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Production and Evaluation of a Realistic Immersive Virtual Reality Organic Chemistry Laboratory Experience: Infrared Spectroscopy

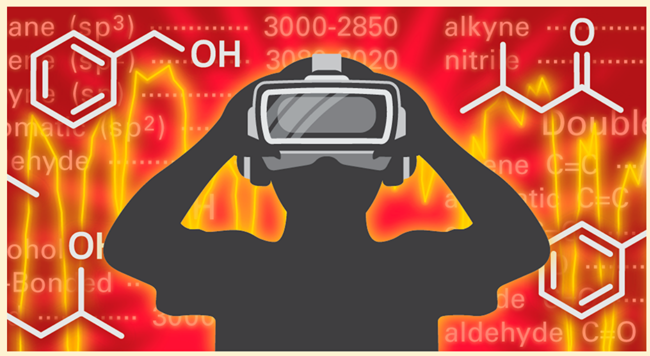
Cathi L. Dunnagan,[†] Devran A. Dannenberg,[‡] Michael P. Cuales,[†] Arthur D. Earnest,[†] Richard M. Gurnsey,[†] and Maria T. Gallardo-Williams*[,‡]

[†]Instructional Innovation Services, Distance Education and Learning Technology Applications (DELTA), North Carolina State University, Raleigh, North Carolina 27695, United States

[‡]Department of Chemistry, North Carolina State University, Raleigh, North Carolina 27695, United States

Supporting Information

ABSTRACT: Using virtual reality (VR) in educational settings is becoming increasingly popular. The feasibility of replacing an instrumentation-based organic chemistry lab with a VR experience has been evaluated. A VR laboratory experience was designed to teach students how to use an infrared spectrometer and elucidate an unknown structure from the resulting infrared spectrum. The resulting first-person VR experience is immersive and realistic, with a teaching assistant guiding the user along the steps required to complete the experiment, including feedback as needed. The VR experience was developed in WondaVR with selections made using gaze navigation. The resulting product was tested with a group of students, and the outcomes for short- and long-term recall were compared with a group of students that did the same experiment in a traditional lab. Results indicate that there are no significant differences in learning outcomes between the two groups, which indicates the possibility of using this tool to offer this organic chemistry lab experiment via distance education. Students that tried the VR experience reported a high degree of satisfaction with the product and no significant usability barriers. These VR experiences could be useful for students who are unable to be present in lab due to disabilities, attendance challenges such as pregnancy, or safety concerns.



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INTRODUCTION

A recent editorial in this *Journal* challenged the chemistry community to ponder the evidence basis for laboratory instruction, considering the time and resources required to continue providing them.[1] Questioning the educational value of laboratories as part of a chemistry curriculum is a recurring theme in chemistry education,[2,3] and one that will continue to be controversial, given the challenges inherent to the determination of learning outcomes in lab courses that are closely aligned with lecture courses. However, articulation of faculty goals and expectations and the clear communication of those expected outcomes to students have been found to be an important component of the lab instruction development process.[4−6]

From a practical standpoint, regardless of their perceived usefulness or cost, even with well-designed laboratories that target meaningful learning outcomes, there are specific circumstances when students are unable to attend lab. Some of those attendance challenges might be permanent, such as in the case of certain disabilities in which the student is unable to stand or use their own hands to handle chemicals. Others might be temporary restrictions on attendance, as could be experienced by a student who is pregnant or has a broken limb, or is unable to attend during a specific time period due to work-related travel or a military deployment. Offering makeup laboratories is expensive (due to the cost of extra instructional staff and chemical expenditures) and sometimes prohibitive due to large enrollment programs and a shortage of lab space. In these very specific cases we hypothesized that some instrumentation-based laboratories could be replaced with a carefully designed virtual reality (VR) experience.

Advances in virtual reality (VR) technology allow users to access immersive, three-dimensional (3-D) content from any location while using low-cost peripheral devices, and are currently being explored as a new and exciting tool in science education, both in K−12 and higher education. VR applications can be used to generate virtual worlds, games, and simulations. The emergence of affordable, high-quality

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360° spherical video recording and production technologies has made this approach possible.[7,8]

Many different VR applications have been developed for use in diverse fields from computer science to biotechnology and have been tested with different degrees of success. In general, these applications are simulations or gamified environments that used stylized aesthetics and animated actors to deliver the content.[9,10] Some realistic two-dimensional (2-D) computer simulations have been developed for use in chemistry courses.[11,12] The role of the viewer in these simulations is becoming increasingly more interactive, but it could be argued that the technology development currently outpaces the instructional design. A recent publication in this *Journal* offers a good overview of the current state of chemistry laboratory simulations, both in 2-D and 3-D environments.[13]

Virtual and augmented reality applications are becoming a part of the educational landscape in chemistry education. Augmented reality has been described as a suitable tool for instruction on instrumentation[14] and some titration techniques,[15] as well as a means to accomplish safety orientation goals.[16,17] Virtual reality is currently being used to offer laboratory tours,[18,19] an approach that helps students overcome fears related with lab environments.

■ PROJECT DESCRIPTION

This study was designed to assess the feasibility of using a VR learning experience to replace a traditional instrumentation-based face-to-face lab in which students are trained to collect and analyze infrared spectra. A second aim was to gather information about the differences in learning outcomes associated with the use of the infrared spectroscopy virtual reality learning experience in an organic chemistry laboratory, as compared to a control group that was taught by teaching assistants in a traditional lab setting. Information was collected in the short term via lab worksheets and postexposure questionnaires and on a two-week delay by embedding relevant questions in the final lab quiz.

The virtual reality experience content was sourced from experienced teaching assistants that had recently taught the infrared spectroscopy lab. Initially, their prelab presentations were recorded and used to develop a script for the VR experience, which was then vetted by the faculty member in charge of the course. Graphic elements were added during the production and postproduction stages to support the content being presented by the teaching assistant. In the VR experience, the virtual teaching assistant works one-on-one with the student and provides assistance as needed. The student is in charge of making all the relevant decisions, and there are opportunities for redirection in the case of a nonproductive decision on the part of the student. Although a professional crew did the filming, editing, and production, teaching assistants familiar with the course wrote the scripts and acted in the videos. These contributions filled the gap between their recently acquired expertise and that of incoming novices. Because they had more immediate familiarity with the perspective of their students, who come from many different majors and a wide range of experience, they were in a unique position to generate targeted instructional content. The format of the experiences was chosen to maximize student use and benefit. In particular, the VR experiences are composed of brief and focused segments to increase the likelihood of student engagement; they were made with the visual reinforcement of on-screen callouts and graphics to increase student understanding, and they were made with active demonstration and participation to provide a useful model rather than strictly static images.[20]

■ METHODS

Course Description

CH222 (Organic Chemistry Laboratory I) is a one-credit, semester long course that is offered year-round. In the summer, the lab meets every week (2 h 45 min long). It is part one of a two-part sequence that is completed by taking CH224 (Organic Chemistry Laboratory II). Typical enrollment is approximately 15,00 students per course per semester, divided into sections of about 20 students, led by teaching assistants (TA) under centralized supervision by a faculty member.

Control and Treatment Groups

Students from four lab sections were randomly divided into control (45 students, 4 sections) and treatment (30 students, divided in 3 groups of 10) groups. All students had completed an online prelab on IR spectroscopy prior to the lab. Control groups had their TAs conduct a lab briefing and supervise the lab. Treatment groups were removed to a separate lab room prior to the start of the lab and asked to view the VR experience on GearVR headsets. In the in-person lab the students worked with partners and had one TA for the whole section. In the VR simulation the students worked individually and had a virtual TA.

The researchers gave a brief (under 10 min) explanation for the creation of VR experiences for the organic chemistry lab; then, students were shown how to use the GearVR headset and headphones. The sessions were monitored by a team of two researchers who were able to assist with technical questions, and they also recorded the duration of the sessions as well as any student interactions. All students (control and treatment) were given a lab worksheet to complete as part of their grade for the lab. Treatment groups also received a follow-up survey immediately after their lab was completed. Four course sections led by three randomly assigned teaching assistants were selected. All sections met at the same time of the day, on three consecutive days. Two weeks after the date of the original observation all the students in the study were given a quiz containing four questions relative to the infrared spectroscopy experiment. Quizzes were collected and graded by the research team. Data collection for this study was conducted during the first summer session of 2018 (May—-June), with the approval of the university's Institutional Review Board (IRB). Participation in the study was voluntary, and all enrolled students chose to participate in the study.

Traditional (In-Person) Lab

The traditional version of the IR lab starts with a briefing by the TA (usually around 10 min) in which the TA covers the main uses of IR spectroscopy, how to use the IR spectrometer, and strategies to elucidate the structure of a compound using a table of IR frequencies. Once the lab briefing is completed, the students choose an unknown compound from a limited list of options and, working in groups of two, collect and interpret the resulting spectrum. Students then complete a worksheet and turn it in to their lab TA.

VR Experience [See Supporting Information: Design of the VR Experience]

The VR experience takes an average of 15 min to complete and can be viewed online[21] or by scanning the QR code in Figure 1

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with the Wonda VR app. See the Supporting Information for an overview of this VR development and design process.

Figure 1. QR Code for IR VR experience.

It can be downloaded to a smartphone and viewed wearing a GearVR headset; it may also be accessed using Google Cardboard with iOS and Android devices enabled with the Wonda VR app. Figure 2 shows screenshots from the VR experience.

Worksheet Questions

The worksheet contained five questions pertaining to the lab the students had completed as seen below. Both groups of students were provided with a standard table of IR frequencies.

1. What are the characteristic IR absorption bands for your unknown?
    a. Alkane vs aromatic
    b. Functional group
2. What are the correct units for IR absorption?
3. What does an IR spectrometer do?
4. What was the purpose of running a background IR?
5. What is the correct set of software commands required to collect an IR spectrum using the instrument available in the lab?

Quiz Questions

Students were provided with an IR spectrum of an unknown compound similar but not identical to one of the options available during the lab. The quiz had four questions that covered IR spectroscopy as seen below. Students were provided with a standard table of IR frequencies.

1. What are the characteristic IR absorption bands for your unknown?
    a. Alkane vs aromatic
    b. Functional group
2. What are the correct units for IR absorption?
3. What does an IR spectrometer do?
4. What was the unknown compound assigned to you?

Students' answers to the worksheet and quiz were evaluated in terms of correctness and totaled by category for each section.

Statistical Analysis

After collecting and organizing the data, Stata (StataCorp LP), a statistical analysis software package, was used to calculate the binomial mean and standard error. These binomial statistics were calculated for two data sets: the responses for students who received video instruction and the responses for students who received TA instruction, to compare the effectiveness of each type of instruction. Cohen's d values were calculated in order to determine the effect size for each video treatment.[22]

■ RESULTS

In our experience (see Table 1), there is minimal difference in student performance between instruction with VR or the traditional lab setting with a TA in the short term. For questions 1−4 on the lab worksheet, the values obtained for the VR and the face-to-face groups are not statistically different. While students in the face-to-face group tend to perform slightly better on question 1 (assignment of characteristic absorption bands), questions 2 (units) and 3 (purpose) are virtually indistinguishable. On question 4 (background IR) the VR students outperform the control group. Some TAs can be more diligent in explaining to their students the need to run a background IR prior to data collection than others, and this might account for the observed difference. Although all the participating TAs were trained at the same time, prior to the lab meeting, and offered the same

Figure 2. Screen shots from the VR experience: (a) TA's welcome with biographical information; (b) safety glasses, first-person point-of-view; (c) selection of a lettered vial of unknown compound; (d) analysis—select the broadest peak.

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Table 1. Comparing Student Performance on Laboratory Worksheets and Quiz Questions Based on Teaching Method

Measure	Traditional Lab Mean Score, $N = 41$	VR Lab Mean Score, $N = 29$	Cohen's d	Effect Size, r
	Worksheet Question			
1	85.4 ± 33.6	69.0 ± 20.6		
2	18.3 ± 37.9	19.0 ± 18.1		
3	71.5 ± 34.3	72.4 ± 24.6		
4	58.2 ± 35.3	72.4 ± 24.6		
5	96.9 ± 27.4	74.1 ± 23.7		
Worksheet average	66.6 ± 17.9	61.4 ± 23.4	0.25	0.12
	Quiz Question			
1	63.4 ± 31.3	58.6 ± 34.9		
2	14.6 ± 15.3	22.4 ± 20.7		
3	75.6 ± 39.9	79.3 ± 39.7		
4	51.2 ± 32.9	55.2 ± 30.5		
Quiz average	51.2 ± 23.9	54.0 ± 23.6	0.12	0.06

resources to prepare their lab briefings, different TAs covered the material in their own way, and in some cases with different amount of emphasis on the steps required to complete the experiment. Meanwhile, the VR TA was an experienced TA, and the lab briefing used in the VR simulation had been reviewed by the instructional team to make sure that it was comprehensive. Question 5 (correct set of software commands) was significantly better in the face-to-face group, indicating that the hands-on experience helped in the recall of commands as compared to gaze navigation in the VR experience.

Table 1 also summarizes the long-term results obtained by including infrared spectroscopy questions in the final lab quiz. VR students did better than the control group in 3 out of 4 questions, even though the difference between the two methods was very small. Overall the VR students performed 2.8% better than those from the traditional lab setting, which results in a Cohen's d value of 0.12 and an effect size of 0.06, indicating that the two methods are virtually indistinguishable in terms of student outcomes, even though the VR experience might have been more memorable than a face-to-face lab.

The average worksheet and quiz values show that student performance varies more when comparing short-term and long-term results than when comparing the two teaching methods. The VR students appear to have retained more information between the time the lab was completed and the end of the semester when the quiz was given. This indicates that the VR lab had a notable impact on the students' ability to remember the lab, more so than the traditional lab setting.

On the basis of the observed outcomes, the interactive, first-person point-of-view IR spectroscopy VR experience was as effective as the face-to-face lab as a means to teach students how to operate an IR spectrometer and how to elucidate simple features of an IR spectrum. Since we did not include any measures of motor skills development as part of the data collection, our assessment is limited to the students' ability to collect and interpret an IR spectrum during the conditions of the experiment.

■ IMPLICATIONS

A realistic, immersive VR lab experience that can be used to teach students how to use an IR spectrometer and how to analyze the resulting spectrum has been developed and compared with a traditional in-person lab with the same learning objectives. Although there are technical challenges related to the production of such an experience, the outcomes of this limited trial are promising and indicate that students that are unable to attend the lab might use the VR simulation as a suitable replacement. The system we have developed offers some cost-savings when compared to a traditional lab makeup and provides great access flexibility to students, both in temporal and spatial terms.

We realize that the lab that was chosen for this study might be representative of a small subset of laboratory experiments, and that our results might not be generalizable to other, more hands-on, conditions. Although we argue that instrumentation-based laboratories are a suitable ground to try such innovations, it is not our goal to replace all organic laboratory sessions with lab simulations, just to offer a suitable alternative. Virtual reality experiences produced in this manner can be used as a suitable replacement for instrumentation-based in-person laboratories for students that face permanent or temporary attendance challenges.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.9b00705.

VR experience development (PDF, DOCX)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: Maria_Gallardo@ncsu.edu.

ORCID

Maria T. Gallardo-Williams: 0000-0002-0056-264X

Notes

The authors declare no competing financial interest.

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