Towards a New Chemistry Learning Platform with Virtual Reality and Haptics

Doga Demirel[1](✉), Abdelwahab Hamam[1], Caitlin Scott[2], Bayazit Karaman[1], Onur Toker[1], and Lyan Pena[1]

[1] Florida Polytechnic University, Lakeland, FL 33805, USA
{ddemirel,ahamam,bkaraman,otoker,lpena4344}@floridapoly.edu
[2] Hendrix College, Conway, AR 72032, USA
scottc@hendrix.edu

Abstract. With COVID-19, colleges had to change the way they handle education. Students had to adapt to remote learning instead of the face-to-face learning they are used to. The transition to remote learning has proved to be difficult, but most courses have translated over without any problems. Unfortunately, the same cannot be said for the lab courses, which traditionally have students conduct hands-on experiments. In order to achieve the same level of effectiveness that the labs had prior to COVID-19; a new system is required. The long-term goal of this work is to develop a complete immersive Virtual Reality (VR) chemistry lab. In the VR lab space, the student can handle chemicals and equipment to simulate an actual chemistry lab. Using a VR headset and haptic gloves, the user will be able to freely move and interact with the virtual lab, fellow students, and their teacher. Due to COVID-19 restrictions, instead of the students testing the virtual experience, we presented a 6-min video demonstration of our immersive VR chemistry lab to 109 General Chemistry students. Students filled out pre- and post-questionnaires. 80% of the students either strongly agreed or agreed with the statement, "I think learning general chemistry with VR and haptics will be more engaging than a standard lecture". For the statement, "I think undergoing the chemistry lab training in a VR environment rather than watching videos will help me learn the basics of chemistry lab better", 71.8% of the students strongly agreed or agreed with the statement.

Keywords: Chemistry · Virtual reality · Haptics

1 Introduction

The onset of the COVID-19 pandemic has drastically changed the way chemistry is taught at academic institutions. Starting in March 2020, many U.S. colleges and universities closed their doors to in-person learning causing students to learn remotely. This greatly hampered the instruction of chemistry labs, where students typically conduct experiments using chemicals and instruments. Instead, students watch videos of experiments, write lab reports on provided data, perform at-home experiments, and use virtual simulations [1]. However, students did not get the hands-on experience of learning the

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correct protocol to work in a lab and handle modern machinery and hazardous chemicals. Given that many schools remain closed to in-person learning, it has become imperative to develop a way that students can learn the skills and techniques of conducting chemistry experiments without having to physically be in the lab. Benefits of a virtual lab would also extend beyond the end of the current pandemic. Students who cannot attend lab because they are pregnant, in the military, or are handicapped would benefit from alternative lab experiences that still adequately prepare them for working in a lab [2]. Even before the pandemic began, the utility of undergraduate labs for General Chemistry courses was called into question [1, 3, 4]. Labs are expensive to conduct [5], and many academic institutions were already experiencing a strained budget. Furthermore, it was questionable if students were actually learning the intended goals [1, 3, 4].

However, despite the cost and questions about learning, if done correctly, labs can be a vital part of the General Chemistry learning experience. Johnstone purposed that chemistry is taught in a three-pronged approach—the symbolic, the microscopic, and the macroscopic. The lecture sections generally emphasize the symbolic material (the chemical symbols, abbreviations, math equations, and variables) and the microscopic material (atomistic movements). Lab is the place where students can learn about chemistry macroscopically, that is, how chemical reactions affect the environment and the surroundings, and students can make connections between the macroscopic and the microscopic and symbolic worlds [6, 7].

Our solution to remote lab instruction is to use virtual reality (VR) head-mounted displays (HMDs) with haptic gloves. VR is beneficial for student learning for multiple reasons including making abstract ideas seem tangible and making students be actively engaged [8]. Our simulation will allow students to explore a realistic lab setting while handling machinery and chemicals. Students can interact with the avatars of other students, the lab assistants, instructors, as well as a "Virtual Buddy" who can act as a resource by answering questions. The haptic gloves will allow the students to feel the weight of the glassware and to handle the lab equipment and chemicals in a safe and controlled manner.

As mentioned above, there is uncertainty about the intellectual benefit that General Chemistry students gain from taking lab. Part of the problem can be attributed to the cognitive overload that students experience [9]. Typically, in a college teaching lab, students are introduced to the instruments and chemicals when they are conducting the experiments. Students not only have to learn the chemistry, but how to handle the equipment and materials as well. Some students do not take lab as part of their high school chemistry course. Even if they had, they may not have seen the same types of instruments and machines. Many of the chemical names sound foreign to the students, which creates confusion [6, 7]. To counter this, Brigham Young University and Purdue University require that their students record videos to verify that they know how to use the equipment before conducting actual experiments. At BYU, instructors have noted a decrease in broken glassware and safety issues [1]. For over three semesters at the University of Western Australia, approximately 75% of level-1 Chemistry students opted to participate in a 360° virtual tour the lab with over 90% of students saying that they agreed that the lab tour familiarized them with the lab setting and approximately 70–90% agreed that they felt prepared for lab [10]. By introducing the lab setting and materials to students in a safe manner that students can explore on their own time, we are hoping to prepare students for actual experiments so that they can focus on the chemical reactions and learning goals rather than be distracted by the lab setting.

Another potential benefit of VR-lab training is self-efficacy. Self-efficacy is defined as the student's belief that their actions can lead to success in a chosen subject or task [11]. A study of students in a social studies class show that student's self-efficacy impacted their goals and eventual academic achievement in the class, which suggests that self-motivation has a large impact on student success [12]. A study of first-year college students shows a direct correlation between student expectations and student success [13]. Therefore, to increase student retention, it would make sense to invest and improve student confidence. The role of VR in increasing self-efficacy needs more research, but there are some promising signs [9]. One way to enhance a student's self-efficacy is to give that student a sense of control [14]. An immersive VR environment would provide this for the student [9]. A meta-analysis of computer simulations and gaming in the classroom showed that students who used interactive computer simulations had more cognitive gains and a better attitude about learning than those in a traditional learning environment [15, 16]. A 2019 study about VR-lab safety training for engineering students showed that students in an immersive VR environment had increased motivation and self-efficacy compared to students reading the lab manual or using VR on a desktop computer [17]. VR training has also been shown to improve the self-efficacy of participants undergoing training for negotiating [18] or classroom teaching [19]. In our planned VR lab space, students would handle their own equipment and chemicals in a safe environment with easy access to a "Lab Buddy," which acts as a resource when the instructor and lab assistants may not be available. Thus, students would control their own learning experience, which should strengthen their confidence when they are ready to conduct experiments in an actual lab.

VR has been used in classroom instruction for decades. Computer simulations have been used to augment lab instruction as far back as 1980 [20]. VR-haptic surgery training has been used since 1998 [21, 22] and remains an important tool for training doctors and surgeons before practicing on patients. VR has been used to train surgeons in how to do laparoscopies, carotid stenting, and ophthalmology [8]. VR-trained surgeons were 29% faster and six times less likely to make mistakes while performing laparoscopic cholecystectomy gallbladder dissection than surgeons with traditional training [8, 23]. These studies show that VR training is effective at preparing doctors. We believe that it can be equally as effective as preparing students for their chemistry courses.

VR has already been in use to teach organic chemistry [24], physical chemistry [25], and biochemistry [26, 27]. In previous studies, students have found that using VR to teach chemistry to be very fun and educational. The "Bug Off Pain" VR game teaches students about the impact that toxins have on pain signaling pathways in the body. In a post-game survey, students reported feeling engaged and motivated to learn more [27]. This and other chemistry VR learning platforms, such as Labster [28], EduChemVR [29], VR-ENGAGE [30], Molecular Zoo, Peroxiredoxin Fish Tank, Protein Backbone Explorer, Nano Simbox iMD, Water VR [31], and MEL Science [32] rely on HMDs, whereas our proposed simulation will allow students to "touch," "feel," and "handle" the chemicals and lab equipment with the use of haptic gloves. Our chemistry lab simulation is designed to allow students to access the lab in a safe and comfortable setting in a way that will give students confidence for the time that they first approach the actual chemistry lab. By being prepared in a virtual space, we anticipate that students will feel more comfortable and have increased confidence, which will encourage them to continue with their chemistry education.

2 Methods

2.1 Application

Our fully immersive virtual environment has four main components: a) Virtual Scene, b) Haptic glove, c) Companion- "Virtual Buddy", and d) Database. Figure 1 shows the overall system design.

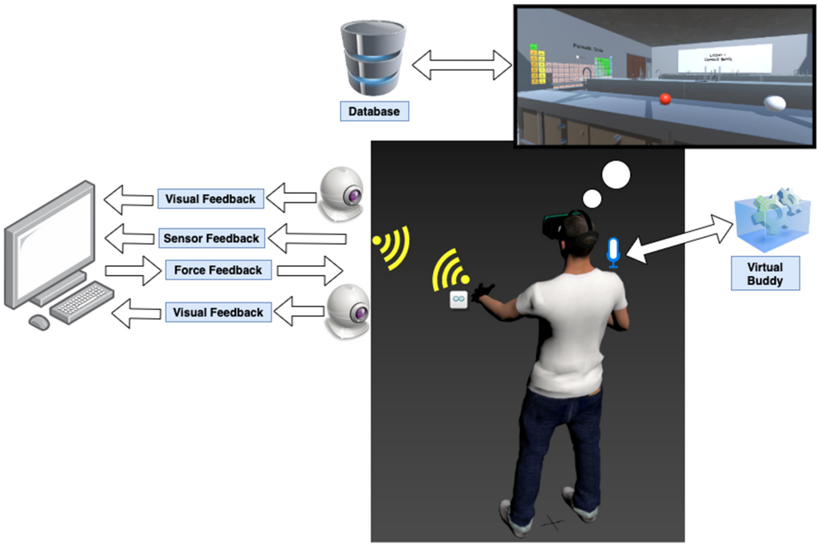


Fig. 1. Overall system design.

The virtual scene has two capabilities: a classroom and a lab. For a realistic rendering of the scene, we used High Definition Render Pipeline and Physically-based Rendering (PBR) [33, 34] in Unity software package. PBR uses bi-directional reflectance distribution function (BRDF) [35, 36] to approximate accurate light-flow models.

We placed an interactive periodic table on the wall of our scene (as seen in Fig. 2). The periodic table has a CPK Color toggle button which changes the colors of elements in the periodic table to CPK colors, which are used to distinguishing atoms of different chemical elements. Clicking on an element in the periodic table will spawn the selected element on the table. Radius and color information for each element will be stored in our MySQL [37] database.

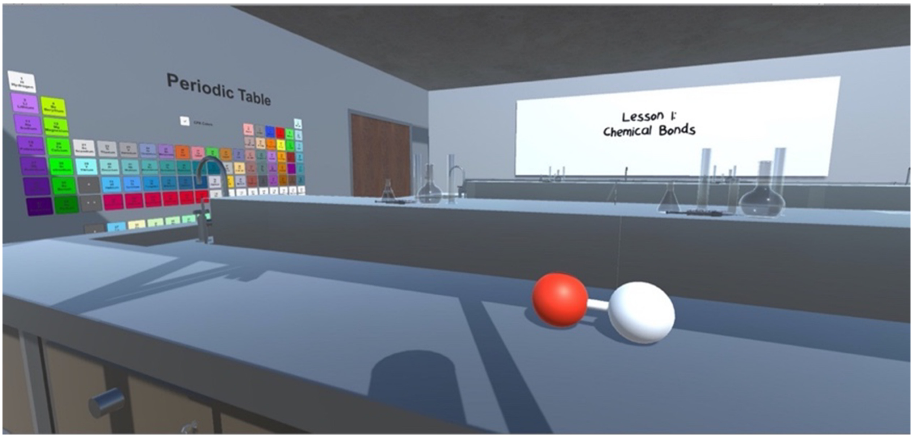


Fig. 2. First-person view in the virtual scene.

2.2 Video Demo

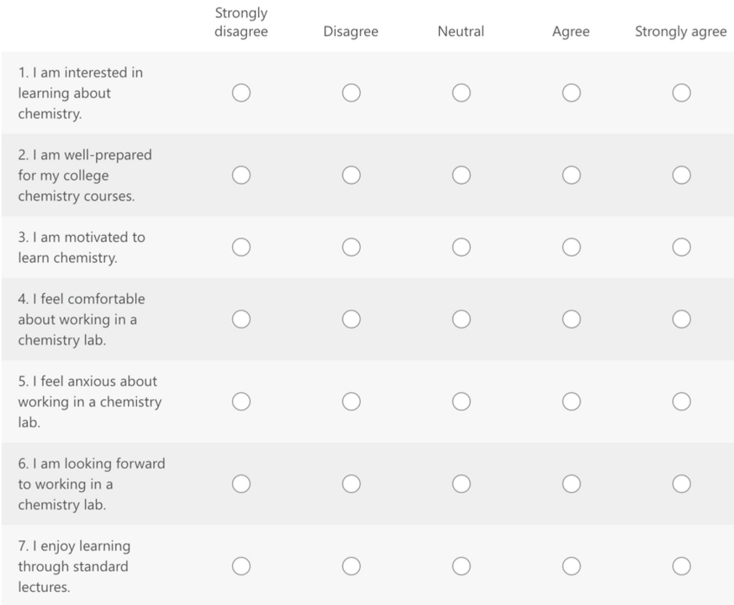
Due to the restrictions of COVID-19, instead of students testing the virtual experience, we presented a 6-min video demonstration of our immersive VR chemistry lab to 109 General Chemistry students at Hendrix College. The video demonstration was two-fold. The first part included information about VR HMDs, haptic gloves, and the reasoning of the study. The students were informed that the study goal is to simulate an actual chemistry lab experience through VR that will allow them to handle chemicals and equipment. They were provided a general overview of the steps they must accomplish: a pre-video questionnaire (which they have already did prior to watching the video), complete watching the video, and then complete a post-video questionnaire. The second part was a full demonstration of our virtual chemistry lab. In the demonstration, we showed a walk-through of the virtual scene which consisted of navigating the lab from a first-person point of view. The students were shown the virtual equipment, white board, the periodic table on the wall, the safety equipment, and the workspace available. The safety equipment is composed of various eye cleaning stations/emergency showers and a fire extinguisher. As the avatar was walking around the virtual avatar, the students could see what the avatar is seeing and hear information about how they would experience this in VR.

The second part also included the interaction with the periodic table to create elements in the scene and compounds by connecting the elements. The students were shown how to pick a particular element from the periodic table and use it in the interaction. Once they select an element the atomic representation of that elements appears. Bringing elements into proximity will form an ionic bond between the two elements, while moving them further will break that bond.

2.3 Questionnaire

The questionnaire started with a general description of the video that the students are about to see as well as a statement on the goal of conducting the study and instructions on filling the questionnaire. This was followed by questions about the participants' demographics. The demographic data were collected to deduce conclusion about the data, however, they were kept anonymous.

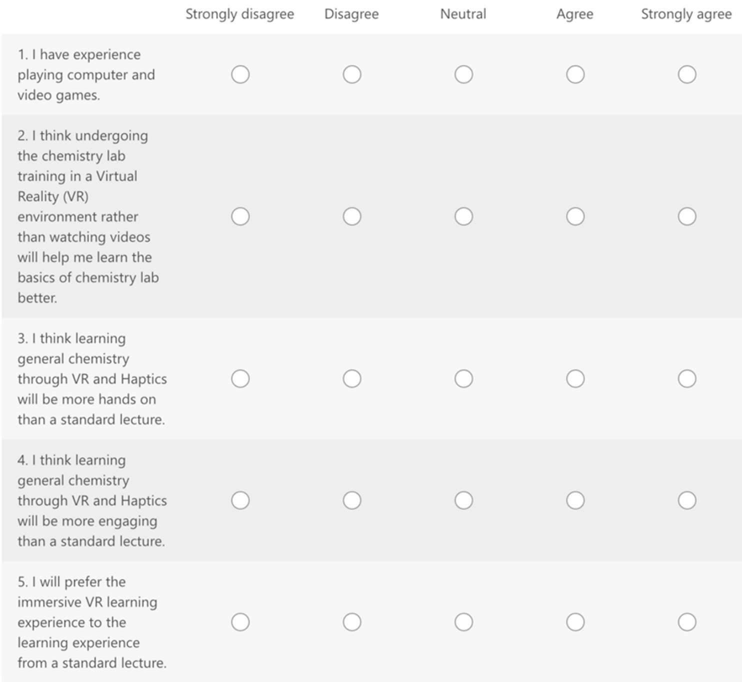
Prior to watching the video, students answered a pre-questionnaire about their background in chemistry and gaming, and their interest, motivation, and preparedness in learning chemistry. The pre-video questionnaire is comprised of Likert-like multiple choice questions (as seen in Fig. 3) and descriptive open-ended questions where the students would fill out information in a given space. The open-ended questions include: "What is your chemistry background?", "Why are you enrolled in chemistry?", "How do you feel about your chemistry course?", and "How do you feel about your chemistry lab?".



	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
1. I am interested in learning about chemistry.	○	○	○	○	○
2. I am well-prepared for my college chemistry courses.	○	○	○	○	○
3. I am motivated to learn chemistry.	○	○	○	○	○
4. I feel comfortable about working in a chemistry lab.	○	○	○	○	○
5. I feel anxious about working in a chemistry lab.	○	○	○	○	○
6. I am looking forward to working in a chemistry lab.	○	○	○	○	○
7. I enjoy learning through standard lectures.	○	○	○	○	○

Fig. 3. Likert-like multiple pre-video questions

After the demonstration of the video, students were given a post-video questionnaire with open-ended and Likert-like questions which outlined how the use of VR and haptics would be beneficial in learning. In both the pre- and post-video questionnaires, the Likert-like questions were anchored with labels strongly agree, agree, neutral, disagree, and strongly disagree (as seen in Fig. 4). The open-ended question for post-video questionnaire was "How has your perception of the study of chemistry changed as a result of this video?".



	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
1. I have experience playing computer and video games.	○	○	○	○	○
2. I think undergoing the chemistry lab training in a Virtual Reality (VR) environment rather than watching videos will help me learn the basics of chemistry lab better.	○	○	○	○	○
3. I think learning general chemistry through VR and Haptics will be more hands on than a standard lecture.	○	○	○	○	○
4. I think learning general chemistry through VR and Haptics will be more engaging than a standard lecture.	○	○	○	○	○
5. I will prefer the immersive VR learning experience to the learning experience from a standard lecture.	○	○	○	○	○

Fig. 4. Likert-like multiple post-video questionnaire questions

3 Results

In this study, a survey consisting of 14 questions is conducted on a total of 109 students. For the statement, "I think learning general chemistry with VR and haptics will be more engaging than a standard lecture", 42.7% of the students strongly agreed with the statement, 37.3% agreed, 11.8% was neutral, 5.5% disagreed, and 2.7% strongly disagreed. For the statement, "I think undergoing the chemistry lab training in a VR environment rather than watching videos will help me learn the basics of chemistry lab better", 30% of the students strongly agreed with the statement, 41.8% agreed, 17.3% was neutral, 8.2% disagreed, and 2.7% strongly disagreed.

The following 7 questions are more relevant for our analysis, and the rest are more related to chemistry itself. For each question, we also use a short abbreviation to simplify tables and visualization of correlation data. These abbreviations are shown in parentheses.

1. (Interested) I am interested in learning about chemistry.
2. (Anxious) I feel anxious about working in a chemistry lab.
3. (Learning) I enjoy learning through standard lectures.
4. (Experience) I have experience playing computer and video games.
5. (Undergoing) I think undergoing the chemistry lab training in a Virtual Reality (VR) environment rather than watching videos will help me learn the basics of chemistry lab better.

6. (More engaged) I think learning general chemistry through VR and Haptics will be more engaging than a standard lecture.
7. (Prefer) I will prefer the immersive VR learning experience to the learning experience from a standard lecture.

For each survey questions, there were a total of 5 possible answers; 0: Strongly Disagree, 1: Disagree, 2: Neutral, 3: Agree, 4: Strongly Agree,

Namely instead of categorical data, we have ordinal values. Therefore, instead of chi-square type tools for correlation analysis, we used Spearman's Rank-Order correlation formula. Because all of our data (i.e. answers) are ordinal values rather than categorical. We are not using Pearson's correlation formula, because we are not interested in linear relationships, rather we are looking for monotonic relationships, whether linear or not. Basically, Spearman's correlation measures monotonic relationships. In the following table, we have the so-called *p*-values, where a small value indicates a strong "monotonic" correlation, and a large value implies the lack of correlation.

Our *p* threshold is selected as 0.05, i.e. if a *p*-value is less than 0.05, we conclude that there is a strong correlation between two variables. All *p*-values which are below 0.05 are highlighted, except the ones along the diagonal which have perfect correlation because of being identical variables.

Table 1. Table of *p*-values for the selected questions. Small *p*-values are highlighted, yellow background indicates positive correlation, whereas gray background is used for negative correlation.

	Interested	Anxious	Learning	Experience	Undergoing	More Engaged	Prefer
Interested	0.000	0.679	0.001	0.160	0.340	0.563	0.763
Anxious	0.679	0.000	0.980	0.304	0.003	0.099	0.108
Learning	0.001	0.980	0.000	0.088	0.543	0.245	0.110
Experience	0.160	0.304	0.088	0.000	0.025	0.003	0.007
Undergoing	0.340	0.003	0.543	0.025	0.000	0.000	0.000
More Engaged	0.563	0.099	0.245	0.003	0.000	0.000	0.000
Prefer	0.763	0.108	0.110	0.007	0.000	0.000	0.000

In Table 1, we see a couple "islands" of "zeros" representing highly correlated variables. The first one is

Island 1 (Experience, Undergoing, More Engaged, Prefer): This island indicates a strong correlation between Experience, Undergoing, More Engaged, Prefer, more precisely.

- (Experience) I have experience playing computer and video games.
- (Undergoing) I think undergoing the chemistry lab training in a Virtual Reality (VR) environment rather than watching videos will help me learn the basics of chemistry lab better.
- (More engaged) I think learning general chemistry through VR and Haptics will be more engaging than a standard lecture.

- (Prefer) I will prefer the immersive VR learning experience to the learning experience from a standard lecture.

As it is clear from this analysis, students who have previous gaming experience will prefer the use of such tools, will be more engaged, and find these tools very advantageous for a better learning experience.

Island 2 (Learning, Interested):

- (Interested) I am interested in learning about chemistry.
- (Learning) I enjoy learning through standard lectures.

The purpose of these questions was simply to assess the reliability of our dataset. These are logically correlated questions, but the wording was quite different. If a majority of students answer a significant portion of the survey almost randomly without reading carefully, one would expect either no or very low correlation between these two questions. However, our analysis shows a very strong correlation between the two, which is an indication of a reliable dataset or survey result.

Island 3 (Undergoing, Anxious):

- (Anxious) I feel anxious about working in a chemistry lab.
- (Undergoing) I think undergoing the chemistry lab training in a Virtual Reality (VR) environment rather than watching videos will help me learn the basics of chemistry lab better.

All of the correlations discussed so far, were positive correlations, whereas here we have a negative correlation. Basically, students who feel anxious about working in a chemistry lab think that undergoing the chemistry lab training in a Virtual Reality (VR) environment rather than watching videos will NOT help them learn the basics of chemistry lab better. In other words, students who are anxious about chemistry do not find these tools really useful to improve their learning experience.

In Fig. 5, we have a visual representation of p-values matrix. While dark blue like colors are representing small p-values, i.e., strong correlation, yellow like colors indicate large p-values, namely lack of correlation. A color bar shown on the right summarizes the relationship between colors and numerical p-values.

Figure 6 show that, majority of students are interested in learning about chemistry. However, the second graph shows that not all enjoy learning through standard lectures. In other words, they would like to see better alternative tools to be used for teaching.

The results from Fig. 7 shows that the proposed immersive VR chemistry tool will be useful not only for a special group of students, but for a broader audience. Because, although a good number of students do not have any gaming experience, some of them still believe that these VR tools will improve their learning experience.

We see a large group of students who answered Neutral (as seen in Fig. 8). These two figures show that, most students consider VR tools as something which will improve their learning experience; however, they seem to be a bit confused and possibly scared about using such tools in a standard lecture.

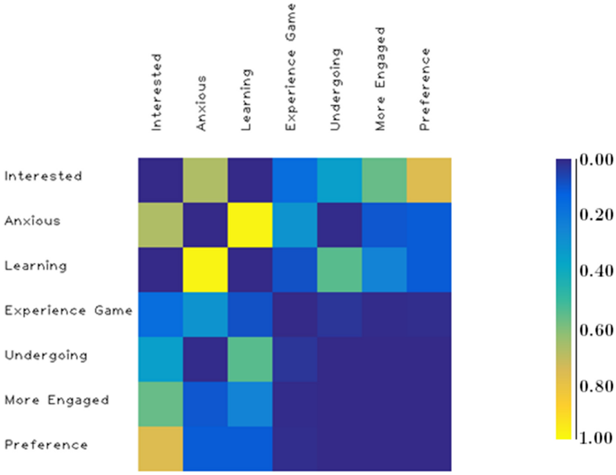


Fig. 5. Spearman's p matrix in color image format (Parula colormap).

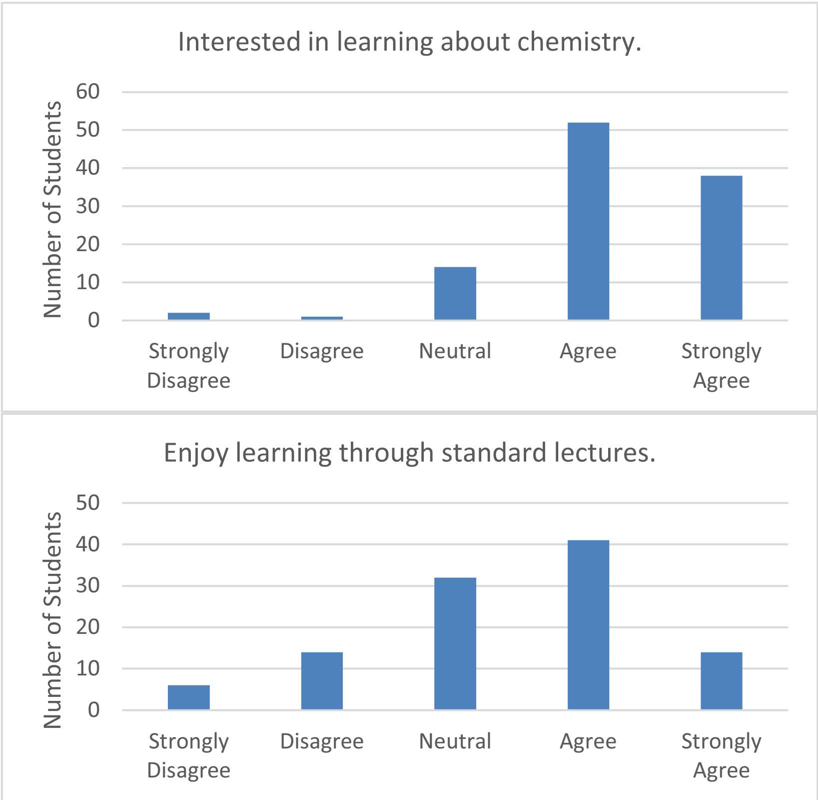


Fig. 6. Comparison of "Interested" and "Learning" answers.

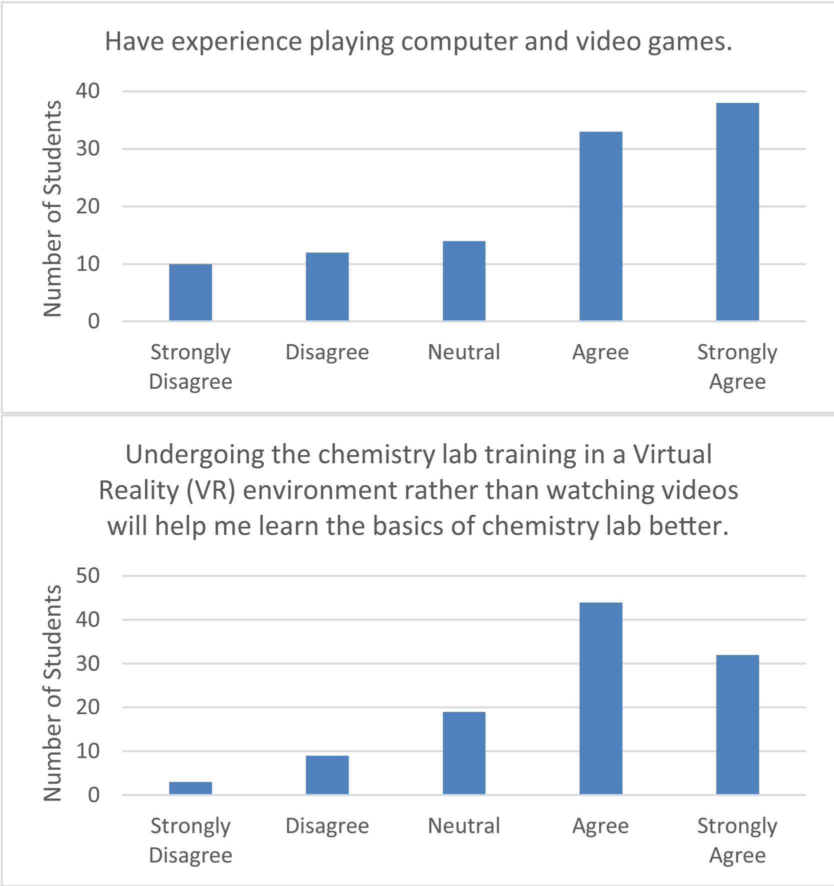


Fig. 7. Comparison of "Experience" and "Undergoing" answers.

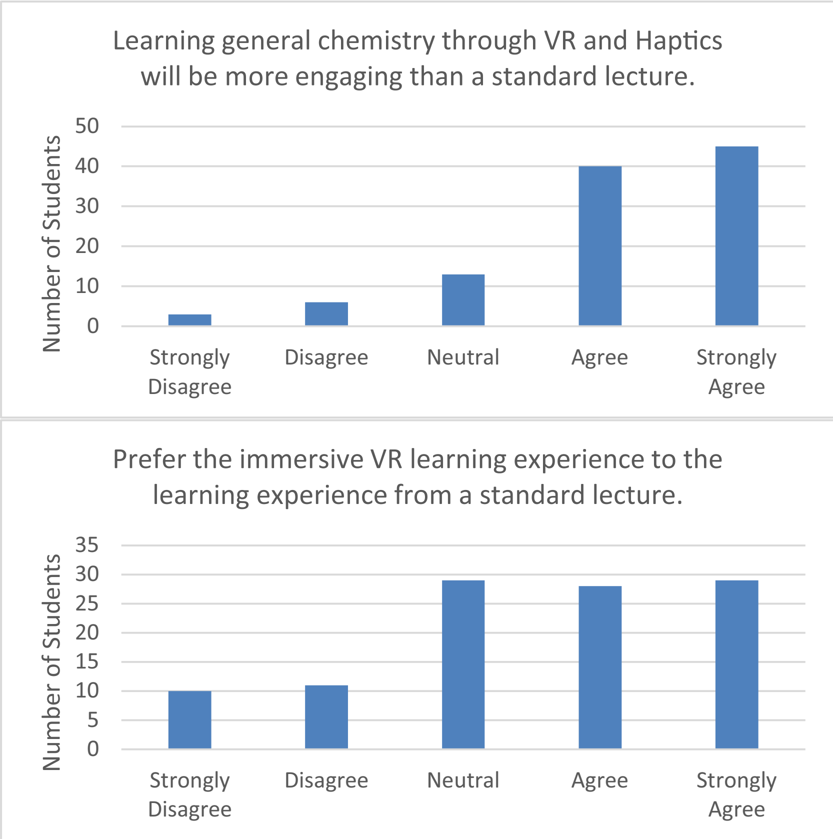


Fig. 8. Comparison of "More Engaged" and "Prefer" answers.

4 Conclusion

With COVID-19, many colleges have had to change the way they handle their education. As a result, students have been unable to engage in face-to-face learning and most educational establishments have switched to remote learning in order to ensure the safety of the students, professors, and staff. Remote learning has its advantages but is not as effective as in-class instruction, especially for lab environments.

In this study, we created a preliminary interactive virtual chemistry learning environment using HMDs. Due to the restrictions of COVID-19, instead of students testing the virtual experience, we presented a 6-min video demonstration of our immersive VR chemistry lab to 109 General Chemistry students. After the demonstration of the video, students were given a post-video questionnaire with open-ended and multiple-choice questions which outlined how the use of VR and haptics would be beneficial in learning. In the post-video questionnaire, students answered 14 multiple choice questions as strongly agree, agree, neutral, disagree, and strongly disagree. For the statement, "I think learning general chemistry with VR and haptics will be more engaging than a standard lecture", 42.7% of the students strongly agreed with the statement, 37.3% agreed, 11.8% was neutral, 5.5% disagreed, and 2.7% strongly disagreed. For the statement, "I think undergoing the chemistry lab training in a VR environment rather than watching videos will help me learn the basics of chemistry lab better", 30% of the students strongly agreed with the statement, 41.8% agreed, 17.3% was neutral, 8.2% disagreed, and 2.7% strongly disagreed.

We also conducted the Spearman's rank correlation coefficients and *p*-values to analyze the correlation between multiple choice questions. It has been observed that students who have previous experience with computer and video games prefer immersive VR learning experience compared to standard methods. The Spearman's test showed a *p*-value of 0.0069 suggesting a strong correlation between the two. Students who have previous experience with gaming, find VR tools more effective compared to online video tutorials. The Spearman test *p*-value was 0.0163 also suggesting a strong correlation between the two. Student who feel anxious about chemistry labs find VR tools more effective compared to online video tutorials. Our study showed a Spearman test *p*-value of 0.0163 also suggesting a strong correlation between the two. We have observed no significant correlation, *p*-value of 0.5628, between the interest level of students to learn chemistry and their level of interest for VR and haptic tools. This result shows that the proposed immersive VR chemistry tool will be useful not only for a special group of students, but for a broader audience.

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