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Virtual Reality Enhanced Education for Chemical Engineering Undergraduates

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ABSTRACT

Technological enhancements have transformed the way people interact with the digital world. Virtual reality (VR) is one of the key experiential technology innovations that has gathered significant attention. This is due to the possibility of immersing users in highly realistic simulations of various interactive scenarios. This study aims to bridge this gap by bringing realistic industrial training and scenarios via VR while enhancing student knowledge retention and experience. Chemical engineering undergraduate students taking the fluid mechanics course participated in starting up a pump in VR—the pump is one of the most commonly used equipment in the chemical industry. They first underwent safety training and pump start-up procedure in guided mode, wherein visual instructions are given within the VR environment. Students subsequently observed their peers (in groups of four or five) complete the same training through a projected screen, while actively giving verbal guidance to the VR user. Following this, students then individually completed the VR assessment for pump start-up to test their recollection rates. While most students missed out a few minor steps such as the checking of the lubrication oil, all the students scored full marks in the personal protective equipment (PPE) selection, and over 80% of the students completed all the critical steps required to start a pump safely. In the survey conducted, students reported that the VR experience had been enjoyable and enriching. An assessment conducted four weeks later indicated that 70% of the students were able to accurately recall the pump operation procedure in the right sequence without any revision or reference to any materials. These results are early indications of the positive impact of VR on engineering education.

Keywords: Virtual reality, engineering education, experiential learning, industrial training, collaborative learning

INTRODUCTION

Digital transformation has impacted the chemical process industry in recent years. New and emerging digital solutions provide both challenges and opportunities in education for the chemical process industries and for process safety (Khan et al., 2020). Virtual reality (VR) is increasingly being adopted in education and workplace training owing to its ability to immerse users in highly realistic and experiential alternative scenarios with interactive features (Pallavicini et al., 2019). VR as a pedagogical tool in higher education has been receiving more attention in recent years. High-quality graphics and immersive content have revolutionised the way students learn by allowing them to explore complex subjects and scenarios that are otherwise impossible to do so in traditional learning. VR therefore provides an opportunity for students to extend theory to practice, which is crucial for the understanding and application of acquired knowledge in certain disciplines such as engineering and medicine.

Current teaching methodologies for the industrial application of unit operations in chemical engineering (ChE) focuses on the extensive use of equations accompanied by schematics and/or videos of the relevant equipment under ideal scenarios. Students thus miss out on various problems that frequently arise from equipment handling, which may significantly affect large-scale production. Without prior opportunities to operate industrial equipment, students face a steep learning curve when starting out as working engineers in chemical plants, which can be daunting. Since students often embark on their internships towards the end of the undergraduate curriculum, VR training can complement student's industrial training by providing the plant environment experience.

Our team has thus built a virtual chemical plant with various unit operations such as a centrifugal pump, distillation column, and heat exchangers to give students a realistic experience of working in the industry (the current work focuses on the developed VR pump). With a virtual chemical plant in place, dangerous scenarios can be simulated with no real physical consequences. Students are also given the opportunity to operate industrial equipment and to familiarise themselves with the expectations of working in a (simulated) chemical plant within a safe and controlled environment. While the consequences of a poorly-tuned control system can range from poor product purity or equipment damage to a potential explosion in real life, experiencing the same scenario in VR allows students to explore the consequences of their actions and to fail safely without incurring any financial or physical damage. The potential benefits of adopting VR in engineering education is promising. One of the major weaknesses of ChE undergraduates is the practical knowledge and operation of pumps (Luyben, 2002). The use of VR in familiarising second year ChE students with industrial operation begins with the operation of a centrifugal pump, one of the most widely used equipment in a chemical plant. This study describes the developed pump VR and its impact on student learning.

Some of the current works in using VR for chemistry include the replication of current laboratory experiences in VR (Dunnagan et al., 2020), or presenting a scenario to students in the form of animations in VR (Limniou et al., 2008). While the ability to view specific animations related to chemical reactions is great for student learning, the challenge posed in chemical engineering is entirely different. In chemical engineering, beyond the ability to design large-scale reactions, engineers need the know-how when it comes to equipment operation. These industrial-sized equipment are physically huge, with frequent need for maintenance. Allowing students to operate an industrial-sized equipment is typically not feasible from a logistic standpoint due to the extensive time required for the equipment to start up in real life (approximately one day to activate certain equipment), when a typical laboratory session lasts approximately three hours. In a small country such as Singapore where space is a constraint, having multiple industrial-sized equipment at its full scale may also be challenging, on top of the safety issues of allowing inexperienced students to operate them. Herein this work, VR is used to circumvent the abovementioned challenges. With VR, students conduct the exploration in a controlled environment, and any hazards are confined within the virtual environment. In addition to the freedom to bring the entire chemical industry to students as and when required, the VR simulation also allows certain processes to be sped up instead of waiting for hours in real time.

LITERATURE REVIEW

In recent years, VR has been found to be effective in improving training and experiences in various disciplines/areas such as chemistry (Limniou et al., 2008; Dunnagan et al., 2020), nursing (Farra et al., 2012), gaming (Pallavicini et al., 2019), orthopedic surgery (Aïm et al, 2016), cardiovascular medicine (Silva et al., 2018), and clinical medicine (Li et al., 2017). Healthcare and engineering are two apt fields for the application of VR. Both deal with situations where the smallest mistake can lead to drastic consequences (e.g., fatalities). Meanwhile, VR is increasingly used in the chemical industry for training as it exposes operators to common safety hazards, improves their cognitive readiness, and increases their motivation (Manca et al., 2013; Fracaro et al., 2021). VR has also found extensive use as an educational and training tool for medicine (Izard et al., 2018). For example, VR simulators has been reported to be effective in hands-on surgical training, pain management, preprocedural planning, patient rehabilitation, and more.

However, the VR application in engineering education has been sporadic at best. The first VR application in ChE education was developed and documented by Bell and Folger (1996), exploring the effects of catalysts and non-isothermal conditions on chemical reactions. They found that the total immersion of students in this educational experience facilitates experiential learning and the ability to teach students with varied learning preferences (Bell & Folger, 1996). Consequently, students displayed strong interest and enthusiasm in learning as VR is an excellent tool for illustrating spatial relationships and exploring environments that are otherwise inaccessible. Bell and Fogler (1996, 2004) subsequently went on to develop a series of educational VR modules covering several core ChE topics at the University of Michigan, and applied VR in virtual chemical plants and virtual laboratory accidents.

It took nearly a further decade for VR to gain popularity, with the development of various VR environments such as polymerisation plants for education, and virtual process engineering platforms for the design of industrial processes (Xinhua et al., 2012; Damian, 2012). The adoption of VR as a training tool to improve learning subsequently picked up pace in engineering and healthcare, owing to its ability to provide onsite training and explore alternatives without physical risks (Manca et al., 2013; Fracaro et al., 2021; Carruth, 2017; Halabi, 2020; Tighe et al., 2021). Industries have also begun to use VR for various purposes, including training sessions, scenario simulations, manufacturing, and prototyping of physical designs (Berg & Vance, 2017; Havard et al., 2019). The application of immersive VR in education and training is found to be largely effective as a pedagogical tool due to its experiential nature and ability to enhance user engagement (Hamilton et al., 2021). With increasing adoption of VR training in industries, providing students with an opportunity to be trained within a VR environment will better prepare them to work in an industrial setting.

RESEARCH QUESTIONS

Given the increasing adoption of VR in education, in this study, we investigate whether

1. there is any preference of learning in an interactive VR environment over regular classroom teaching?
2. there is any difference in student assessment outcomes between students who attempted only training within the VR environment, and students who attempted both training and assessment within the VR environment?

METHODS

Participants

The participants of this study were second year chemical engineering students who took the course CN2122A "Fluid Mechanics" as one of the compulsory modules in their curriculum. Students were briefed that all VR-related activities are purely voluntary, and all VR-related assessments were formative in nature. To encourage student participation, they were informed that the VR activity would greatly help build their understanding of pump operations taught in this course. CN2122A was offered in Semester 2 of Academic Year 2020/21 to a class of 49 students; 44 of these students showed up for the in-person VR session.

Design and procedure

The students were only involved in learning the startup of a VR pump in this course. The content of this VR session was designed by ChE educators in NUS, in collaboration with industry partners who have extensive experience and a strong background in chemical unit operations. We focused on simulating the pump startup procedure to match the real industrial scenario as closely as possible. The developed VR covers the basic standard operating procedure (SOP) of a centrifugal pump startup process, and is complementary to the theory of centrifugal pumps covered in regular classroom sessions. There are four sets of VR laptops and four sets of Oculus Quest 2 headsets. Each group, comprising four to five students, would take turns to enter the VR environment individually.

Each participant was given the opportunity to go through the VR training in guided mode, wherein visual prompts and instructions were given (within the VR environment) for the safety gowning procedure before starting up a pump (Figure 1a). During this process, occasional assistance was given by the instructor to help the user familiarise himself/herself with using the controllers, as well as to explain the intricacies and rationale behind the SOP of starting up a pump. In the meantime, other group members would observe the participant's activities via the laptop screen, giving audio prompts and discussing as and when the need arises. Students within the group would take turns to undergo the training within the VR environment and observe the training process of their peers through a projected screen.

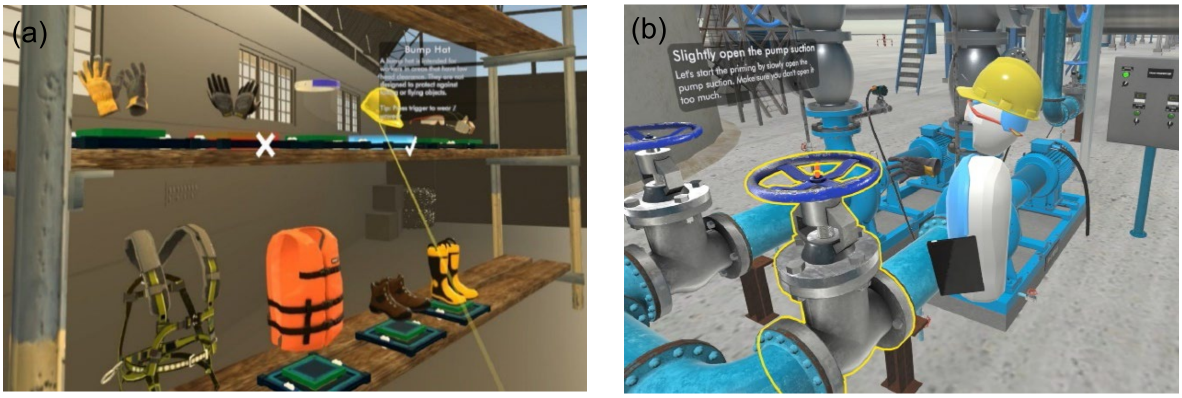

Figure 1a. First-person view of the gowning room for the VR user to select the appropriate personal protection equipment (PPE) prior to entering the plant site.

Figure 1b. Third-person view of the guided mode training for the centrifugal pump startup with visual prompts provided. Both first- and third-person views are available in all the VR scenarios.

Amongst the students who attended the VR session, 43 students participated in the VR training, with one student opting to observe the process through a projected screen due to his high tendency for motion sickness. This student then volunteered to stay on for two VR sessions to familiarise himself with the pump startup procedure, in order to compensate for his inability to participate physically in the VR activity.

Once all students in that group went through the guided mode training for the pump startup (Figure 1b), students volunteered to undergo the pump startup procedure in assessment mode (within the VR environment) to test their ability to recall the steps that need to be followed (see Appendix A). During the assessment in VR, apart from the lack of visual prompts within the VR environment, all other settings remain unchanged. While a student in the team undergoes the assessment in VR, his/her teammates are encouraged to give audio prompts to guide the user on the subsequent steps to be taken. By doing so, learning takes place as a team as they figure out the steps together, integrating both engineering logic and the newly acquired VR training to start up the assigned pump. Amongst the 43 students who participated in the VR training, 25 attempted the VR assessment mode for pump startup (Figure 2). The remaining 18 students who did not enter the VR environment to complete the assessment were actively involved in giving audio prompts to their participating teammate. The average VR assessment mode score of these 25 students was 82.84%, and the average time taken to complete the pump startup procedure was 7.35 minutes.

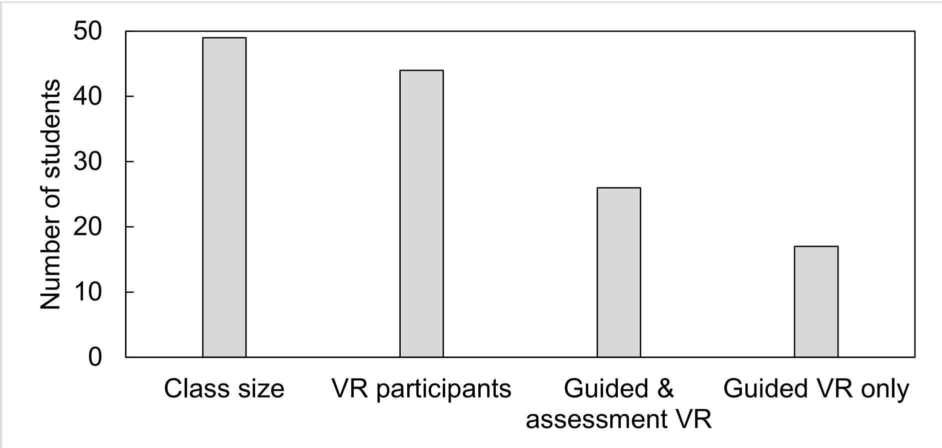

Figure 2. Histogram depicting the VR participation rate and the breakdown of students who participated in both guided and assessment mode as well as students who participated in guided mode VR only in CN2122A.

At the end of the VR session, students participated in a short survey to gauge their impression of the VR session (Appendix B). The questions are as follows:

1. What are some of the notable things you have learnt in VR environment?
2. How would you rate the VR experience (on the scale of 1 to 5, 5 = Extremely Positive, 1 = Extremely Negative)? What were the main aspects of the VR experience that determined your rating?
3. How well did the VR experience stimulate your curiosity about the pump?
4. What would be one thing you wish to see or have in the next version of the VR experience?
5. If given the choice, would you choose the VR activity, traditional chemical engineering problem sets as homework, or traditional lecture for CN2122A? (Assume that all other variables remain unchanged.)
6. Which method do you think helps you remember better, watching someone else use the VR model or you using the VR model yourself? Which sequence would help you learn better? Doing guided mode multiple times then trying assessment mode, or cycle between these two modes?
7. When it comes to starting up the pump, what are some differences between watching someone use the VR model versus you using it yourself?

Approximately four weeks after the VR session, students participated in a formative online quiz to test their recollection rate in both safety and pump startup. The first quiz question required students to select the correct personal protection equipment (PPE) required before they can conduct field operations. The second quiz question presented a randomised sequence of the pump startup procedure, and students were tasked to rearrange it in the right sequence. A summary of the quiz questions is given below:

1. What are the mandatory personal protective equipment (PPE) one needs to use while operating a pump?
    a. Bump hat
    b. Eye shield
    c. Safety shoes
    d. Wellington boots
    e. Gas mask
    f. Face shield
    g. Life jacket
    h. Safety harness
    i. Safety gloves

2. Following are the steps involved in safe start-up of an industrial pump. List them in the correct order of execution.
    a. Open tank valve and common discharge valve fully
    b. Slowly open pump suction
    c. Open around 20 to 30% discharge valve
    d. Request DCS switch ON using tablet
    e. Open 10–20% pump suction for selected pump
    f. Slowly open up to 20% pump discharge valve
    g. Fully close the discharge vent

h. Fully open pump discharge valve
i. Put motor switch to Auto on control panel
j. Shutdown pump or troubleshoot pump if an error occurs

3. What would be your first response when a pump stops working? (Provide list of actions)

4. If the pump has a problem, but you have no idea what the issue is, what would be your first corrective action?

The SOP for pump startup was made available to the students via the school learning management system, and had been explained to them during the VR session. However, it is worth noting that only one student actively referred to the uploaded SOP during the quiz, as indicated by the download statistics. The remaining students attempted the questions based on what they had learnt from the VR session.

RESULTS AND DISCUSSION

Specific outcomes of the project were analysed through the formative online quiz and student survey detailed above. The student survey was conducted during the VR session. All the students who participated in either guided and/or assessment VR mode participated in the student survey, and provided their feedback on the VR activity.

Analysis of quiz results

Out of the 25 students who attempted both guided and assessment modes in the VR environment, 24 students participated in the online quiz and scored an average of 73/100 (standard deviation = 3.99) in their ability to recall the pump startup procedure in the right sequence. Each step of the procedure is given equal weightage in the score, and the correct placement of the sequence of steps would gain them marks for the relevant steps. The steps are broken down into three broad categories: (i) pre-checks to ensure the pump is safe and ready for use, (ii) line-up to ensure the fluid is flowing in the right direction, and (iii) pump start-up. A jumbled-up sequence will only result in deduction of marks for the related steps within the category. The question was replicated from the VR content and written in text format, with appropriate descriptors and terminologies.

All the 18 students who only attempted the guided mode VR participated in the online quiz and scored an average of 57/100 (standard deviation = 6.16) in the same question. A two-sample one-tailed t-test (assuming unequal variances) was done to compare the procedural skills of these two groups of students, with a significance level of 5%. Results from the t-test showed that the difference in score between the two groups has a p-value of 0.066, indicating that we cannot reject the possibility that there could be no difference in learning between the two groups. Further studies with larger groups of students can be conducted to ascertain if there is indeed any difference between students who attempted only the training mode versus those who attempted both the training and assessment modes. At this point, it is also worth noting that all the students who skipped the VR training session but attempted the quiz scored zero in the same question.

The possible reasons for the slight difference between the quiz scores is two-fold. When students first attempt the guided mode VR, it familiarises them with the new VR environment (i.e., the plant layout), the use of VR controllers as well as the procedures. This is a significant amount of information to absorb for a short session—students took an average of 8.8 minutes to complete the guided mode training (Figure 3). Students who attempted the assessment mode in VR took an average of 7.35 minutes to complete the task, likely due to greater familiarity of the VR setting despite the lack of instructions leading them to the next steps. VR encompasses both locomotion and several gestures involving gross motor coordination, which results in a relatively high degree of sensory-motor engagement. The gestures required to activate the pump start up involve significant gross motor coordination that are gesturally congruent to the content learnt. Examples of these include the physical turning of virtual gate valves with the user's arms in large circular motions and physically bending down to check the virtual engine oil levels. Hence, there is a significant amount of kinaesthetic learning during both training and assessment within the VR environment. Compared to those who observe and guide their peers undergoing the VR assessment through the projected screen, VR users are exposed to a greater extent and duration of embodied learning, with multiple afferent and efferent neuron pathways activated in the learner's motor system. While students who observe the VR assessment through a projected screen still learn through discussion, learning takes place with reduced kinaesthetic component and a lower extent of embodied learning. There is increasing evidence of significant differences in the levels of knowledge retention with varying degrees of embodied learning—a richer perceptual experience results in better student learning and understanding (Black et al., 2012; Lindgren & Johnson-Glenberg, 2013; Johnson-Glenberg et al., 2016).

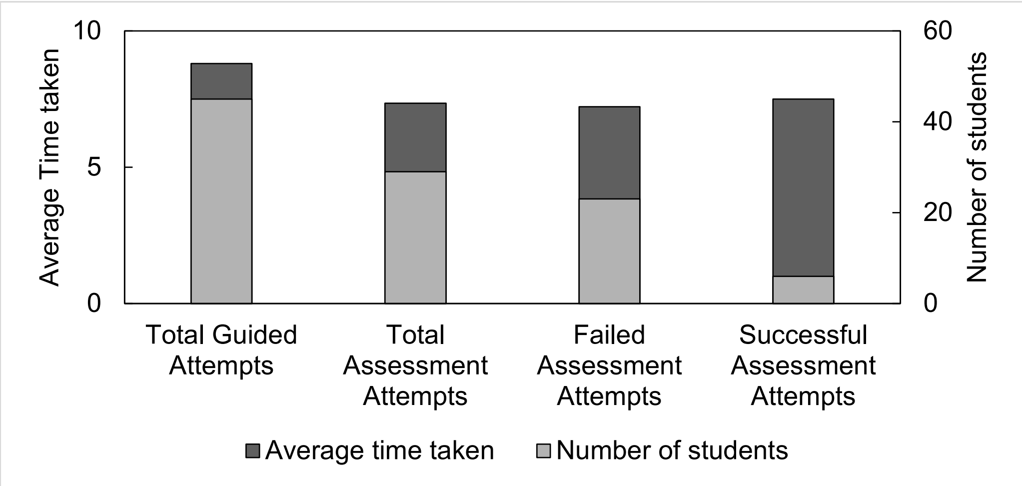

Figure 3. Graph depicting the average time taken for the completion of the guided mode and VR assessment mode respectively.

In addition, students also gave verbal feedback that they mainly followed the instructions given in the guided VR mode, without much thought to the exact sequence and rationale behind each step. This is in spite of being briefed of the rationale and general procedure prior to the VR session. It is only when students are subjected to the VR assessment activity that they realise the gap between what they have learnt during the guided mode training and what they need to know during an actual startup process. It is thus an indication that there is lower cognitive demand during a simple task execution by following specific instructions, thereby resulting in lower memory retention. This is consistent with the findings of Furtado et al. (2019), where a deliberate attempt to reduce the cognitive load during closed concept map construction resulted in lower delayed test scores in participants, owing to reduced levels of memory retention.

Students also gave feedback that it was during the VR assessment that they started applying their logical thinking skills to bridge the gap between what had to be done and what the team remembered collectively. The difference between participating in VR and prompting others while being in a non-VR environment is the immersive environment of the VR, and the need to actively execute the required tasks in VR. Much of the onus is on the user within the VR environment to figure out and execute the steps required for task completion, while the other team members' participation mainly revolves around the discussion of possible next steps.

Figure 4 depicts the distribution of assessment scores from the VR activity. Students who are interested in the VR assessment take turns to participate in the activity and discuss in a group on the possible next steps to be followed, based on the error made by the previous participant. In a study conducted by Lam et al. (2010), it is found that the cognitive demand is higher during the preparation stage immediately prior to task execution that requires movement, and that the cognitive demand is greater for trials following an error, compared to trials without an error. A student doing the assessment in VR would therefore experience a higher level of cognitive demand and processing. This is due to the need to recall the training steps involved and/or speculating on the next possible steps based on previous error (if any), on top of the need to mentally process the points discussed within the group during the assessment. The amount of cognitive engagement for a VR user would inevitably be much higher compared to peers who only observe the assessment in VR through a projected screen.

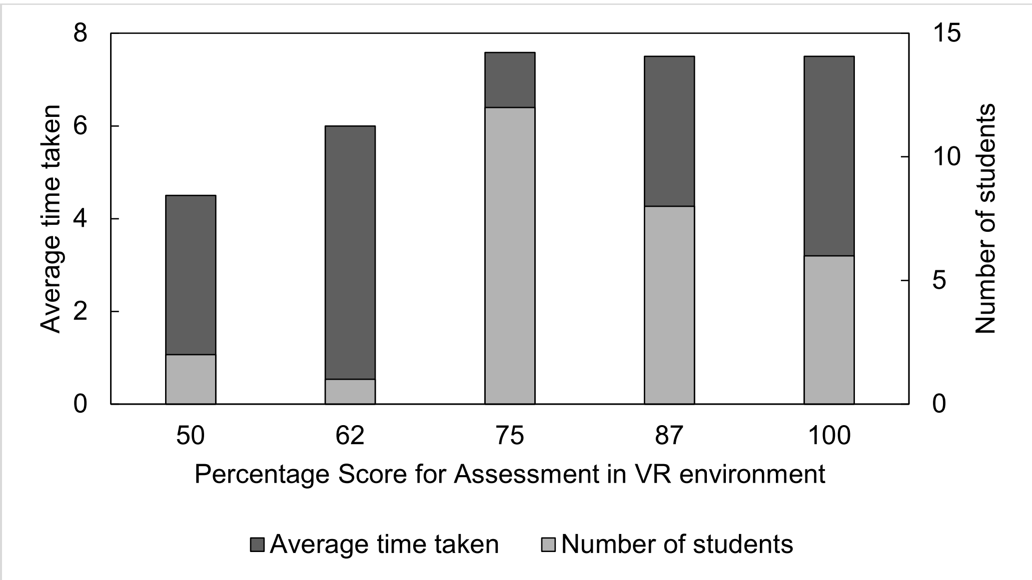

Figure 4. Histogram of score distribution and time taken for the completion of assessment within the VR environment.

Students who attempted both the guided and VR assessment modes benefit from repeated exposure to the same content, a greater extent and duration of embodied learning, and a higher cognitive demand compared to students who only had to follow explicit instructions in the guided VR mode. The level of memory retention of students who attempted both guided and assessment VR modes would thus be higher, thereby explaining their greater ability to recall the pump startup procedure compared to students who only attempted the guided mode VR. In the same online quiz section where students were required to select the appropriate PPE before going onsite, the scores of students who attempted both the guided and assessment VR modes were statistically higher than students who attempted only the guided VR mode (p-value = 0.0391). This difference likely stems from the repeated exposure students had when they attempted both VR modes, thereby making a stronger impression in their memories and enhancing their recollection rates.

Table 1 has a list of selected questions used in the formative assessment during the VR session. The student performance in these questions is summarised in Figure 5, which shows that most students were able to answer the questions correctly, indicating that the required learning outcomes of the VR session have been well achieved.

Table 1

Selected questions used in the formative assessment

Number	Question
Q1	What are the mandatory personal protective equipment (PPE) one needs to use while operating a pump?
Q2	What would be your first response when a pump stops working? (Provide list of actions)
Q3	If the pump has a problem, but you have no idea what the issue is, what would be your first corrective action?

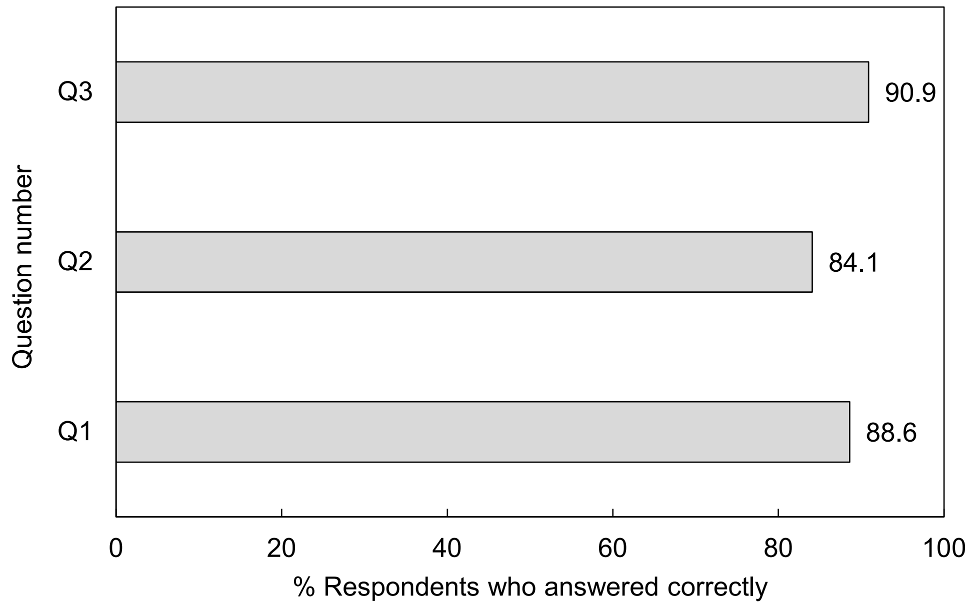

Figure 5. Student performance in the formative assessment (during the VR session).

Analysis of survey results

The purpose of the student survey was to understand their perceptions of the quality of the developed VR pump model and their overall learning experience in the VR environment. As mentioned earlier, the survey consisted of carefully crafted quantitative and qualitative questions to assess the expected outcomes (a sample survey form is included in Appendix B). The student responses are summarised in Table 2.

The majority of students (81.2%) who participated in the survey rated the VR experience positively, highlighting the interactive and immersive experience that facilitated their learning and incited greater curiosity in pump operation. Students were asked to indicate the notable things they learnt in the VR environment. Most of the respondents mentioned the pump start-up/shut-down procedure and the visualisation of internals. Approximately 76% of the respondents mentioned that the VR experience stimulated their curiosity about industrial pumps. Figure 6 shows a summary of students' preference on the teaching-learning approaches. More than 60% of the respondents prefer incorporating VR activity into the course content.

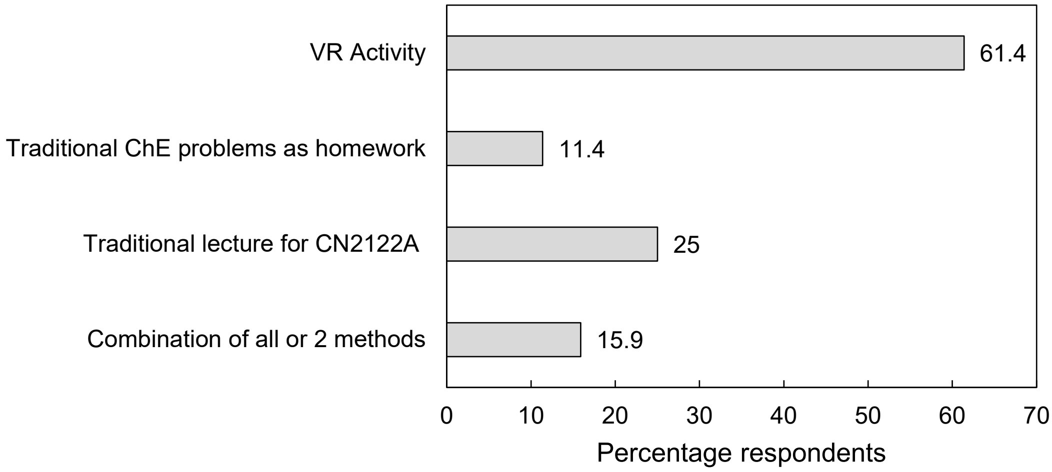

Figure 6. Students' indication of preferences on teaching-learning approaches.

When asked to indicate their preference for integrating the VR activity as part of the course, as opposed to learning about pumps solely from traditional lectures, 88.6% students suggested to integrate the VR activity into the curriculum. To evaluate the retention of knowledge by the students from the VR activity, a delayed online quiz was conducted four weeks after the VR session. Results from this quiz indicated that 70% of the students were able to accurately recall the pump operation procedure in the correct sequence, without any revision or reference to any materials. These results are early indications in our project of the positive impact of VR on ChE education.

Student were asked to indicate the main aspects of the VR experience that determined their rating. A simple text analysis of the collected response is summarised in the word cloud in Figure 7.

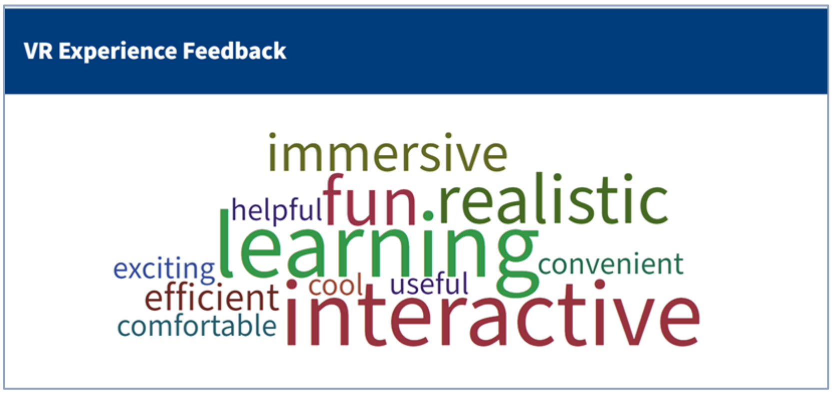

Figure 7. Text analysis of collected responses from students.

Some notable comments on VR experience and suggestions for improvement are summarised in Table 2:

Table 2

Qualitative feedback from students based on their VR experience

	Comments
Experiences	• *Clear and fun way of learning, how to start a pump with clear instructions along the way.* • *Interesting, different, more interactive.* • *Comfortable working environment* • *A platform to learn from mistakes with severe consequences.* • *The VR was extremely realistic and helped me learn the actual working of the pump.* • *It is an effective means to supplement the knowledge from class.*
Suggestions	• *The VR was extremely realistic and helped me learn the actual working of the pump. But I feel disconnected (not able to read).* • *Realistic but dizzy.* • *Disorienting, but fun.*

The encouraging feedback from students is an indication that they prefer inclusion of VR models in teaching and find it useful.

The technologies for VR have improved rapidly alongside a dramatic reduction in associated costs over the past decade. However, the technology is still evolving, with active research and development (R&D) in the areas of VR-ready graphics processing units (GPUs), head-mounted displays (HMDs), and associated firmware/software. Various conflicting factors such as cost, space availability, processing power, and form factor have to be carefully considered while deploying the VR training system to ensure a seamless experience for the end user. The participant feedback captured in this study (Figure 8) indicates the limitations of VR-based training systems.

Figure 8. Text analysis of collected feedback and suggestions from students.

Virtual learning environments require higher computational loads as compared to traditional PC-based teaching methods. Proper implementation and monitoring of dynamically evolving user interactions in VR is necessary to ascertain training effectiveness, which further adds to the computational complexity. The VR

HMDs are currently limited in terms of the available computational power, leading to a "laggy" or "glitchy" experience. This is being addressed by high-performance computing and computer graphics researchers.

Another frequently reported issue with VR is the subjective discomfort associated with various elements of a VR headset. The push for a wider field-of-view has increased the challenges of correcting lens distortion in VR. Motion to photon latency causes an uncomfortable and dizzy feeling with prolonged usage. These issues are being actively researched by visualisations and optics research groups.

OTHER INSIGHTS

One of the potentials of using VR in engineering education is the ability to create a safe environment for students to learn how engineering systems and equipment work under various situations. Creating a simulated environment that closely relates to how systems work in reality gives students a safe space for exploratory learning. This also prevents potential damage to real process equipment, or wastage of actual chemicals and consumables during the learning process. VR also provides students with an experience without compromising their health and safety. (Kumar et.al., 2021)

In addition, with the speed of technological developments and the space constraint that some higher education institutions face, the ability to create a virtual replica and simulation of real plant scenarios that use the latest industrial technologies can prove to be highly beneficial for education. The adoption rate of VR in industries has been on the rise in recent years. VR has been used to simulate the design and prototyping of various products such as automobiles, provide safety trainings and other industrial trainings for new hires (Berg & Vance, 2017; Rocca et al., 2019, Kaarlela et al., 2020). The use of digital twins in production facilities that continuously update and improve themselves based on real data collected is worth noting (Havard et al., 2019). Digital twins are used in the process industry to monitor and predict faults and failures in the processes. It also provides opportunities for optimisation in real-time (Havard et al., 2019). When used in tandem with VR systems, real-time data exchange between the actual process and the virtual plant provides a reality-simulated training environment for students. They can also gain insights on the idea and practice of using a digital twin framework for the prediction and optimisation of processes and production (Min et al., 2019).

The use of VR as a safety training tool has also been commonly adopted in the industries to simulate unsafe situations such as fires, explosions, construction and mining hazards, emergencies, co-worker injury, and other workplace hazards (Kaarlela et al., 2020). VR creates an opportunity for real-life and dangerous situations to be simulated in a safe and immersive manner for training and education purposes. It also enables training to take place remotely in the event of a pandemic, and even allows for multiple users from several places to participate in a group training when required (Glassey & Magalhaes, 2020). This convenient feature of VR has a far-reaching impact, especially when physical gatherings prove to be difficult, time-consuming and/or costly.

CONCLUSION

The technological advances in recent years have created many opportunities for pedagogical interventions to enhance student learning. The encouraging results from our ongoing work on the use of VR in chemical engineering is testimony to that. The developed industrial-scale VR pump has been instrumental in helping students visualise and interact with physical systems in VR, and understand related concepts. It allows students to, in a safe environment, explore the start-up and troubleshooting procedures for an industrial pump. The pump VR model implemented in CN2122A was well received by most students. Approximately 82% of participants rated the VR experience positively, highlighting the interactive and immersive experience that facilitates their learning. Most students supported the inclusion of VR activity as part of the module, as opposed to learning the concepts solely from traditional lectures. Students enjoyed a positive deviation from traditional learning, and displayed great enthusiasm during the VR session.

While there is no strong evidence of better learning between students who attempted only the VR training versus students who attempted both the training and assessment modes within the VR environment, the latter group experienced a higher cognitive load in the immersive learning environment, and this could potentially have greater impact in their levels of knowledge retention. Further studies with larger student populations need to be done to ascertain if there is any significant difference between these two groups. If a significant difference in learning and retention is found between these two groups, then the manner of engaging learning within the VR environment in education can be fine-tuned to optimise technology-enhanced learning.

Through our preliminary studies, we found that VR helped students retain knowledge (remembering and understanding) of the correct sequence of the pump operation procedure, even after four weeks since they participated in the VR learning activity. The future development of our VR training systems will also aim to enhance student learning in the higher-level cognitive skills (Bloom's Taxonomy) of analysing and evaluating more complex simulated scenarios that allow students to solve problems within the VR environment, either independently or collaboratively. With VR training gaining traction in the process engineering industry, engaging our students in VR training in their undergraduate courses prepares them for actual tools used in the industry and hence, ensures that they are better prepared for their future work.

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APPENDIX A. Centrifugal Pump Start Up SOP

APPENDIX B. Survey and Assessment Questions

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