press a button to acquire feedback on the current state of the experiment. This plays an animation which displays the outcome of the experiment in its current state and outputs a success or error message depending on if the assembly is correct (Fig. 7).

3.3.2. Virtual Reality Laboratory Simulation

A VR laboratory simulation was created for the study using the Unity game engine along with the Unity XR plug-in and the Obi Rope package. The source code for the simulation is available at http://github.com/adamski201/VRLaboratory. Custom scripts were also written for the simulation using the C# programming language. The simulation utilizes roomscale-based locomotion, and so the virtual environment was scaled to a 5x5 m mat in the physical environment where the study took place. 8x MSAA anti-aliasing and anisotropic filtering were used.

Figure 8: The laboratory environment produced for the VR training simulation.

The reflux procedure was the same as the one found in the DLM simulation. In the simulation, the user carries out the procedure by trial and error, and trying out different options is encouraged. The user is informed when a mistake is made by an error message that displays in the virtual environment, and this guides them to make a correction.

The virtual laboratory simulation was planned using software development principles (Table 1), including a *spike*, which is an early prototype; a *minimum viable product* (MVP), a stage of production where project feasibility can be evaluated and user testing can be performed to guide further development; and a *minimum sellable product* (MSP), which describes the minimum set of features for a marketable and launchable product. For this study, the aim was to meet the features appropriate for an MVP as this was suitable given the timeframe for a bachelor's project.

The virtual laboratory was low-detail and contained a fume cupboard, two desks constricting the real-life play area, and a whiteboard (Fig. 8). The fume cupboard contained a mixture of static and interactable objects, including a hotplate with a heating mantle, a clamp stand, a beaker with fluid, two water tubes (labelled 'sink' and 'tap'), and a clamp. On one desk was placed a cork ring and a box containing various objects. The objects contained within were interactable and consisted of a stopper, a condenser, a round-bottom flask, a vial of anti-bumping granules, a spatula, and two wires for securing tubing. The stopper acted as a "distractor", whose role was to provide an opportunity to make a mistake that users could learn from.

Table 1: Project plan showing features necessary for a "spike", MVP, and MSP.

Feature	Spike	MVP	MSP
Environment & appearance			
Primitive floor plane environment.	☑	☐	☐
Laboratory environment produced using non-primitive assets.	☐	☑	☑
Essential sound effects - fume cupboard noise, condenser running, etc.	☐	☑	☑
Non-essential sound effects e.g. glass "chink" upon contact.	☐	☐	☑
Untextured/simple colour fills.	☑	☐	☐
Basic textures.	☐	☑	☐
High-resolution, stylistically coherent textures.	☐	☐	☑
Fluid interactivity			
Basic fluid graphics: primitive cylinder.	☑	☑	☐
Advanced fluid graphics: fluid fills container mesh and "flows" as expected (possible using shader graphs?)	☐	☐	☑
Basic fluid transfer: single fluid from container to glassware.	☑	☐	☐
Advanced fluid transfer: transfer and keep track of various named fluids.	☐	☑	☑
Fluid depletes when vessel is inverted.	☐	☑	☑
Particle effects to accompany fluid draining when vessel is inverted.	☐	☐	☑
Interface			
No interface	☑	☐	☐
Error message displayed upon mistake being made	☐	☑	☑
Associated error sound effect	☐	☑	☑
Fade-in upon game start.	☐	☐	☑
Ability to reset environment to initial conditions.	☐	☐	☑
VR implementation			
Room-scale VR environment, tracking player movement.	☑	☑	☑
Primitive object representing VR controller with direct interactors.	☑	☑	☑
Hand models representing VR controller.	☐	☑	☑
Finger tracking with animated changes to hand model.	☐	☐	☑
Socket interactable mesh upon hover.	☑	☑	☑
Prevent both hands from grabbing same object (visual bug), with exceptions if any 2-handed objects exist.	☐	☐	☑
Prevent socketing with non-user-selected interactables upon collision, where necessary.	☐	☑	☑
Game objects respawn if they fall out of the guardian zone.	☐	☐	☑

Dynamic objects could be picked up, moved, and rotated by the user. Picking up an object provided haptic feedback via the vibration of the controller. Compatible objects could be attached, such as the clamp to a 'socket' on the clamp stand. The Unity XR Socket Interactor script was used to develop this functionality. Socketing controlled the attachment of multiple items, including the vial to the vial lid, tubing to the condenser, stopper to the condenser, flask to the cork ring, condenser to the flask, flask to the heating mantle, and wires to the tubing.

A basic fluid simulation was developed, which resulted in the “liquid container” and “pour liquid” scripts. Fluids were represented by primitive cylinders assigned to parent container game objects. This was necessary because of the technical difficulty of implementing simulated fluids that conform to the walls of a vessel; using cylinders circumvented this problem while meeting the standards for an MVP. Colliders were used to detect when one container was pouring into another container. While the colliders on the receiving container and the pouring container intersected, the receiver container’s ‘liquid’ cylinder would be continuously scaled along the vertical axis and simultaneously moved upwards. This gave the appearance of the container being filled. The simulation also allowed tracking of anti-bumping granules, named fluids, and fluid depletion when a container was inverted. The fluid simulation script was additionally used to fill the condenser when the water flow was enabled (Fig. 10).

Figure 9: User picking up an anti-bumping granule from the vial using a spatula.

Other important physics interactions were involved in the anti-bumping granules and the water tubing. The granules were represented by spheres and could be captured with a spatula and placed in the round-bottom flask using Unity's built-in physics engine. The water tubing physics was implemented using the Obi Rope external package, which enabled realistic rope physics such as bending and stretching.

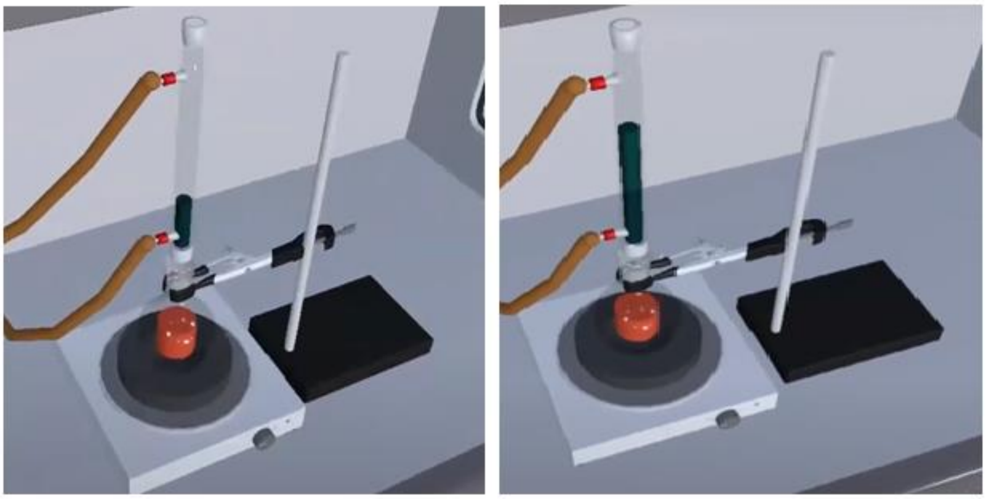

Figure 10: The condenser filling up using the liquid container script functionality.

The feedback and assessment system in the VR simulation was adapted from the DLM simulation, including all potential errors except for the use of a small flask. Error messages were kept consistent between the two simulations. Real-time feedback was triggered when a mistake was made, using scripts on each dynamic object associated with an error to monitor the system state and trigger a Unity Event. The Unity Event called a function in an Error Handler script, which displayed the error on the whiteboard. Corrections were similarly made by triggering calling a Unity Event to remove the error message from the board.

The reflux controller script monitored the experiment's progress by accessing the public functions of the individual component's controller scripts. The controller scripts provided unique functionality. For instance, the condenser controller script monitored water flow by calculating the water dial's rotation in 3D space and computing the heights of each water tube along the vertical axis of the condenser. Once these were determined to be in the correct state, the script called the Fill() function on the condenser's liquid container script (Fig. 11).

```
// Fills the condenser with water when tubes are attached correctly and water is on
private void HandleCondenserInternal()
{
    if (tubesCorrectlyAttached && dial.Value <= 0.2)
    {
        condenser.FillContainer("Water", material);
        PlayAudio(); // Plays bubbling SFX
    } else
    {
        condenser.EmptyContainer();
        PauseAudio(); // Pauses bubbling SFX
    }
}
```

Figure 11: Code snippet from the Condenser Controller class, which handles the filling and emptying of the condenser using function calls from the LiquidContainer class.

Sound effects were used in the simulation for certain actions, such as filling the condenser with water or indicating an error. Royalty-free sound effects were sourced online, and the design was fully spatialized. A 'machine hum' sound effect representing the fume cupboard ventilator provided a source of ambient noise. A boiling sound effect played upon completion of the procedure, which was visually accompanied by an animation.

3.3.3. Procedural Understanding Assessment

In the procedural understanding assessment, participants assembled the reflux apparatus in the physical VR lab (Fig. 12). Each participant's procedural path (e.g. Fig. 13) was analysed

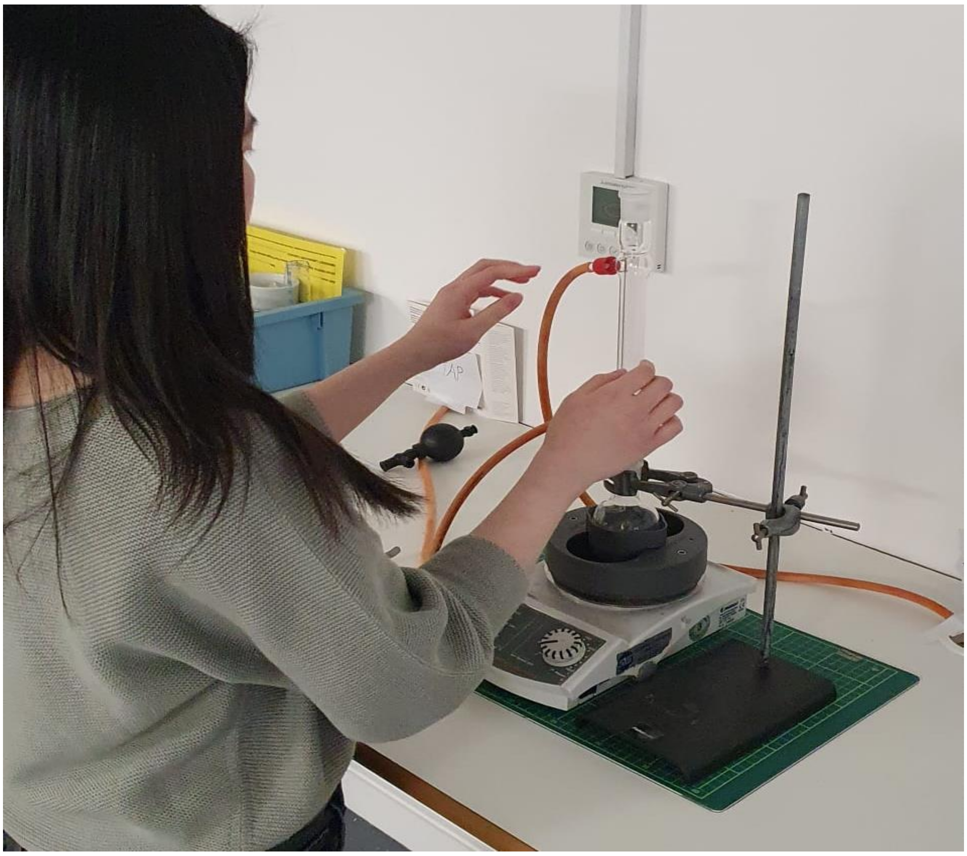

Figure 12: Student undertaking the procedural understanding assessment.

from video footage and total assembly time and the number of mistakes were recorded. Participants were provided with the necessary equipment, excluding wires as they are not used with modern glassware. The condenser was placed in a box of distractor glassware. Water flow and filling the condenser were also excluded. Labels for the source and exit of water flow were provided, indicating "tap" and "sink" respectively.

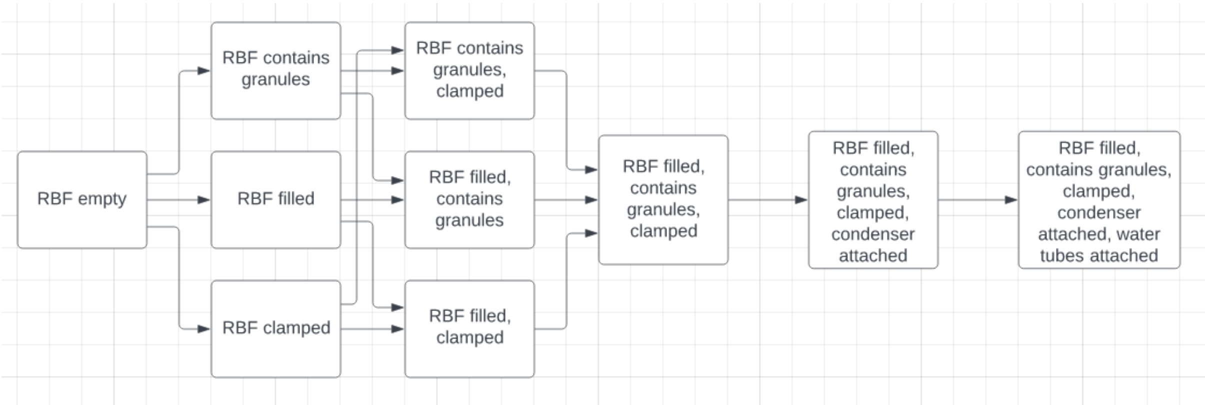

Figure 13: Possible routes (without mistakes) for the reflux procedure used in the procedural understanding assessment.

3.3.4. Pre-Intervention Questionnaire

A pre-intervention questionnaire assessed participants' practical chemistry experience, including their level of educational attainment and confidence in performing the reflux experiment. The participants in the VR group were additionally asked about their familiarity with immersive VR technology. The confidence level was measured using a 7-point Likert scale.

3.3.5. Post-Intervention Questionnaire

A post-intervention questionnaire was administered to measure participants' confidence regarding the reflux experiment after completing the VR or DLM intervention. Participants were also asked to rate how much enjoyment they experienced during the intervention.

For the VR group, additional questions were asked to evaluate the user experience of the VR simulation using a 7-point Likert scale. These questions examined qualities such as presence ("I felt that I was truly 'there' in the virtual world instead of looking into it through a device"), attention ("I was conscious of being watched and this distracted me from being fully immersed in the virtual world"), and interactivity ("Interacting with the environment was reliable; unexpected interactions did not occur"). The questions were adapted from the surrounding literature.[100,101] The final section was adapted from the Cybersickness in Virtual Reality Questionnaire (CSQ-VR)[102] and examined feelings of nausea, dizziness, disorientation, postural instability, fatigue, and visually induced discomfort.

3.3.6. Apparatus

The DLM training simulation was accessed on a desktop computer with a 24-inch monitor and a mouse for interaction. The VR group used the Meta Quest 2 HMD and controllers for unrestricted viewing of the 3D environment and roomscale-based locomotion (Fig. 14). The procedural understanding assessment was recorded with a Samsung Galaxy S10+ mobile phone.

Figure 14: Participant interacting with the VR simulation.

3.4. Procedure

Participants attended the experiment individually at the VR laboratory at the University of Bristol Chemistry building. Intervention groups were assigned randomly before the experiment took place. Each participant was given 30 minutes to complete the experiment.

Participants completed a pre-intervention questionnaire upon arrival, which measured their practical chemistry skill level and, in the case of the VR group, their prior VR experience. The control group completed the DLM web application training simulation on a computer, while the VR group undertook an Oculus VR demo to familiarize themselves with the Oculus Touch controllers before completing the VR simulation.

After completing the intervention, both groups retook the procedural understanding assessment. This was followed by a post-intervention questionnaire which included extra questions regarding user experience and cybersickness for the VR group. All participants completed the entire experiment within 30 minutes.

4. Results

The data sets obtained from the procedural understanding assessment were assumed to be normally distributed and were tested for significance using an independent two-sample t-test. For the "total mistakes made" data set, a Mann-Whitney U-test was performed as it was more appropriate given the lack of variance in the VR group. Results with a p-value less than or equal to 0.05 were considered statistically significant.

One participant (Participant 1) from the DLM group was unable to complete the procedural understanding assessment. To address this, the analysis was first conducted with the exclusion of Participant 1, and then secondly with maximum values assigned to their time taken and number of mistakes made.

When Participant 1 was excluded, the VR group completed the procedural assessment faster on average than the control group (as shown in Fig. 15), but this difference was not statistically significant ($p = 0.55$). However, the VR group made fewer mistakes than the control group (as shown in Figure 16), which was statistically significant according to both the t-test ($p = 0.018$) and the Mann-Whitney U-test ($p = 0.050$).

When Participant 1 was included and assigned maximum values, the VR group completed the procedural assessment faster, but there was no statistically significant difference in time taken ($p = 0.20$). The total number of mistakes made was lower for the VR group than the control group and this effect was significant according to the Mann-Whitney U-test ($p = 0.025$), although not the standard t-test ($p = 0.099$).

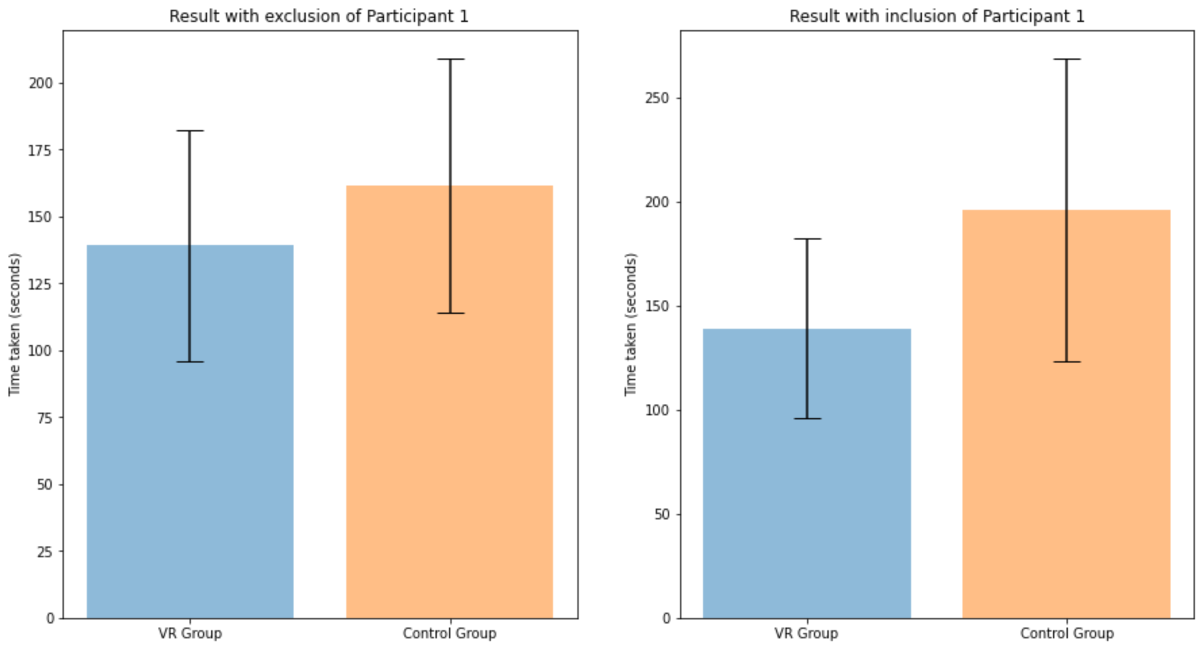

Figure 15: A comparison of the mean time taken to complete the procedural understanding assessment between the VR group and the control group when Participant 1 was excluded (left) and when Participant 1 was included (right). Error bars represent the standard deviations of the samples.

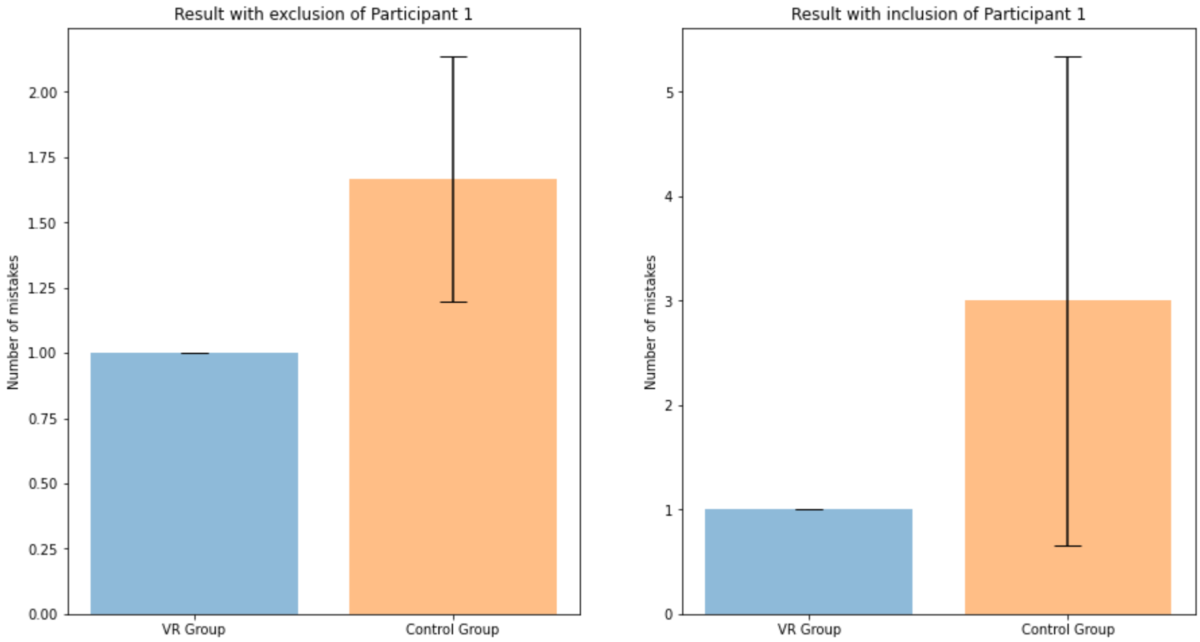

Figure 16: Comparison of the mean number of mistakes made during the procedural understanding assessment between the VR group and the control group when Participant 1 was excluded (left) and when Participant 1 was included with values imputed (right). Note the lack of variance for the VR group, which was a result of chance and the small number of samples. Error bars represent the standard deviations of the samples.

The study gathered data on participant enjoyment and confidence in assembling the apparatus pre- and post-intervention using a questionnaire with a 7-point Likert scale. Qualitative answers were converted to numerical values, and normality was assumed. The results were tested for significance using a standard two-sample t-test.

The VR group reported a significantly greater level of enjoyment than the control group ($p = 0.0034$). Furthermore, the results indicate a lower amount of variation and thus a greater consistency in the enjoyment experienced by the VR group. Both groups reported similarly low confidence pre-intervention, but the VR group demonstrated a significant increase in confidence post-intervention ($p = 0.000081$), while the control group had a minor increase in confidence that was not statistically significant ($p = 0.18$).

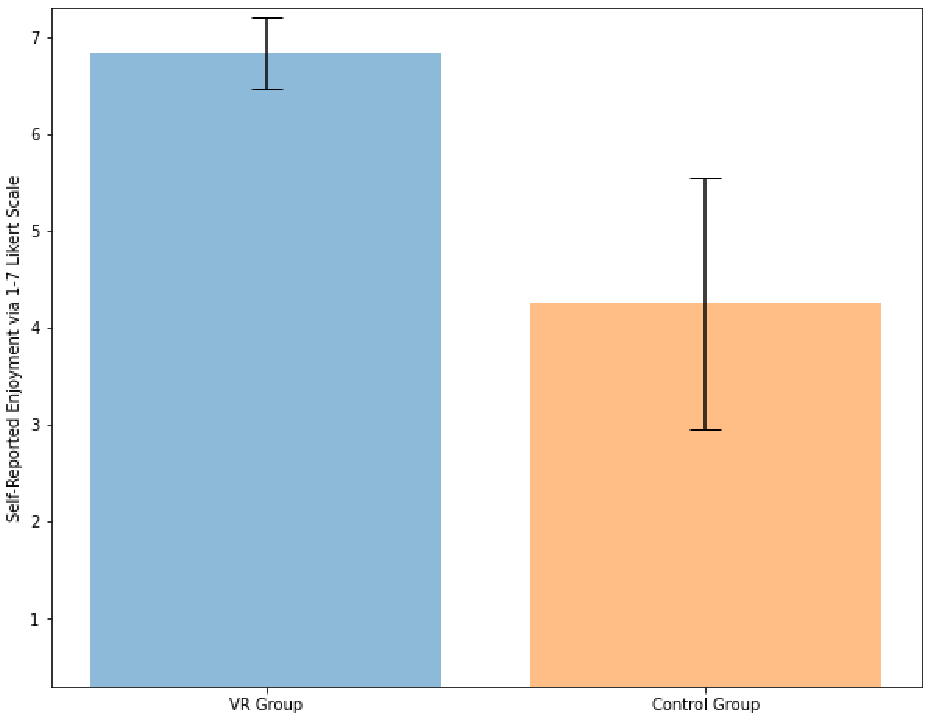

Figure 17: Comparison of the self-reported enjoyment experienced by participants between the VR intervention (left) and the DLM intervention (right). Error bars represent the standard deviation.

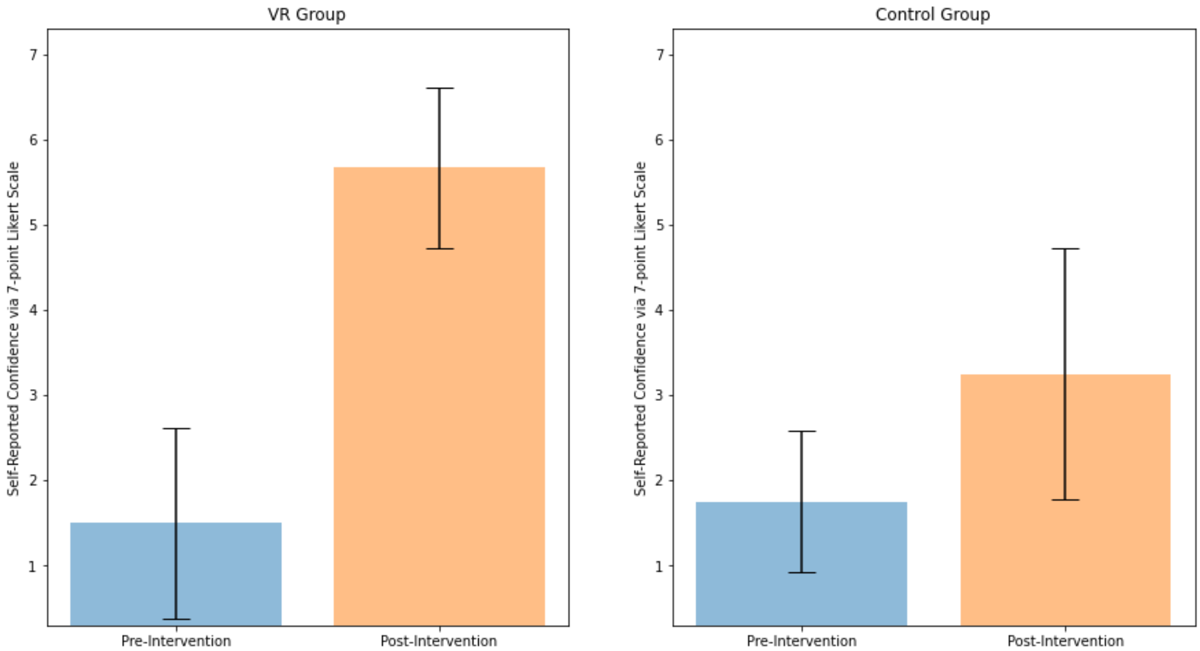

Figure 18: Figure 19: Comparison of the self-reported confidence in assembling the reflux apparatus experienced by participants before and after their assigned intervention. The VR group (left) showed a statistically insignificant increase in confidence (p = 0.000081). Error bars represent the standard deviation.

The pre-intervention questionnaire results indicated that all but one participant in the VR group was VR-naïve. User experience metrics were also gathered via the post-intervention questionnaire for the VR group. Questionnaire items examined relevant qualities such as attention, perceived presence, and ease of interaction using a 7-point Likert scale (shown in Table 2).

Table 2: Results from the VR Post-Intervention Questionnaire.

Category	**VR Post-Intervention Questionnaire Item**	**Mean**	**Standard Deviation**
Presence	"I felt that I was truly 'there' in the virtual world instead of looking into it through a device."	5.7	0.82
Attention	"I still paid attention to my surroundings outside of the virtual reality."	3.0	1.3
Attention	"I was conscious of being watched and this distracted me from being fully immersed in the virtual world."	3.2	1.3
Vividness	"The visual display quality was excellent and I could see clearly."	5.2	1.8
Vividness	"The information provided through audio made the environment seem more real."	4.5	1.4
Interactivity/Usability	"Using the controllers to interact with the environment was simple and easy to pick up."	6.2	0.75
Interactivity/Usability	"Interacting with the environment was reliable; unexpected interactions did not occur."	5.5	1.9
Interactivity/Usability	"Using the controllers was intuitive and I was not conscious of them while interacting with the VR environment."	5.0	1.7
Usability	"The headset was comfortable."	5.0	1.5
Cybersickness	Did you experience nausea (e.g., stomach pain, acid reflux, or tension to vomit)?	1.0	0.0
Cybersickness	Did you experience dizziness (e.g., light-headedness or a spinning feeling)?	1.0	0.0
Cybersickness	Did you experience disorientation (e.g., spatial confusion or vertigo)?	1.2	0.41
Cybersickness	Did you experience postural instability (i.e., imbalance)?	1.3	0.52
Cybersickness	Did you experience a visually induced fatigue (e.g., feeling of tiredness)?	1.0	0.0
Cybersickness	Did you experience a visually induced discomfort (e.g., eyestrain, blurred vision, or headache)?	1.0	0.0

Table 3: Significant Pearson correlation coefficients between feelings of presence and statements from the VR Post-Intervention Questionnaire. Low correlations have been excluded. The low sample size may have introduced statistical artifacts.

	"I was conscious of being watched and this distracted me from being fully immersed in the virtual world."	***"The visual display quality was excellent and I could see clearly."***	***"The information provided through audio made the environment seem more real."***
PRESENCE	-0.49	0.71	-0.53

5. Discussion

5.1. Is an immersive VR laboratory simulation suitable for teaching procedural knowledge?

The principal finding of this paper is that participants who learned the reflux procedure through an immersive VR simulation committed significantly fewer errors than those who learned through a non-immersive 2D web-based application, implying a greater level of procedural understanding. The VR group also demonstrated a larger increase in confidence regarding the reflux procedure after performing the intervention compared to the control group, supporting this finding. This result is consistent with similar studies such as those by Sankaranarayanan, who used immersive VR to teach a fire response procedure, and Bharathi & Tucker, who taught engineering students to assemble a household appliance.[94,95]

One possible explanation for the results of this study is that procedural knowledge is best learned through hands-on experience, as the process of "learning by doing" is a key characteristic of this type of knowledge.[103] The immersive nature of VR, which allows for realistic and interactive simulations, may provide a more authentic experience of performing a task, and this can aid in the cognitive process of learning and remembering the procedure. This contrasts with previous works, which have used Cognitive Load Theory to propose that the high sensory fidelity of VR adds an extraneous load that hinders learners' ability to absorb relevant information.[79] However, the present study investigated *procedural* knowledge (i.e. “know-how”) whereas the previous works most often tested *declarative* knowledge (i.e. simple factual recall) and *conceptual* knowledge (knowledge of the underlying theory or “know-why”). Therefore, the apparent conflict with Cognitive Load Theory may be explained by the fact that, unlike the case of declarative knowledge, sensory information is not extraneous and is instead conducive to the learning of procedural knowledge. This could mean that haptic, visual, and auditory information may reinforce the learning of a procedure in some way.

An alternative explanation for the study's positive outcome could be that the design of the VR simulation minimized cognitive load. This was primarily achieved by using room scale-based locomotion, which has been suggested to reduce cognitive load compared to other locomotion methods as it utilizes automatic spatial updating processes in the brain.[49] Additionally, environmental detail was kept to a minimum as according to Cognitive Load Theory this could provide extraneous information and overstimulate the user.[104] However, this hypothesis contradicts the findings of Harman *et al.,* who demonstrated that variations in VR environmental detail did not affect procedural knowledge.[105]

The practical implication of this finding is that immersive VR could be viable as a pedagogical tool for the learning of procedural knowledge. This presents a multitude of opportunities for its usage. In relation to chemistry teaching laboratories, immersive VR simulations could be used to practice dangerous procedures in a safe environment before carrying out the real task, or for additional practice outside of timetabled laboratory sessions. It could also reduce costs associated with running a physical laboratory and provide flexible and long-distance learning. If sufficiently advanced, it could even replace teaching laboratories as a whole. While this last sentiment may be deemed controversial, Chan *et al.* previously demonstrated that non-immersive computer-based virtual chemical laboratories can provide equal or greater educational outcomes than a physical laboratory, and proposed that immersive VR laboratories could be even more effective than their non-immersive counterpart (though this is as of yet largely unexplored).[93] However, a holistic approach is likely to provide the best learning outcomes and thus an immersive VR laboratory may be more suited as a supplement to the real laboratory.

The study found that participants in the VR group enjoyed the simulation more than those in the web-based simulation group, and this enjoyment may have contributed to their higher engagement with the learning material and increased procedural understanding.[106] However, it is important to note that this effect may not persist in the long term, as enjoyment may decrease as students become more familiar with the VR experience. In addition, enjoyment may not be beneficial when it is hedonic. Van der Heijden argues that information systems that are hedonic in nature cause users to focus on extracting pleasure rather than engaging in productive use.[107] Thus, the significant enjoyment that participants experienced could imply that they found the experience hedonic which may have limited the extent of their learning. Therefore, while enjoyment may have played a role in the study's findings, it is unclear if it was a significant contributor to the procedural skill acquisition that took place.

Another factor which may have contributed to the positive outcome of this study was the participant's lack of familiarity with the VR hardware. On one hand, a lack of familiarity could impede the participant's ability to learn from the VR simulation given that they were learning how to use the device at the same time as learning the relevant material, which would be consistent with Cognitive Load Theory. On the other hand, the lack of familiarity with VR hardware may have contributed to the positive outcome of this study by causing participants to approach the learning material more carefully and patiently, potentially leading to a greater focus on the experience and better learning outcomes. This explanation is consistent with a study by Harman *et al*. which found that prior immersive VR experience was negatively associated with performance on a procedural knowledge recall task.[105] Further research is needed to fully understand the impact of novelty and familiarity on learning in immersive VR.

Overall, there are several factors which could contribute to the positive results of this study. However, identifying the responsible factor or factors is beyond the scope of this research and requires further investigation. Notably, these findings contradict Cognitive Load Theory, which is often used to justify the low effectiveness of immersive VR in education. This suggests that either Cognitive Load Theory is not a comprehensive explanation or that, unlike other aspects of the cognitive domain, procedural knowledge benefits from the sensory fidelity of immersive VR. Alternatively, cognitive load may have impacted the extent of learning in the VR group but was minimized, resulting in a positive effect over the control group. However, it should be noted that due to the study's small sample size, the discussion presented here is exploratory in nature.

5.2. How well-designed was the VR simulation?

The study's post-intervention questionnaire provided valuable insights into the quality of the VR simulation and its impact on the participants. The questionnaire revealed that the participants experienced to some extent a sense of presence during the VR simulation. This was also associated with positive scores on questions about vividness and interactivity. In particular, the question about the display quality of the HMD showed a strong correlation with reported feelings of presence. That all three question groups had positive ratings suggested that this part of the questionnaire was effective, as it is expected that feelings of presence emerge only when the degree of vividness and interactivity is satisfactory. These results indicate that the simulation was effective in creating an immersive experience that produced feelings of presence among participants.

However, one question from the ‘Vividness’ category received mixed results. The question asked participants how they perceived the use of audio to contribute to environmental realism and this likely caused confusion among the participants, which was brought to the attention of the researchers by participants - one of whom expressed “There was audio?”. The VR simulation used audio effects for key interactions, such as the sound of water running when the water flow was enabled through the condenser, and the ambient noise of the fume hood. It was intended that audio would enhance the environmental realism and induce greater presence. However, the absence of sound effects for minor interactions, such as placing a glass on the table or filling the flask with liquid, may have reduced the overall audio information and environmental realism. Furthermore, the Meta Quest 2 uses speakers instead of headphones, which may have decreased audio quality and reduced attention to audio information. The results suggest that greater audio detail may be necessary for participants to actively notice it and enhance environmental realism, and the use of headphones may provide better audio quality. Additionally, clearer and more specific questions related to the use of audio in the VR simulation may be needed to obtain more consistent results.

The questions from the "Attention" category were included in the questionnaire as focusing on the virtual environment was crucial to experiencing a sense of presence. Fernandes *et al.* had previously reported that the perception of being watched while using an immersive VR device limited feelings of presence by diverting attention away from the virtual environment.[108] To investigate this, one question in the questionnaire asked participants whether they were conscious of being watched and if this distracted them from being fully immersed in the virtual world. Interestingly, participants generally disagreed with this statement, and the scores for this question had a negative correlation with feelings of presence. This is consistent with Fernandes *et al.*'s findings, but the participants in the present study did not feel like they were being watched, even though they were being monitored for health and safety reasons. This may have reflected the personalities of the participants; participants who signed up for the study likely did so because they were excited to try VR, while those who would feel anxious may have declined to participate. The result could also be because Fernandes *et al.*’s study involved a video game whereas this study involved a training simulation. It is possible that being watched while engaging in a pleasurable activity may be more distracting than being watched while learning, which is something students may be accustomed to as they often learn in the presence of a teacher.

One positive finding from this section of the study was that participants generally found the controllers easy to learn and intuitive when interacting with the simulation. Participants generally agreed that they were not conscious of using the controllers, which indicates that learning the controls did not increase cognitive load. The design of the controls was a crucial consideration, and it was decided to use only the "trigger" button to simplify the control scheme. This button is a standardised feature for "grabbing" objects in VR devices, and the Meta Quest controllers were designed to provide some degree of kinaesthetic feedback by making it feel like participants were grabbing an object when holding the trigger. This control scheme worked well for the reflux experiment, which is a relatively simple procedure. However, it was observed that participants found using the spatula to pick up and deposit anti-bumping granules challenging. Additionally, the procedure did not effectively teach participants how to set up the clamp, and participants struggled with this aspect during the procedural understanding assessment. These findings are in line with Jensen and Konradsen's research, which suggests that immersive VR is currently unsuitable for learning psychomotor skills using available peripheral devices.[72] A few participants also reported that they found the controls distracting and unintuitive. This was most likely due to their unfamiliarity with the device and the fact that people have different rates of acquiring new practical skills. With further practice, this effect could be reduced. In summary, while the control scheme was intuitive for most aspects of the simulation, there were still some challenges related to the more dextrous parts of the simulation, and these findings may not generalize to more difficult procedures.

While the score for the reliability of interaction within the simulation was favourable, the high standard deviation suggests that not all participants had the same experience. This question aimed to assess the prevalence of bugs and poor implementations in the simulation, and the results showed that some users did encounter these issues. The most likely cause of this perception was bugs in the physics simulations. During development, the behaviour of the water tubes and granules within the vial was problematic and unpredictable, and bugs related to these were observed during the experiment. Despite spending extensive time on bug-fixing, the root causes of these issues could not be identified. This highlights a common challenge in the development of VR games and simulations. Unlike non-VR games that have extensive tutorials, tips, library documentation, and online community discussions, VR games often lack such resources due to the technology's recency and the relatively small size of the developer community. Although VR development tools have made significant progress in recent years, community-provided information, such as best practices, is difficult to find or even non-existent, and documentation is frequently incomplete. The author notes that obsolescence within the XR toolkit was frequent, but information on any updates was scarce or entirely unavailable. This made solo development without prior knowledge or expertise particularly challenging, resulting in longer development times and a higher prevalence of bugs.

Finally, the findings of the cybersickness section of the questionnaire indicate that very few participants experienced any effects of cybersickness. This is likely due to the focus of VR hardware manufacturers on reducing cybersickness in their devices; this is supported by the findings of Caserman *et al*. who reported that modern VR devices have much lower incidence rates of cybersickness compared to their predecessors.[82] The few experiences of cybersickness in the VR simulation were described as "very mild" and were limited to postural instability and disorientation. These effects may have occurred as some users needed time to acclimate to the disembodiment of VR.

Overall, the study demonstrates that an individual with no prior experience in software development or game development can create a high-quality immersive VR simulation without the need for a dedicated artist, thanks to the abundance of free 3D assets available online. The findings suggest that developing a VR simulation does not have to be expensive or time-consuming. The availability of VR development tools like the Unity engine has made it technically feasible and cost-effective to create such software. As a result, the lack of VR software may no longer be a barrier to its adoption in educational institutions in the coming years.

6. Limitations

The limitations of this study are as follows:

- The study cannot identify the specific features of immersive VR that contributed to the positive outcome, making it difficult to provide practical contributions. However, the study has shown that novelty, enjoyment, interactivity, and presence may all play a role to varying degrees.

- The sample size was small, limiting the study's rigour, so the results cannot be used to draw significant conclusions. Hence, this study served primarily as a pilot study for further research at the University of Bristol.

- The intervention and overall study length were of short duration. It is noted in multiple reviews of the literature that more long-term studies are needed in this area of research.[72,86] As noted in the discussion section, the novelty of the experience may impact the amount of learning that took place and thus longer exposure times or multiple sessions could minimize the confounding effect. Longer-term studies could also examine how student attitudes towards immersive VR change as they gain familiarity with the technology.

- Only one procedural task was measured and thus findings may not be generalisable. This study looked at a relatively simple chemistry experiment to measure procedural knowledge gains, but it is not clear whether these results apply to more complex experiments and indeed procedures outside of the field of chemistry.

- The underlying pedagogical theory was adapted from a 2D web-based simulation, and it may not be the optimal approach. Determining *how* to use immersive VR to teach procedures is an important area for future research to maximise learning gains. As Chan *et al.* argue, collaboration between VR software developers, lecturers, and educational technologists is needed.[93] This collaborative effort would help ensure that VR simulations are designed with effective pedagogical approaches in mind and thus can be seamlessly integrated into existing educational institutions.

7. Conclusion

The study set out to determine if an immersive VR simulation could be used to teach procedural knowledge. Although the study was largely exploratory, it is shown that immersive VR simulation may be viable for this purpose, which is consistent with the surrounding literature. Furthermore, while previous studies have looked at the learning of declarative knowledge, the author believes that this is the first time a study looking at procedural knowledge has been conducted in the context of an immersive VR laboratory using a high-end HMD and peripheral device. Furthermore, the study shows from a technical perspective that the development of a high-quality immersive VR simulation is financially feasible and highly accessible. The results of this study suggest several potential areas for future research:

- Examining the long-term effects of immersive VR interventions on procedural learning. Novelty most likely played a role in the outcome of this study and investigating this aspect is of key importance to determine the sustainability of this approach.
- Exploring different options for instructional theory to guide the development of immersive VR simulations. With more and more studies beginning to show immersive VRs effectiveness for procedural skill acquisition, it may be time for studies to start investigating *how to* use it rather than only if it *can* be used.
- Examining the effects of immersive VR on learning procedural knowledge across various subject areas and more complex chemical experiments is necessary to determine the generalizability of the findings.

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