JOURNAL OF CHEMICAL EDUCATION

Breaking the Access to Education Barrier: Enhancing HPLC Learning with Virtual Reality

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Cite This: https://doi.org/10.1021/acs.jchemed.4c00540 | Read Online

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ABSTRACT: This research focuses on an innovative approach to the practical teaching of High Performance Liquid Chromatography (HPLC), specifically exploring the application of Virtual Reality (VR) in undergraduate education. Traditionally, the exposure to HPLC instrumentation for undergraduates has been limited due to a substantial student population and the prohibitively high costs of these systems. To overcome these challenges, we developed our own in-house multi-user VR software, as well as a VR digital twin model of HPLC instruments in our laboratory and placed multiple copies of these in a training environment, aiming to simulate a realistic, interactive, and immersive learning HPLC environment. The investigation of its effectiveness included a group of first year undergraduate students with no previous HPLC experience, aiming to assess the reception of the VR learning environment among a student cohort. The use of the VR software positively influenced student engagement with HPLC training. Survey results indicate that the majority of students greatly enjoyed the VR sessions, with many students reporting a heightened interest in practicals and self-reporting that they learned better than they would have using text or PowerPoints, though formal assessment is needed to quantify its impact on learning outcomes. Notably, students reported a heightened confidence in their operational understanding of the instrument and exhibited a more profound grasp of the underlying theoretical concepts. In light of these findings, we propose that VR learning environments equipped with digital twins of laboratory equipment can greatly enhance practical teaching, particularly in areas constrained by equipment accessibility. This work, therefore, offers compelling insights into the potential of VR learning environments in reshaping HPLC practical teaching in undergraduate education.

KEYWORDS: *High Performance Liquid Chromatography (HPLC), Virtual Reality, Digital Twins, Undergraduate Education, Digital Training, Chemical Education Research*

INTRODUCTION

According to Chemistry and Biosciences Subject Benchmark Statements issued by The Quality Assurance Agency for Higher Education in the UK, hands-on laboratory experience is a fundamental component of scientific education that enables students to develop practical skills, deepen their understanding of theoretical concepts, and prepare for future careers in their field, and remains an indispensable tenet of science education.[1,2] However, as the complexities of scientific equipment have increased access to specialized laboratory equipment is often limited due to financial considerations, safety concerns, or availability, with safety concerns being cited as one of the biggest detriments to specific equipment training.[3,4] This creates significant challenges for educators in delivering a comprehensive laboratory curriculum, particularly in fields such as chromatography, where the cost of the equipment is prohibitive for many institutions. While this problem is challenging for educators in High- or Middle-Income Countries (HMIC), this problem is exacerbated in Low-/Middle-Income Countries (LMIC) where economic resources for education are less abundant. Further to this, research into the disparities in education for marginalized groups of students, including those with physical and learning disabilities, is well documented across STEM subjects.[5,6] This inequality leads to enduring education training barriers for certain students, which ultimately limit their potential in the posteducation jobs markets.

High Performance Liquid Chromatography (HPLC) is a widely used analytical technique in many fields of science, including chemistry, biochemistry, pharmaceuticals, and

Received: May 8, 2024
Revised: September 4, 2024
Accepted: September 6, 2024

environmental science. It is an essential tool for identifying and separating complex mixtures of molecules, and its applications are widespread in research, development, and industry. Incorporating HPLC training in undergraduate education provides students with a unique opportunity to develop technical skills and gain experience with an essential piece of laboratory equipment. HPLC training enables students to learn about the principles and theory behind the technique, acquire practical experience in sample preparation, calibration, and instrument operation, and develop analytical thinking and problem-solving skills.[7]

While videos and 2D online interfaces allow for some level of substitution of in-person training on high-end equipment such as this, they cannot fully replace detailed three-dimensional in-person training. However, enabling technologies such as Virtual Reality (VR), can offer a potential solution to these challenges as with the simple addition of a low-cost headset (~$400), students can interact with digital twin models of machines costing several $10,000s.

The importance of seeking effective alternative approaches to in-person instruction is well documented. During the COVID-19 pandemic, multiple methods of delivering online remote learning within STEM subjects were investigated, including 360° videos, mobile phone applications using Augmented Reality, and PC based simulations.[8−10] Despite these efforts, many approaches failed to provide the same level of engagement as real-life practical sessions. However, research during the COVID-19 pandemic began to explore how well VR applications may bridge the gap between remote learning and in-person learning experiences. A scoping review by Chan et al. indicates that VR experiences provide greater learning outcomes than passive media such as 360° video or PowerPoint slides, especially in cases where students must actively complete a task or problem solve, and that learning outcomes for VR experiences were comparable to hands-on instruction.[11]

The use of VR for chemical sciences education is also well documented, for example as a new visualization tool for molecular modeling, stereochemistry, and atomic orbital structures,[12−16] an alternative to wet laboratories and to teach prohibitively expensive or dangerous techniques in a safe manner,[17−22] and for laboratory health and safety instruction.[23] These examples demonstrate the ability of VR to create immersive, interactive, and safe learning environments that can simulate laboratory equipment and procedures. In particular, digital twin models offer a high level of fidelity, enabling students to engage with and manipulate realistic representations of laboratory equipment and processes. In addition to this, VR can provide greater opportunities for access to scientific education for students with disabilities as VR can be used anywhere and at any time without the need for students to have physical access to a laboratory.[19] Creating inclusive learning environments will be crucial in the future education of students, especially in a world which is more online than ever before.

Cognizant of these challenges with traditional laboratory-based practical's and following our own research into the applications of VR software, in this work we now describe our development and use of a detailed and engaging VR HPLC training software to address these training deficits for undergraduate education. The software was developed in-house using Unreal Engine 4.27 and true-to-scale 3D modeling of Agilent HPLC instrumentation, with simulated physics to create an immersive learning ecosystem (Supporting Information). The software was subsequently used in a series of workshops for 160 undergraduate students at the UCL School of Pharmacy, enabling students to gain hands-on experience with HPLC equipment and enhance their understanding of the theoretical concepts involved. This preliminary study sought to assess the practical considerations associated with running VR workshops for a large number of students, and aimed to evaluate student's attitudes toward this novel teaching approach using an online survey tool.

METHODOLOGY

Design and Development of the Software

The VR training workshop was designed to complement an established laboratory-based session centered around the separation of sulfonamide antibiotic drugs with diverse physicochemical properties (Supporting Information). During the wet lab segment, students were assigned the task of identifying sulfonamides in a mixture through thin layer chromatography (TLC), using both normal and reverse phase techniques. The VR training program replicated this task but employed a different separation technique (HPLC) for comparison with TLC. By integrating the VR training into the existing laboratory class, students were able to benefit from the advantages of both approaches, creating a comprehensive learning experience. The incorporation of VR technology served as a complementary tool rather than a complete replacement for practical sessions, underlining its potential to enhance educational outcomes.

The design of a virtual reality (VR) experience plays a pivotal role in determining the level of benefits derived from its usage.[24] Meta-analysis has found that active learning within a VR environment, such as being given a specific task to complete, enhances the VR experience and the quality of information retained.[25] Therefore, we aimed to develop a VR experience involving the use of VR headsets that involved the students moving around the environment as opposed to 360-degree videos, and required students to take a more active approach to learning than would usually be employed. Creating an interactive VR environment allowed the students to obtain a more realistic experience of working in a HPLC laboratory and ensured that students stayed engaged throughout the experience.

The software was developed in-house using Unreal Engine for both the PC and Oculus Quest 2/3 headsets. To cultivate an immersive and true-to-life experience, it became imperative to generate 3D models within the VR environment that were both realistic and interactive. To accomplish this, the open-source computer-aided design (CAD) software, TinkerCad (Supporting Information), was employed to construct an accurate representation of an Agilent HPLC instrument. The initial design was subsequently exported to Autodesk Fusion 360 for refinement (Supporting Information). Noteworthy interactive features integrated into the instrument included a solvent tray capable of accommodating solvent bottles, interactive compartments for loading sample trays and columns, and a pump (Figure 1). The overall design of the machine in VR enabled students to carry out various tasks required for the successful setup and running of HPLC instruments, including loading solvent bottles which students had to retrieve from around the laboratory, loading samples

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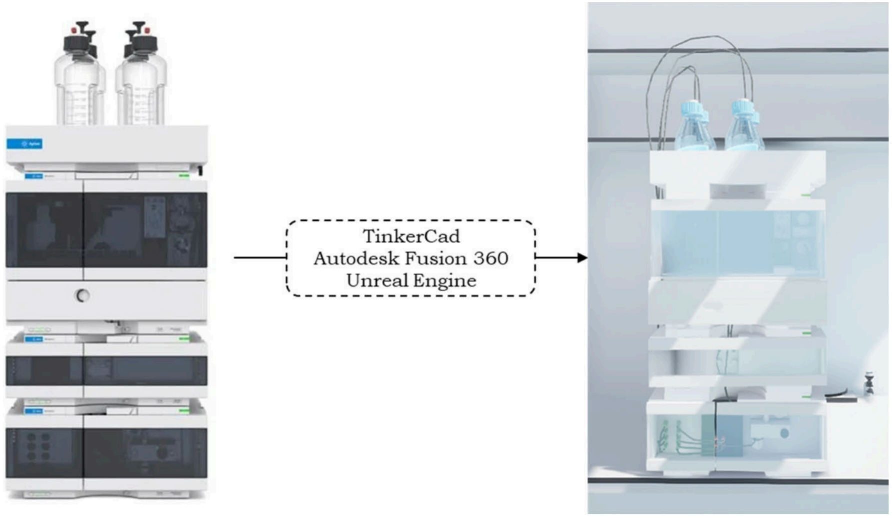

Figure 1. Agilent HPLC instrument modeled using CAD software TinkerCad and Autodesk Fusion 360.

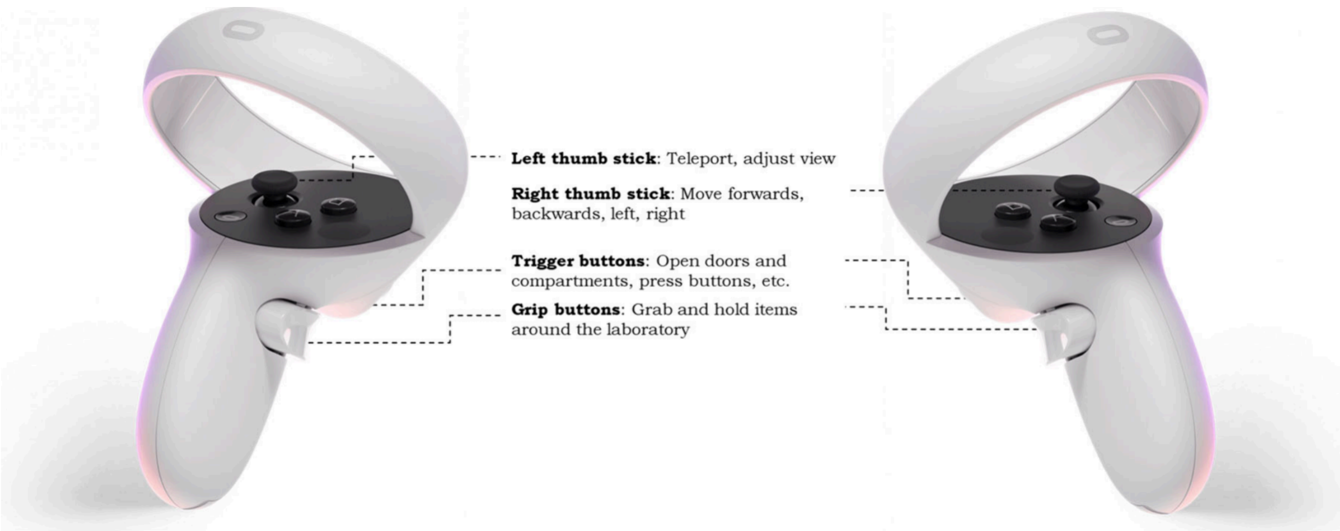

Figure 2. Controls used within the software on the Oculus Quest 2 controllers.

into a sample tray and then into the instrument, and loading the column in the correct compartment and orientation.

The rest of the environment was designed to be easily navigable. Multiple rooms in VR kept the students engaged throughout the course of the workshop and allowed for each space to be designed according to the desired learning outcomes for each portion of the workshop.

■ CONTROLS

Control within the VR experience was designed to be simple and intuitive. Students were encouraged to use both the left and right thumb sticks for movement. The two trigger buttons on the front of the Quest 2 controllers could be used to interact with the environment (Figure 2), such as opening doors or HPLC instrument compartments, and joining the correct multiplayer session. Lastly, the two grip buttons on the side of the controllers could be used to grab and hold objects within the laboratory, including solvent bottles, sample vials and trays, and columns. Students were actively encouraged to reach out and grab items in the laboratory environment and try to place them in their respective HPLC instrument compartments. Due to the headsets being precalibrated for boundary and floor level, there was no need for students to use any of the other buttons on the controllers.

■ LOGIN AND MULTIUSER CAPABILITY

The VR software was designed to be both single user and multiuser enabled in nature, where students could run individual sessions offline, or use it in multiplayer mode in a class setting. Having multiple students and tutors able to access a shared host session fosters greater communication and instruction and allows for the host of the session to guide users more expertly through the VR software via demonstrations and precise guidance. It also improved teamwork, as students were encouraged to work collaboratively during the hands-on portion of the workshop, where students were split into smaller groups of 2−3 people per HPLC instrument across the four instruments in VR. Multiuser capability using sessions also allows for collaboration on a greater scale, as multiuser VR enables students and educators from different locations globally to collaborate in a shared virtual space.

Given that the experience was designed to be multiuser, it became crucial to consider the appearance of other users in VR. As seen in Figure 3, avatars were designed to be

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J. Chem. Educ. XXXX, XXX, XXX−XXX

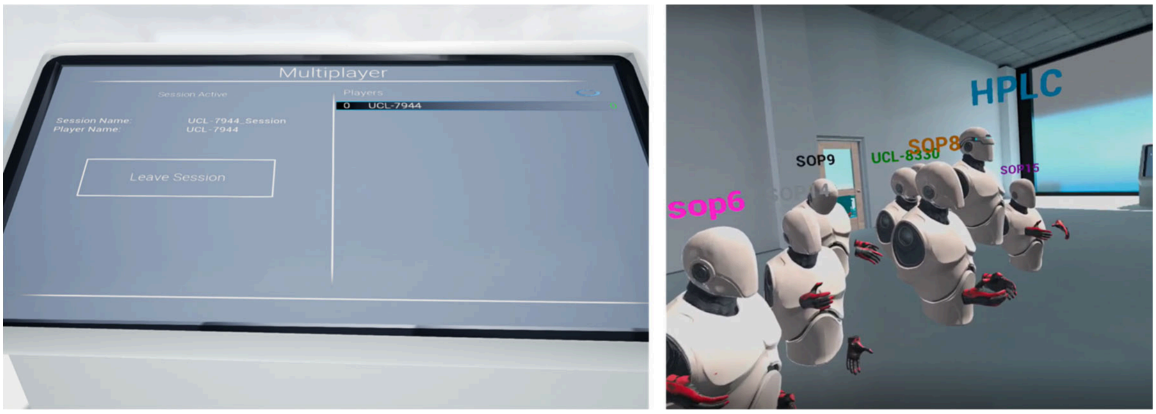

Figure 3. Console located within the first room of the software that enables hosting of multiplayer sessions.

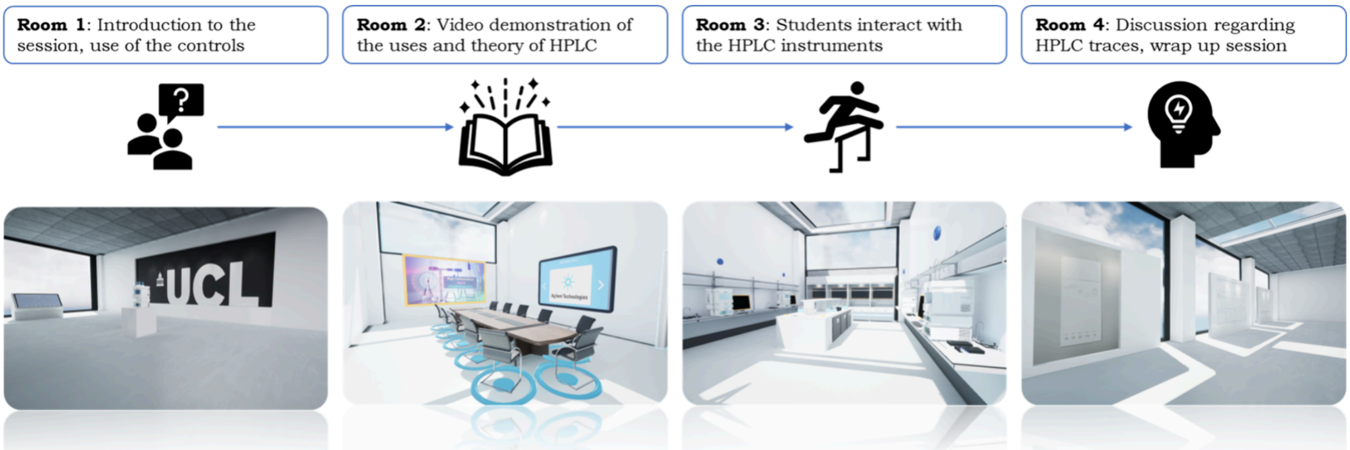

Figure 4. Software design of multiple rooms designed to optimize the VR experience.

purposefully featureless to enable a sense of anonymity, to boost confidence for students performing tasks in VR. The host, operating on a PC version of the same software, was distinguished by a different name, and a visor.

■ DESIGN OF THE WORKSHOP

Given the interactivity of the environment in VR, the way the software was designed to be experienced was of crucial importance, especially given that we anticipated that the majority of users for this software had no prior experience in using VR, although the results of the study indicated that a large number had tried VR before (48% prior experience; Figure 8). As such, each stage of the experience was designed particularly to ensure user comfort. The first room was designed with the purpose of both being a space to introduce students to the workshop, and to enable students to get to grips with the VR controllers and software (Figure 4). Students (and demonstrators) were given copies of the instructions beforehand to view to try to ease the speed of access (Supporting Information). Students were encouraged to try moving around the room using the two thumb stick controls on the Oculus Quest 2. After this, an introduction to the layout of the session was given before students were encouraged to navigate to the second room. This room required students to watch a HPLC instructional video which was 6 min long. This was to enable students to recover from the initial excitement of using VR for potentially the first time, and refresh students on the theoretical concepts behind HPLC equipment prior to the hands-on experience. Room 3 consisted of a virtual laboratory outfitted with four digital twin HPLC instruments. Students were split into four groups of about 2−3 people per group and were encouraged to follow a large instructional slide about how to set up the HPLC instrument. Lastly, the students were taken into the final room to see HPLC example chromatograms and to wind-up the session. Table 1 summarizes the activity each student worked through during the workshop, the average time spent on each activity, and the knowledge acquired.

Table 1. Proposed Plan of the Workshop Session, with Time Spent on Each Activity and the Learning Objectives for Each Stage

ACTIVITY		TIME SPENT	KNOWLEDGE ACQUIRED
Introduction by Laboratory Technician to HPLC		2 minutes	Purpose of the workshop
Introduction by PhD student to VR		5 minutes	• How to use the Oculus Quest 2 controllers • How to put on the headset and adjust straps • How to adjust volume if necessary • How to join the correct session
VR	Room 1: Introduction	2 minutes	• Introduction to the VR environment • Gaining confidence using the controls • Overview of the HPLC machine
	Room 2: HPLC video	6 minutes	HPLC theory and applications
	Room 3: HPLC laboratory	10 minutes	Hands-on experience in setting up and running a HPLC instrument
	Room 4: Chromatograms	2 minutes	Chromatogram analysis and comparison to other chromatography techniques (Thin Layer Chromatography)
Close session		1 minute	Objectives achieved during the session How to leave feedback via the online assessment tool.

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Figure 5. UCL undergraduate students partaking in the VR HPLC training workshop.

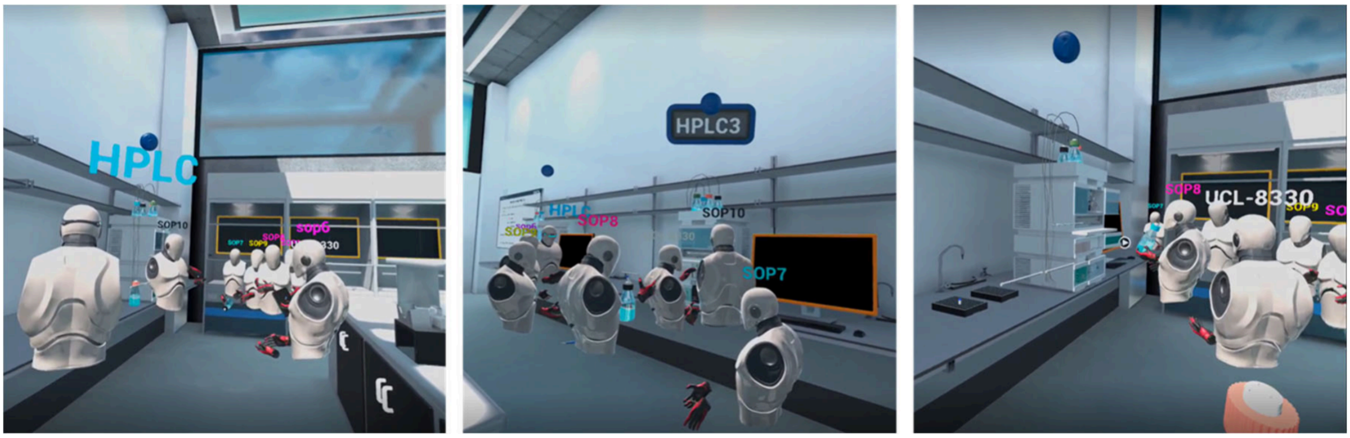

Figure 6. Students gather around an HPLC instrument for a demonstration in VR.

■ RUNNING THE UNDERGRADUATE WORKSHOPS

Over the course of 2 days, a total of 160 students participated in the HPLC VR training workshops. These were led by five Ph.D. students and a Technical Staff member. A total of 14 Oculus Quest 2 headsets were fully charged (10 for use and 4 for spares) and had the required software preinstalled. Headsets were all preconfigured to be connected to WiFi, checked for controller battery level, and on all the headsets, the floor level and stationary boundary had been precalibrated. In the software itself, the username and password had already been entered and the username for each headset had been personalized so that we could quickly identify users in VR and match them to the correct student for troubleshooting. There was one spare headset, and one headset which one of the demonstrators could use to help in the VR program. A PC was used for hosting sessions, and this was connected to a monitor in the workshop area so that people not wearing a headset could always see what was happening (Figure 5).

In terms of physical space required, an empty laboratory was used. Each headset was spaced 2 m apart to enable room for the stationary boundaries to be established and ensure there were no collisions between students and the physical environment. Chairs were provided as some students preferred to sit during the more passive portions of the workshop, such as when the instructional video was playing in room 2. It was also crucial that the space contained multiple charging points, for charging in between sessions, and that all headset stations could easily view a large monitor to follow along with the session should the student chose not to continue in VR (Figure 6).

Students were brought into the laboratory in groups of between 9 and 12 and were instructed to stand beside one of the headsets. A brief introduction to HPLC theory was given by the Laboratory Technician, and then the workshop began with an introduction to VR given by one of the demonstrators present. On average, it took 10 min for these two introductory sessions to conclude and for every student to have entered VR and the correct session. Once all students were in VR, the workshop was conducted as according to Table 1, as students were encouraged to navigate the VR environment and complete the tasks in each room (Figure 7). Time spent in VR varied from session to session depending on Ph.D. student presenting in each room, and any technical issues encountered, but on average the time spent in VR was 20 min. This is significantly faster than the other laboratory-based workshops which were occurring simultaneously on the same day.

During one full day of 7 workshop sessions, in which over 70 students were taken into VR, only three students reported feeling too dizzy to continue with the workshop. Multiple students decided to take off the headset during rooms 2 and 4, and instead watch the video or the explanation of chromatograms on the large screen. It was noted that when asked, these students reported having vision problems within the software,

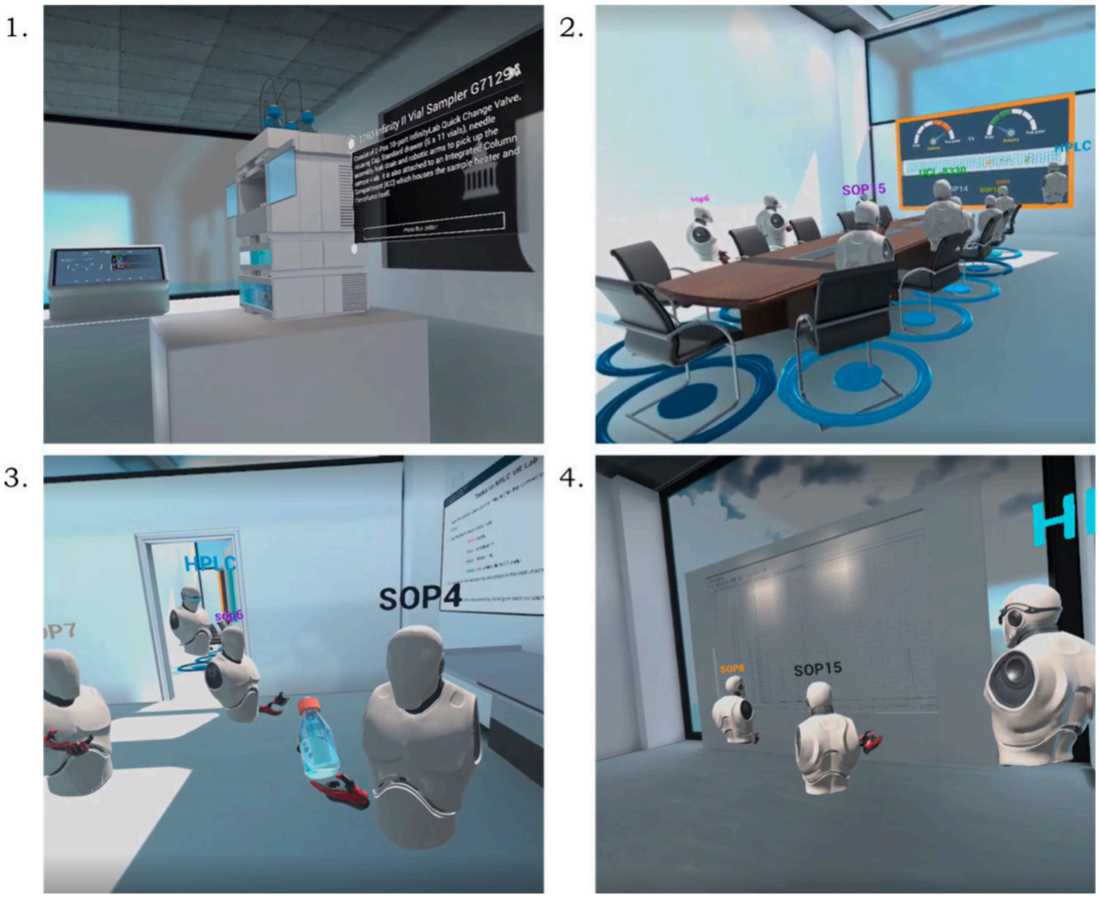

Figure 7. Students progress through the 4 rooms in the VR software.

and were able to see more clearly on the monitor. It may be that the design of the software needs to be reconsidered to assess the real-world benefits of having these sections of the workshop carried out in VR as opposed to traditional methods. However, it may also be the case that this issue could be mitigated by having dedicated time to adjust each student's headset to fit properly and have the correct interpupillary distance (IPD), to reduce dizziness or to provide VR training before the actual sessions.

■ TROUBLESHOOTING

Over the course of the 2 days running the workshops, several repeating issues presented themselves, and it became necessary to mitigate these issues effectively and quickly in order to continue with the sessions in a timely and well-organized manner. Such issues ranged from hardware issues such as depleted battery life, to user-interaction with the headsets, most notably discomfort and motion sickness. Common issues, as well as solutions developed, can be seen in Table 2.

Table 2. Common Issues Encountered and Ways They Were Resolved

Issue Encountered	Solution Developed
Motion sickness	Students were encouraged to remove the headset if feeling motion sick and follow along by watching the monitor.
Battery life	All headsets were fully charged before the morning session, and over lunch.
Joining the correct session	At the end of each session, headsets were logged out and a new host session was started. Demonstrators ensured everyone joined the correct session prior to starting.
Reaching	Students were encouraged to reach only within the stationary boundary.
Standing/ Sitting	Students were encouraged to sit for the instructional video, but it was found that standing was preferable for the active portion of the workshop to quickly turn around and reach for things.
Use of Quest controllers	A demonstration on how to use the controls was given at the start of each session, prior to the students wearing the headsets.

■ RESULTS

Student Feedback

Feedback was obtained via a postworkshop online assessment tool (Supporting Information). This included a series of quantitative questions in which students were asked to rate their satisfaction on a scale of 1 to 5, with 1 being "very dissatisfied" and 5 being "very satisfied". Students also had an opportunity to leave written feedback (Figure 8).

Overall feedback was very positive, with students saying that the practical was "engaging and enjoyable" and reporting that the VR experience improved their theoretical understanding of chromatography and HPLC instrument setup. Notably, an average score of 4.2 out of 5 was obtained for the question "I enjoyed the VR HPLC session", and an average score of 4.2 out of 5 was also obtained for "VR based practical's have good potential." This indicates the high level of engagement students exhibited with the new technology, and their willingness to incorporate it into their future curriculum. Surprisingly, the students were neutral with regard to "VR based practical's can replace physical practical's" (2.5) as we had predicted that they

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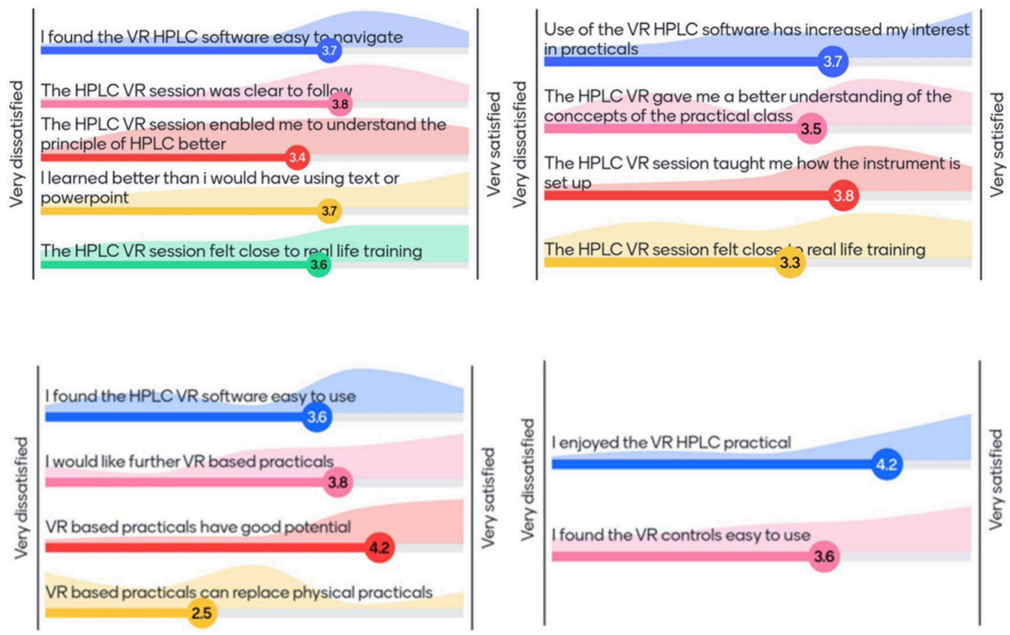

Figure 8. Feedback obtained in response to the VR HPLC training workshops via an online assessment tool.

would score this negatively due to fears of losing real hands-on practical experiences. We attributed this positivity to the fact that the practical was intuitive and also designed to supplement the hands-on practical rather than replace it. However, this supports the development of further VR based practical's, with a score of 3.8 out of 5 for those wanting more VR based practical's in the future, and especially in situations where financial considerations prohibit access to hands-on practical training.

■ DISCUSSION

Overall feedback indicates a strong sense of enjoyment and engagement with the VR workshop, with quantitative scores being reiterated by written feedback such as "Overall I found the practical to be very engaging and enjoyable". Given that in this study only qualitative feedback was obtained, this area of research would benefit from further analysis into the effect of VR on laboratory-based skill acquisition and retention, although previous meta-analysis in the area has indicated that VR benefits from high levels of engagement from students, a key indicator of learning retention.[26] Given that this VR session was an additional workshop, and was not designed to replace hands-on instruction, there was no comparator for quantitative data to be drawn from, though this is something that ought to be investigated in future research.

In addition to positive student feedback, the sessions were relatively straightforward to run and technical issues that occurred could be quickly resolved. Compared to traditional laboratory-based practical's, the VR session was faster, and enabled each student to get hands-on time with the equipment. Lastly, the VR session was widely accessible to the student cohort, with less than 5% of students unable to complete the practical due to issues with motion sickness or blurry vision.

Despite these positives, this preliminary study also highlighted some existing barriers which must be considered and overcome when planning future VR workshops and educational programs, as discussed below.

■ TRAINING BARRIERS

Prior to these sessions, 52% of students had not used VR before. As such, much of the feedback obtained related to usability of the technology. Although above average scores were obtained for the questions "I found the VR HPLC software easy to navigate", and "I found the HPLC VR software easy to use" of 3.7 and 3.6 respectively, in written feedback it was highlighted by students that they would have appreciated more time to become accustomed to the controls and to wearing the VR headset before the workshop began. One student remarked "It may have helped if we had slightly more time to get used to the controls···" while another student wrote "More time has to be given for the students to get accustomed to the software". One potential solution for this issue could be a prior session to the workshop which is purely focused on the VR hardware rather than the software, in which students are taught how to correctly adjust headsets to fit comfortably, and gain experience using the controllers. This would also enable students to have a better idea of what to expect prior to the workshop so that they can come better prepared and more ready to engage in the learning objectives of the workshop. However, if VR is incorporated and integrated within programs, this issue will be reduced to only the first couple of sessions potentially across an entire course.

■ TECHNICAL ISSUES

Given that this was the first time this software had been tested by such a large student cohort, there was some valuable feedback obtained regarding the technical aspects of the workshop. A few of these issues have already been discussed in the Troubleshooting section, however feedback from students highlighted additional aspects of the VR software they would like to be changed or improved. For instance, one student noted that it would be beneficial for the Instructor of each VR session to be visually distinct within the software, so that they could more clearly follow their actions. Further comments indicated additional visual issues within VR such as being able to see other student's laser pointers, leading to confusion, and

https://doi.org/10.1021/acs.jchemed.4c00540
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a certain amount of static when trying to read slides or instructions. Such feedback will help to make the next iteration of software more user-friendly, providing clearer instruction and a more cohesive learning experience.

■ CONCLUSIONS

VR is significantly enhancing education, especially within scientific education, where it can break down long-standing educational barriers and enable students to engage with scientific material in innovative ways. In particular, VR offers a novel way to overcome the prohibitive costs associated with training and acquiring cutting-edge equipment, which significantly impacts LMICs. In response to these challenges, an immersive and interactive VR training software was developed to allow first-year undergraduate students at the UCL School of Pharmacy hands-on practical experience in setting up and running a HPLC instrument. By using this VR technology, students were able to actively engage with the educational material being taught and reported feeling a greater sense of engagement with the VR session compared to traditional text or PowerPoint formats. While students acknowledged that they would have benefitted from more time to fully acclimate to using the Oculus Quest 2 headsets, many students saw the potential that VR had for future integration into their curriculum.

The integration of VR into science education represents a transformative shift toward overcoming long-standing obstacles prohibiting the delivery of high-quality education, while providing students with new and immersive experiences that enhance their learning, problem-solving skills, and ability to tackle real-world scientific challenges. In future work, it would be pertinent to quantify the effect that these new teaching paradigms have on learning outcomes, to best identify how and where these tools might fit into existing scientific education curriculums.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.4c00540.

Further detailed information covering the VR software and information on how to access the digital laboratory (PDF)

Associated undergraduate experiment (PDF)

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Notes

The authors declare the following competing financial interest(s): Dr. Stephen Hilton is the Director of 3D Synthesis Ltd. - a company focused on 3D printing and Virtual Reality.

■ ACKNOWLEDGMENTS

We extend our thanks to the students at UCL School of Pharmacy on the MPharm course, for their willingness to participate in these workshops and their feedback. We are grateful to the Maplethorpe Fellowship for support for Z.M. and to Scott Bader and LifeArc for the provision of a studentship for M.T.

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https://doi.org/10.1021/acs.jchemed.4c00540
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