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Work-in-Progress—Virtual Learning Laboratories for High School Chemistry Lab: An Immersive Learning User Study

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Abstract. In this work-in-progress, we investigate the outcome of a Virtual Learning Environment (VLE) teaching chemistry at high school level. The question we raised was whether or not a virtual representation of chemistry labs would have a comparable impact to the learning experience with a real live lab. We identified several challenges for the VLE such as tangibility and a necessary degree of realism for chemical reactions. We created a representation of a chemistry lab in VR, designed to administer several chemical experiments, which can be found in K-12 chemistry courses, and tested a group of participants using the VLE against a testgroup in real life in terms of learning outcome and immersive perception using a modified game experience questionnaire. We found, that our results strongly indicate a comparable learning experience of our virtual chemistry lab environment in comparison with a real life lab for our specific experiments.

Keywords: VLE, Chemistry, User Study.

1 Introduction

Barriers affecting learning outcomes in classroom-based K-12 education are tied to socioeconomic obstacles and a lack of specialized course structure for students with disabilities [1,2]. The growth in popularity of virtual learning tools in recent years has engendered various alternative course structures that can continuously be updated without excessive overhead expenses and be customized to suit the learning needs of students. Arguably the most immersive virtual learning tool is virtual reality which can provide spatial cues that supports problem-solving and memorization, thus improving overall knowledge acquisition [3-8].

Nowadays Virtual Learning Environments [9-11] are well investigated and tested against real life experience to further increase our knowledge about VLE performance and feasibility in the modern classroom [12] such as typical STEM applications, especially for classically tangible sub-fields of Physics such as Newtonian Mechanics [13], Gravity [14–16], Special Relativity [17], and Electrochemistry [18-20].

We present the results of a qualitative survey for a user study comparing participants' learning experience in a natural chemistry laboratory environment [21,22] to a VR-based version as part of a VLE [23] for K-12 education in chemistry [23,24] Several educational tools for online, web-based or virtual chemistry applications are well investigated [25,26]. The questions in the survey were constructed to identify whether VR experiments can potentially assist learning outcomes. Furthermore, the cost-benefit of learning in a virtual environment was considered when interpreting our survey results.

VLE's in general and our VR-based chemistry course in specific can circumvent the cost of an introductory chemistry lab with a lower-bound cost of $400k [27]. In contrast, VR headsets that host our virtual chemistry environment can be purchased for a fraction of the costs. Public institutions with lower budgets and home educators can access virtual lab spaces that would typically only be accessible to a minority of well-endowed universities.

Additionally, VR learning environments would also increase physical accessibility for students with physical ailments or disabilities and provide students with a safe laboratory environment. VR headsets like the HTC Vive or Oculus Quest 2 allow navigating virtual environments by standing or sitting. Many of the physical operations that can be completed in a VR headset are transferable to their stand-alone controllers, where users can be seated. Additionally, a virtual environment can increase the safety of operating a chemistry laboratory by completely removing exposure to any harsh chemicals present in a classroom-based laboratory environment.

2 Methodology

For this study, we developed an immersive virtual learning environment in which participants completed all steps of the hydrate lab, following proper lab safety and equipment protocol.

A hydrate is a compound containing water molecules bound to another compound. The hydrate lab measures the percentage (mass) loss of water in a hydrate salt, achieved through heating the hydrate to evaporate the water. The resulting dehydrated compound is known as anhydrate. By comparing the mass of the original hydrate to the mass of the anyhydrate, the chemical formula for the hydrate salt used in the experiment can be determined.

Our test group consisted in sum of n = 41 participants and our study was conducted in three steps. 1. We first assigned participants a pre-questionnaire to assess demographic information and prior experience with chemistry. 2. Participants completed one of two versions of the hydrate lab. A sub-group of n = 21 participants used our virtual simulation to complete the simulation, while our control group of n = 20 participants completed the traditional live experiment. 3. Participants were given a post-questionnaire to determine comprehension and effectiveness of the experiment. Participants in the virtual simulation group were asked additional questions regarding their experienced immersiveness using the game experience questionnaire [28,29].

Fig. 1. Virtual environment for the hydrate lab. Lab instructions were displayed on the chalkboard for participants to reference during the experiment.

2.1 Development

For this study, we identified a chemistry experiment that is commonly taught in K-12 education classrooms and decided on a hydrate mass-balance experiment which will be referred to as the “hydrate lab”.

Our VLE development tools are Unity 2020.3.26f1 for designing, Visual Studio 2019 for scripting, and PlasticSCM for source control. We utilized packages from the Unity Asset Store to build our virtual environment. To display and interact with the virtual lab, we used an HTC Vive Cosmos Elite and the corresponding SteamVR package in Unity. A wide view of lab environment design is shown in Figure 1.

The live version of the experiment was conducted in a chemistry classroom with all necessary equipment for the hydrate lab, including: crucible, crucible cover, distilled water, tripod with mesh screen, Bunsen burner, tongs, electronic mass balance, and copper (II) sulfate pentahydrate.To understand the core chemistry aspects of the lab and proper use of equipment, we performed multiple live trials of the lab in a chemistry classroom. The data we gathered from our trials were used to accurately develop the formulas in our simulation. Additionally, we utilized random number generation to simulate human error in the initial hydrate sample mass and final mass after dehydration. With these formulas and error mechanisms in place, we implemented VR hand controller interactions with equipment and scripted interactions between lab objects.

In order to approximate the live experiment as closely as possible, most of our development in creating an immersive experience was in refining aspects of the scene and project settings. A major focus of our development was collisions handling between various objects in our environment to maximize participant immersion, hence we used composite meshes to render equipment that would be interacted with most. Additionally, we adjusted the masses of equipment held by participants during the experiment to move, fall, or roll at a sensible rate. These changes when combined with the SteamVR hand colliders made a massive improvement in realism and made it easier for participants to complete the experiment.

2.2 Live Experiment

A live version of the experiment was conducted as a control to gauge the effectiveness of our virtual simulation. Participants were given a paper with the hydrate lab procedure, briefed on pre-lab information, instructed on lab equipment use, and notified of safety and emergency equipment locations. A chemistry professor then guided participants through the experiment from setting up their workspace to conducting the experiment and performing calculations, followed by clean up procedures. Upon completing the live experiment, participants filled out an experience survey.

2.3 Simulated Experiment

In an empty testing space of 6.5ft x 6.5ft, participants engaged in the virtual reality experiment using HTC Vive Cosmos equipment. Before starting the simulation, participants were instructed on how to safely use and adjust the VR equipment. Participants were also taught the hand controller bindings for interacting with the virtual environment. Once participants were situated with the VR equipment, the simulation was launched with conductors available to answer any questions and assist with the experiment.

During the simulation, the chalkboard in the virtual classroom contained all of the lab instructions. Participants had to complete the same steps as those who performed the live experiment, including: using the mass balance to weigh the initial hydrate sample, using tongs to safely move the sample onto and off of the Bunsen burner, waiting for the sample to completely dehydrate and cool down, and obtaining the final mass. For performing calculations, participants were instructed to remove their headset and write the data needed on paper, since a virtual drawing system would have been more difficult to use than traditional pen and paper. Upon completing the experiment, participants filled out an experience survey that had additional questions regarding immersion.

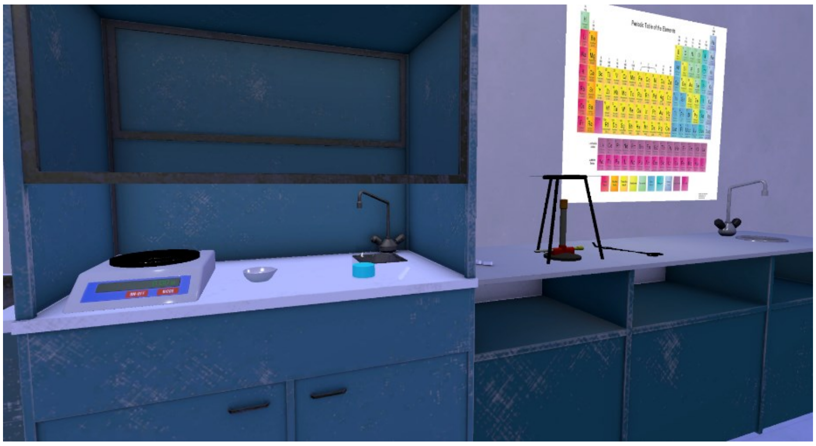

Fig. 2. Equipment setup in the virtual lab environment. Necessary equipment was displayed in a manner in which participants could easily find the tools needed for each step.

2.4 Questionnaire

All participants were required to complete a questionnaire before and after their respective versions of hydrate experiment. For participants who engaged in the virtual simulation, additional questions for levels of immersion were documented.

1) Pre-Questionnaire: Participants completed a pre-questionnaire before engaging with the hydrate experiment. Both test groups were given the same set of questions, assessing their background with chemistry and knowledge of lab etiquette. The questions asking participants on their familiarity with chemistry lab environments, techniques, and safety took numeric responses from 1 -5 with the scale being: (1) "Not familiar at all," (3) "Somewhat familiar," and (5) "Extremely familiar."

2) Post-Questionnaire: After completing their respective hydrate experiment, participants completed a post-questionnaire. Participants were asked for their feedback on presentation of chemistry concepts, lab instruction clarity, and data collection experience. Feedback questions took numeric responses from 1 - 5. Scoring for each question was labeled with their respective keys: (1) "Not clear at all," "Not effective at all," "Very difficult," (3) "Somewhat clear," "Somewhat effective," "Somewhat difficult," and (5) "Very clear," "Very effective," "Very easy."

If participants were part of the virtual simulation group, they were asked to complete an additional two sets of questions regarding immersion during and after the simulation. Both sets of these questions took numeric responses from 0 - 4 with the following key: (0) "Not at all," (1) "Slightly," (2) "Moderately," (3) "Fairly," and (4) "Extremely." These immersion questions allowed us to gauge the effectiveness of learning in a virtual environment.

3 Demographics

As learning outcomes are dependent on demographics [30], we collected demographic information from participants including age group, gender, ethnicity, annual household income, employment, and highest level of education. Our test group consisted of n = 41 participants with n = 21 participating in our virtual simulation and n = 20 participating in the live experiment control group. 85.3% of participants (n = 35) experienced chemistry through a public school education. Additional demographics statistics are shown in Figure 3.

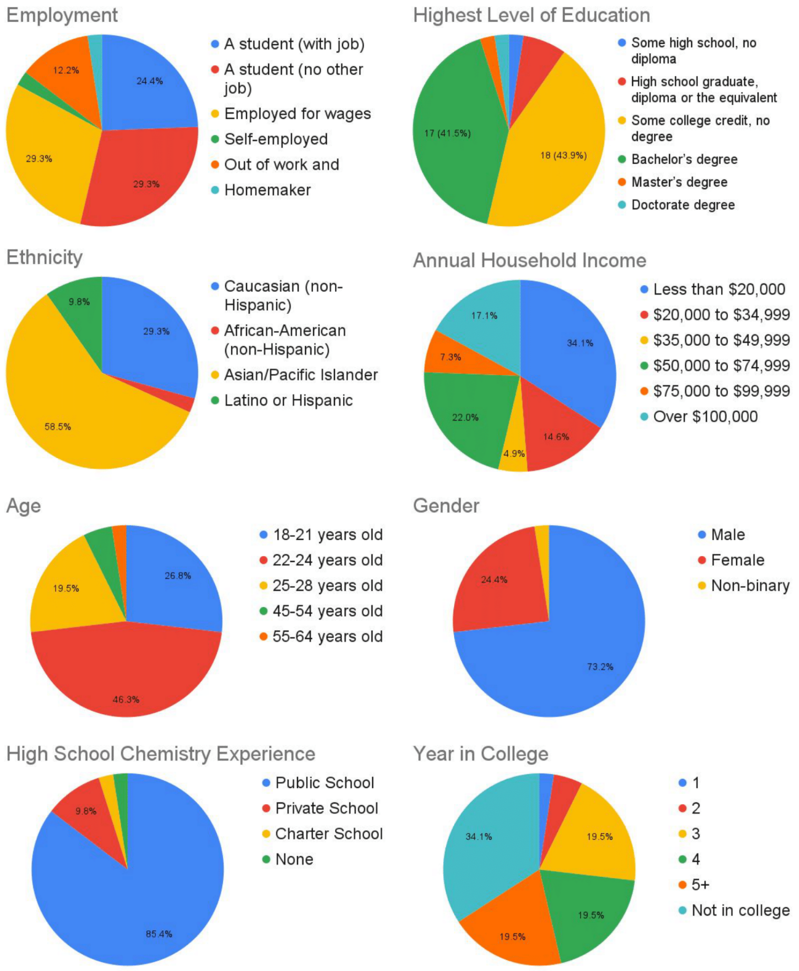

Fig. 3. Group demographics. The distribution of participants' age, gender, ethnicity, income, employment, education, year in college, and high school chemistry experience.

At the time of the study, 65.9% of participants (n = 27) were in college. Of those participants, 66.7% (n = 18) had a primary field of study that was engineering based with the majority being computer science, followed by electrical engineering and mechanical engineering. The distribution of college majors is shown in Figure 4.

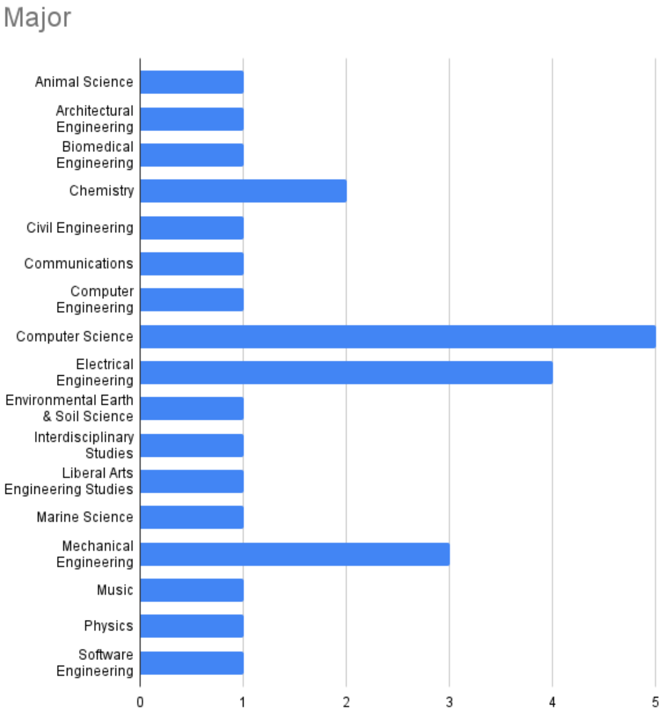

Fig. 4. Field of study demographics. The college major distribution of participants currently in college (n = 27).

Participants generally had some experience with chemistry lab environments as well as techniques and safety. 85.3% of participants (n = 35) were at least somewhat familiar with chemistry lab environments and 87.8% of participants (n = 36) were at least somewhat familiar with chemistry lab techniques and safety. Additional statistics of participants' familiarity with chemistry is shown in Figure 5.

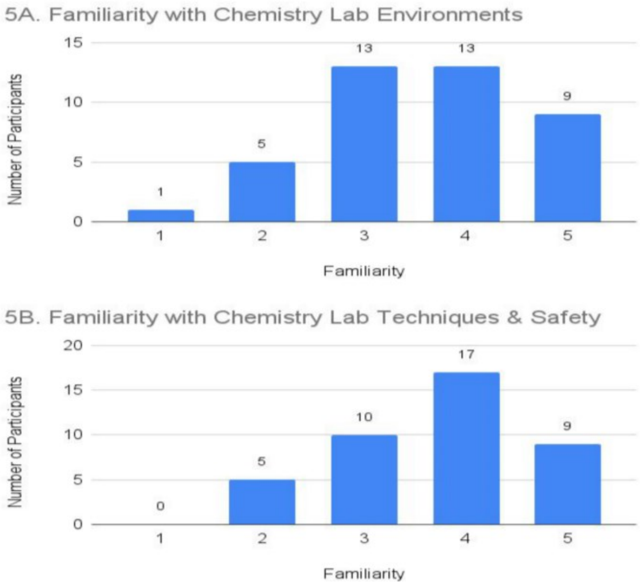

Fig. 5. Chemistry experience background. 5A) The distribution of participants' familiarity with chemistry lab environments. 5B) The distribution of participants' familiarity with chemistry lab techniques and safety. Both charts use the same key with 1 being not familiar at all, 3 being somewhat familiar, and 5 being extremely familiar.

4 Results

Both groups conducting the experiment have successfully achieved correct calculation results in their traditional/virtual lab environment.

Hence, our investigations regarding differences and commonalities between those two modii (traditional and virtual) focus on the perceived experiences of the participants.

The rating of the effectiveness of concepts explained in the control lab versus the virtual simulation lab is shown as a column chart in Figure 6.

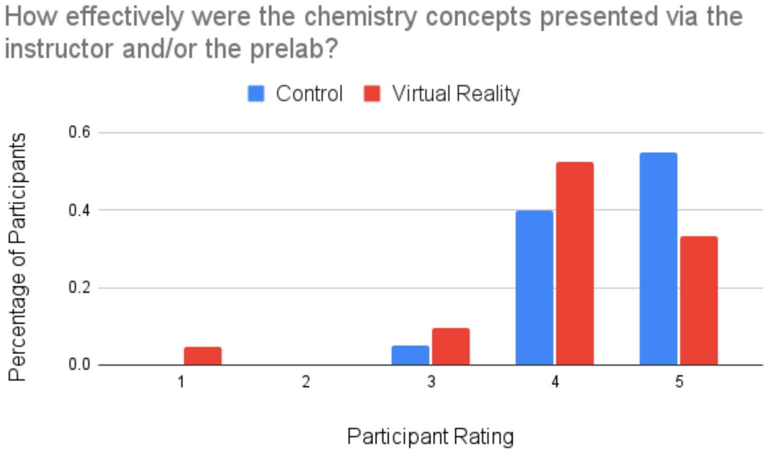

Fig. 6. Effectiveness of instructor/prelab presentation of concepts. The distribution of participants' feedback scores for virtual (red) and control (blue) groups, with 1 being the lowest score and 5 being the highest score.

On average it was found that the presentation of chemistry concepts during the virtual experiment were to be seen as less effective than those conducted live. This could be largely due to environmental constraints: During the live experiment, a chemistry professor was present at all times, while the virtual experiment only had computer science students as conductors. Originally, we planned the deployment of our virtual labs with an educator presenting students with chemistry concepts and pre-lab information before the simulation. Due to COVID-19 safety measures this was not an option as the VR testing space was significantly smaller than the chemistry classroom used.

These discrepancies can be further explained through potential human error. Many participants in the virtual group spent a majority of their time in the simulation trying to learn how to use VR hand controllers and needed reminders for the controller bindings. Compared to using traditional lab equipment which is more intuitive, those in the control group could focus more effort in retaining information taught during the live chemistry experiment. Additionally, virtual group participants were possibly surprised by the immersiveness of the lab, focusing more on the virtual environment and interactions rather than understanding the core chemistry concepts presented. Consequently, after completing the virtual experiment, participants may not have learned as much as they would have compared to the live experiment, where a chemistry professor was available to further explain chemistry concepts needed to solve the mass-loss calculations.

Figure 7 presents a column chart comparing the simplicity of instructions delivered between the virtual and control groups. On average, participants in the virtual group scored the clarity of lab instructions higher. This could be attributed to the clear and concise steps listed on the virtual classroom's chalkboard. The virtual chalkboard text is large, clear, and easily readable from afar, versus the live lab which was taught using a combination of verbal instruction and a paper handout. These results were expected since virtual participants had an isolated area with all necessary equipment to conduct the experiment, leading to more focus than control group participants who had to move around more in the chemistry classroom to gather equipment and data.

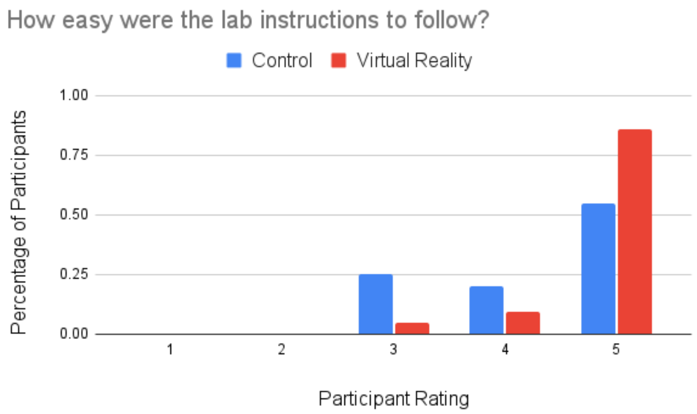

Fig.7. Lab instruction fluency. The distribution of participants' feedback scores for virtual (red) and control (blue) groups, with 1 being the lowest score and 5 being the highest score.

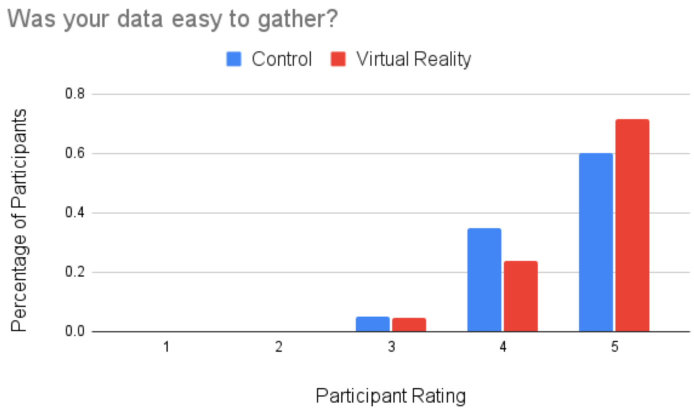

Fig.8. Simplicity of data collection. The distribution of participants' feedback scores for virtual (red) and control (blue) groups, with 1 being the lowest score and 5 being the highest score.

The ease of gathering data between the virtual and control groups are compared in Figure 8. On average, by a small margin, participants scored the virtual lab higher on the simplicity of data gathering. In the virtual experiment, conductors outside of the virtual space were recording data for the participant while they carried out the experiment. We chose this method because the planned deployment of our virtual labs would have students working in pairs, where they each take a turn performing the virtual simulation and recording data. Similarly, our control group experiment had participants working in groups of two or three people, where one participant could focus on recording data. As a result, the participant responses for data gathering were within range of the expected values. An instant text display of measurements on the virtual mass balance may have given the virtual lab a slight advantage over traditional mass balances where there is a brief wait period for the mass measurement to normalize.

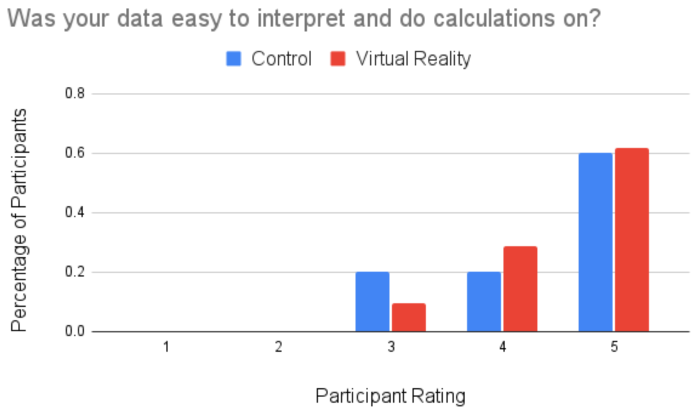

Fig. 9. Ease of interpretation of data and calculations. The distribution of participants' feedback scores for virtual (red) and control (blue) groups, with 1 being the lowest score and 5 being the highest score.

The perceived difficulty in regards to data interpretation and calculations are shown in Figure 9. On average, virtual group participants found that data gathered from the simulation was more difficult to interpret and perform calculations on. To preserve educational integrity, we decided that our simulation would not solve calculations for participants. Virtual group participants were expected to solve the hydrate calculations traditionally on paper or a note-taking device using the data our conductors recorded for them during the simulation. However, some participants expected calculations to be solved by the simulation, explaining the discrepancy between feedback scores. As a result, they may not have enjoyed the experience of solving calculations outside of the simulation and these results were expected. In the planned deployment of our virtual labs, there would be an educator available to guide students through interpreting and calculating data after the virtual experiment.

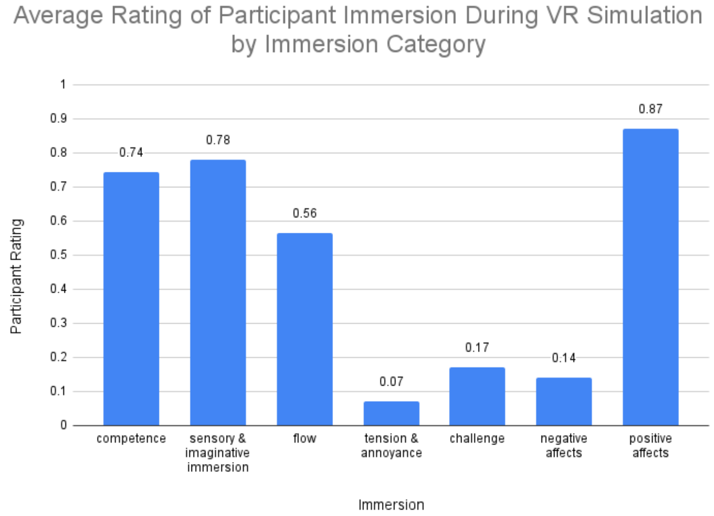

Fig. 10. Average immersion feedback from participants during the simulation by immersion category.

Figure 10 displays virtual group participants' evaluation of their experience within the hydrate lab simulation. Each component is numerically ranked between 0 and 1, with 0 indicating total disagreement and 1 indicating total agreement. These immersion feedback results suggest that the average participant was highly immersed in our simulation. Although they noted minor challenges, this did not stimulate frustration or an unfavorable mentality in creating an engaging environment and positive learning experience for participants.

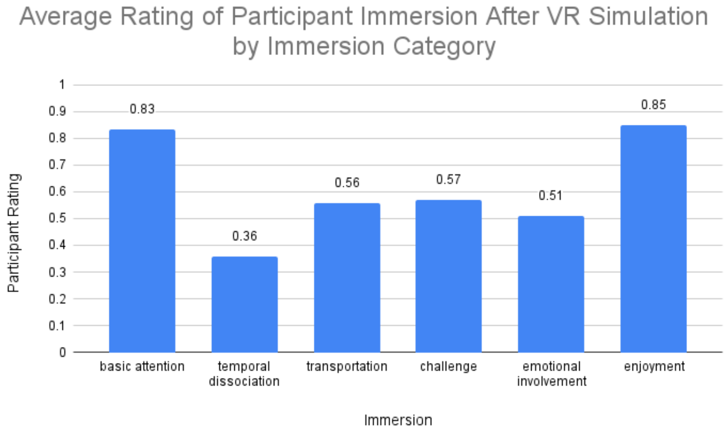

Fig.11. Average immersion feedback from participants after the simulation by immersion category.

The immersion feedback from virtual group participants after the simulation can be evaluated from Figure 11. The goal of our post-simulation survey was to examine the correlation between learning outcomes and levels of perception and attention. We interpret participants' reports of high attention and enjoyment as the most important categories in bringing out our immersive educational results. Categories that scored lower, including challenge, transportation, emotional involvement, and temporal dissociation can be improved upon through more intuitive controller bindings, fixed teleportation points within the virtual classroom, and other technical features that immerse participants more in the virtual experience.

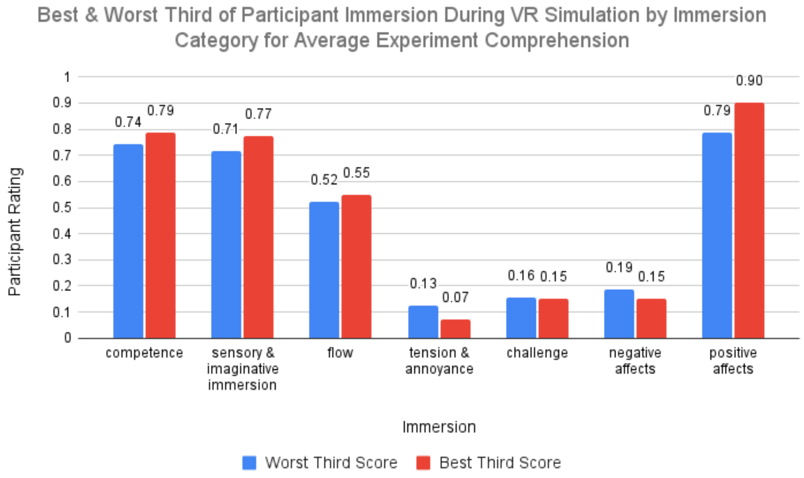

Fig.12. Immersion feedback from participants during the simulation for all immersion questions for both the worst third score (blue) and the best third score(red): Participant Rating vs Level of Immersion.

In investigating the correlation between the immersion survey results and comprehension of the hydrate lab, we focused specifically on the questions listed in figures 6 to 9 for these relations. These questions gauged understanding of lab concepts and simplicity in completing and analyzing the hydrate experiment. Participants who were able to complete the entire virtual experience with ease scored higher feedback values for the questions in figures 6 to 9. As a result, participants who scored higher potentially indicates that they were more focused on immersion in the simulation than worrying about performing the experiment correctly. Figure 12 shows that participants who answered the clarity and effectiveness questions the highest reported a greater level of competence, sensory immersion, flow, and positive effects.

5 Conclusion and Future Work

From our results, we determined that our simulated experiment is comparable to its live counterpart, and would be an educationally effective alternative for students in situations where a live experiment is inaccessible. Through our research, we have established that using a VR simulation to conduct chemistry lab experiments achieves similar and possibly better learning outcomes than traditional methods of conducting lab experiments. In particular, the participants who used our virtual hydrate simulation achieved equal or higher comprehension of the chemistry concepts and an ability to retain the procedures performed in the experiment. We also saw a correlation between greater comprehension of lab concepts with higher levels of immersion.

This project can be expanded upon by improving the hydrate labs as well as adding new labs. There are multiple ways we could improve immersion in the future, with a major focus on enhancing participants' interactions between the hand controllers and virtual lab equipment. For example, rendering hands rather than the controllers with different finger poses while holding virtual equipment would significantly add to immersion.

The educational value of the hydrate lab could also be improved upon. A crucial part of learning is 'learning by failing'. Currently the virtual lab guides participants to perform the lab perfectly through fail safes and progression-blocking mechanics. Removing these fail-safes and progression blocks by modifying scripts with variability in results that correspond to participant mistakes would allow more opportunities for critical thinking and is part of a future study.

Since conducting this study, we have expanded our virtual lab base to include a flame test lab in which users heat various metallic chemicals on a flame to produce flame color changes. The next lab that would be ideal to implement and observe results from would be a titration lab.

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