JOURNAL OF CHEMICAL EDUCATION

pubs.acs.org/jchemeduc
Article

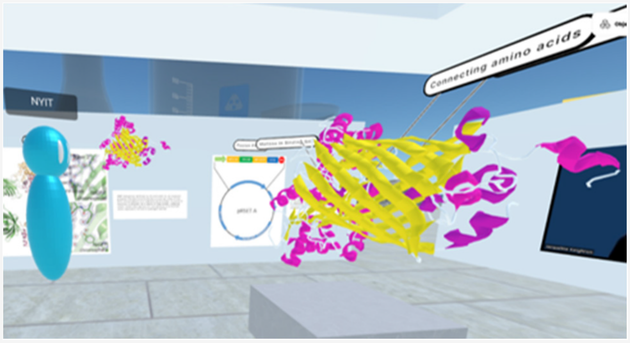
Exploring the Structure of Proteins and Other Biomolecules with a VR Museum: Lessons in Classroom Integration

Nicole Calma-Roddin,* Kevin Park, and Jacqueline Keighron*

Cite This: J. Chem. Educ. 2023, 100, 2574−2582
Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: The three-dimensional nature of macromolecules is often difficult for undergraduate students to grasp. This leads to difficulties in understanding key concepts in Biochemistry, such as protein function and conformational change. Virtual reality (VR) technologies, which can aid students in three-dimensional visualizations, have been shown to increase student motivation, but published reports do not universally agree about whether VR improves student comprehension. Here we present the implementation of a VR experience that was designed to complement existing biochemistry experiments and an analysis of both student engagement with and understanding of the material presented in VR. Results indicate that students enjoyed this interactive, immersive activity and suggest evidence of increased understanding. However, the effectiveness of the VR experience—and effective assessment of such an experience—may depend on a number of factors.



KEYWORDS: *Upper-Division Undergraduate, Biochemistry, Web-Based Learning*

INTRODUCTION

Traditional classroom materials depicting macromolecules rely on 2D images in textbooks and on projector screens. However, the use of 2D images does not allow students to fully appreciate the reality of these 3D structures. While small molecules can be aptly represented with physical models using molecular modeling kits, larger structures such as proteins are difficult to display in three dimensions, although such 3D representations are the best way to bridge the spatial manipulation gap.[1−7] This leaves two-dimensional representations of crystal structures, electron microscopy images, and cartoon depictions as the primary examples used by instructors in courses like Biochemistry and often leads to difficulty as students attempt to learn key concepts (such as protein folding, binding interactions, or conformational change) without a way to visualize the molecules in three dimensions.

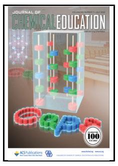
Virtual Reality in Education

Virtual reality (VR) technology allows individuals to visualize and perceive a virtual environment in an immersive way, as though they have been transported to a different space. Beyond just allowing users to perceive a space, VR also allows users to interact with virtual objects in the environment. While this technology is becoming popular for entertainment purposes, it is also a vital educational tool used in many fields, including (but not limited to) training in the military,[8] medical applications,[9] and sports.[10] In traditional classroom settings, VR methods have been used for many topics from writing[11] to physics[12] to engineering.[13] VR methods help students interact with course content in an embodied, experiential manner. For some topics, this kind of interaction is otherwise impossible, for instance, due to safety concerns or because the content is physically inaccessible for other reasons, such as the microscopic biomolecules discussed above.

Previous research has shown that activities using head-mounted VR displays generally improve the student experience. For instance, prior work has shown evidence of increased student motivation[14−17] and engagement.[14,16,18] Students also rate VR as more helpful to the learning process compared to text or video.[15] In addition to VR methods improving the student experience, a recent meta-analysis found that head-mounted VR learning is also more effective than traditional teaching methods or VR learning that uses less immersive desktop displays.[19] However, VR learning is not a monolith, and some prior studies have found that students do not perform better when using head-mounted VR displays.[16,17,20]

Here we discuss the implementation of a VR activity into a biochemistry lab using VR headsets that allow students to interact with their classmates while exploring a virtual environment tailored to accompany an existing laboratory

Received: October 14, 2022
Revised: May 22, 2023
Published: June 8, 2023



https://doi.org/10.1021/acs.jchemed.2c01015

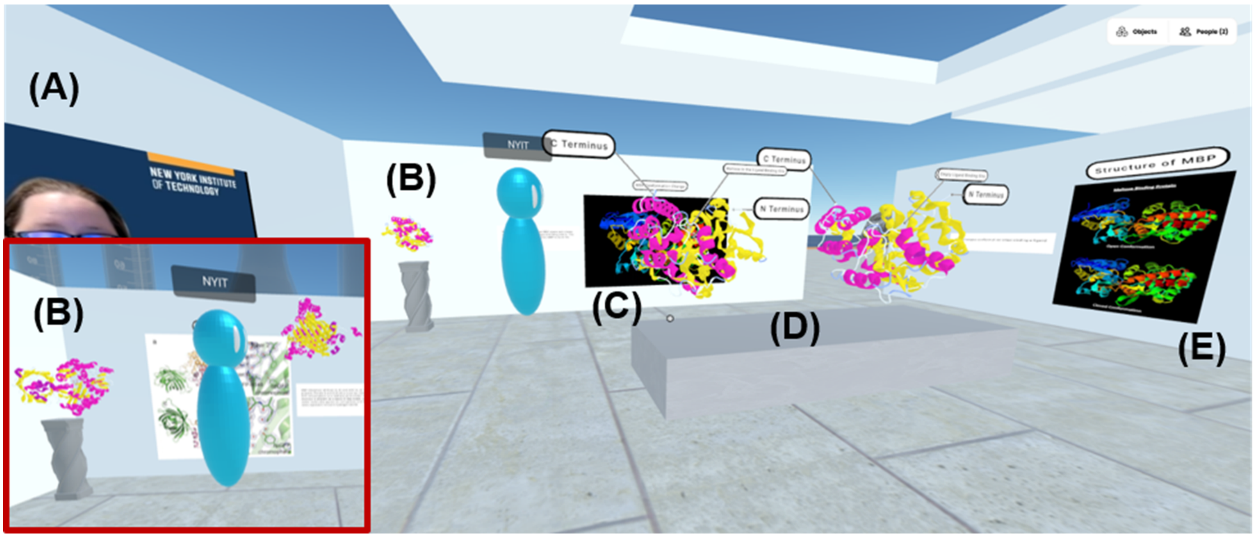


Figure 1. View of a student's avatar in a room of the 3D interactive museum created in Mozilla Hubs showing the structure and function of maltose binding protein (MBP). The virtual room is navigable, including a video introduction (far left, A); an interactive model that can be picked up, rotated in hand, expanded, and placed down in a new location (left, B); relevant GIFs (center, C) and images (far right, E) along the walls with accompanying descriptions; and the large models in the center of the room (right, D) showing two conformations of the MBP protein. Inset (lower left): a student's avatar exploring the interactive model of the MBP biosensor (directly in its line of sight) in another room of the museum.

protocol. The goals of this work are (1) to help biochemistry students increase their understanding of molecular structures by actively engaging with the 3D representations of proteins and smaller biomolecules such as carbohydrates and (2) to address how the impact of a VR activity may differ for different content and/or types of learning. Specifically, we sought to meet these goals while implementing the activity and assessing content knowledge in ways that would be consistent with how this would typically be done in the classroom setting.

■ INTERACTIVE VR MUSEUM

The ability to see and manipulate molecules in 3D (viewing them from different angles and in different positions) can aid students in better comprehension of the structures. The self-paced, immersive, and collaborative nature of the activity may also help students engage more deeply.

The learning objectives for this project were for students to

- Appreciate the 3D structure of proteins and basic biomolecules
- Gain a better understanding of protein structure and function
- Visualize the conformational changes that can occur in a protein when binding to a ligand
- Become familiar with the use of a protein as a biosensor

Existing Laboratory Experience

The VR activity was integrated into an existing multiweek laboratory protocol focusing on the purification, characterization, and application of a chimeric histidine-tagged maltose binding protein with circularly permeated green fluorescent protein (MBP-GFP) as a biosensor for maltose in food-based samples. Students received an overview of the protein and techniques used from printed material in the laboratory manual, relevant primary literature, and prelab discussions with the instructor in addition to the more generalized materials from lecture and the textbook.

Specific experiments in this protocol included the following:

1. Purification of the MBP-GFP biosensor from *Escherichia coli* lysate using Ni(II)NTA affinity chromatography
2. Bradford assay
3. SDS-PAGE
4. Fluorescence-based binding affinity assay
5. Fluorescence-based quantification of maltose in food samples brought in by students

VR Activity

The VR activities and environment were designed and developed using the Spoke web editor by Mozilla Hubs, a Web XR system. The virtual space and activities were designed and developed by a professor specializing in the fields of User Experience and User Interface (UX/UI) with the help of graduate students in that program and in collaboration with the course director for Biochemistry to complement the existing laboratory materials.

The space was laid out as a Biochemistry museum containing five rooms: (1) an open lobby with a video introduction to the activity; (2) a room depicting maltose, including the chemical structure, background information on disaccharides, the chemistry of carbohydrate cyclization, anomers, and reducing sugars, and introducing the polysaccharide maltodextrin, a biologically relevant ligand of MBP; (3) a room dedicated to MBP, including models of the open and closed conformations, video of the protein changing conformation as maltose binds, and background information on the protein; (4) a room for GFP, including a central model highlighting the internal chromophore and information describing the chemistry behind the fluorescence and the origin of the protein; and (5) a room dedicated to the MBP-GFP biosensor, including information about the expression and isolation of the protein from *E. coli*, the biosensor's structure, and its analytical use.

Each of the four topic-specific rooms contained a brief background video (Figure 1A), "posters" with images or gifs with descriptive text (Figure 1C,E), one or two large 3D models of the room's theme molecule (Figure 1D), and a small 3D model of the room's theme molecule (Figure 1B).

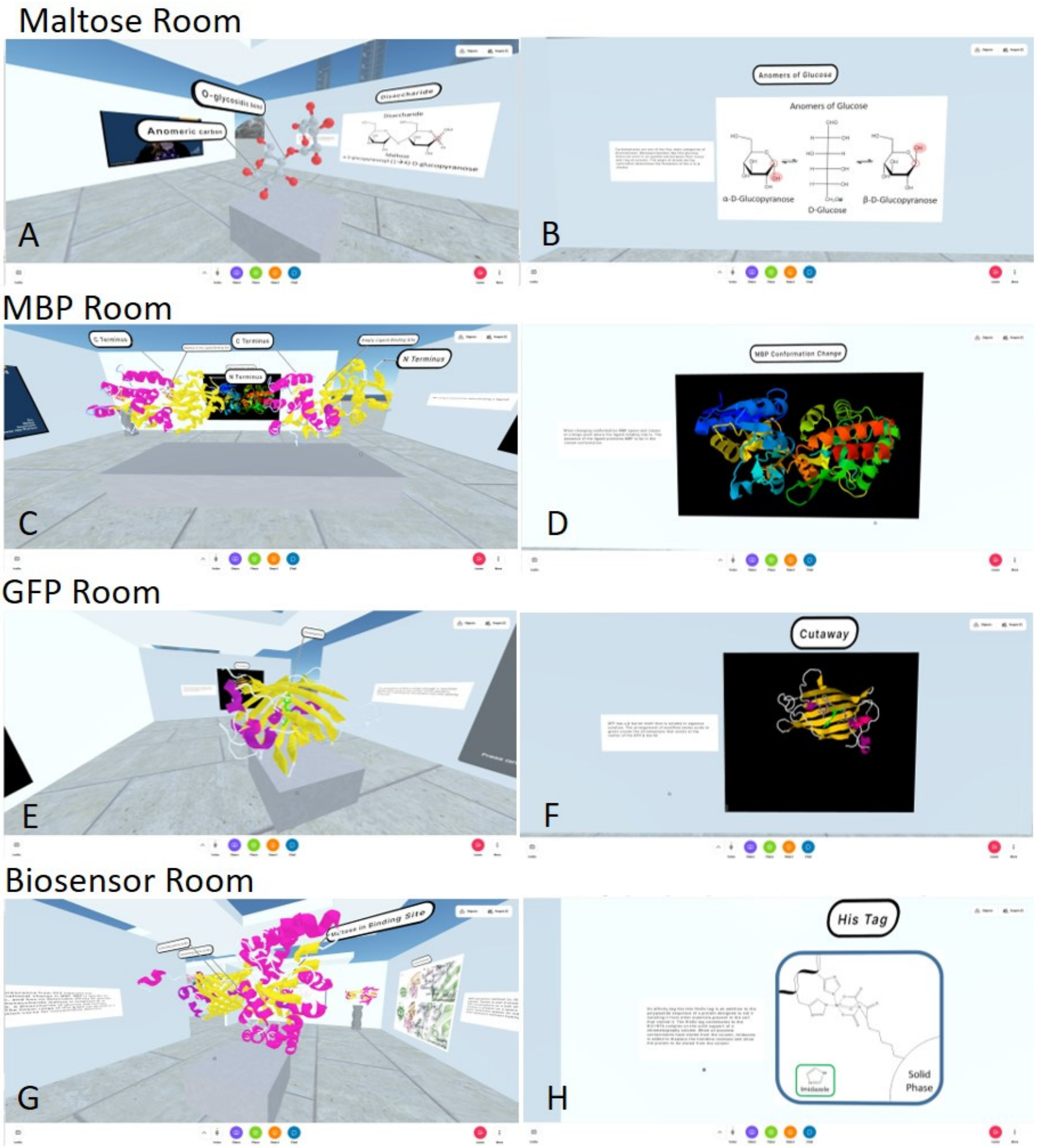


Figure 2. Additional images of the VR museum showing the large 3D models and example wall elements from each room: maltose (A); anomers of glucose (B); MBP in both the open and closed conformations (C); a gif showing the motion of MBP changing conformation (D); GFP (E); a cutaway showing the chromophore at the center of GFP (F); the MBP-GFP biosensor (G); and depiction of the affinity chromatography mechanism used to purify the biosensor protein (H).

Participants were able to pick up these small 3D models in order to hold and interact with them (e.g., rotate, expand, etc.). Additional images of the VR museum are shown in Figure 2. Once created, the museum was duplicated so that students could participate in smaller groups but experience the same museum content and design.

The use of an Internet-based VR activity allowed us to create an interactive activity that students could engage in using a variety of formats. Students could engage in this activity using a desktop/laptop computer or VR headset. The activity could be accessed in the classroom or at home, synchronously or asynchronously. An instructor could lead students through the museum as a tour guide or allow students to walk through in a self-paced format, either individually or collaboratively with other students. In this kind of activity, students can collaborate during a synchronous remote class (or potentially even have in-person students able to collaborate with remote students during a hybrid learning experience).

Student Participants

This exercise was conducted in the laboratory component of a college-level one-semester Biochemistry course. Students were expected to have previously completed General Chemistry I and II, Organic Chemistry I, and General Biology I. Most students had also completed General Biology II and a one-semester course in Genetics and were coregistered for Organic Chemistry II.

Table 1. Pretest and Posttest Statistics

Section	Test[a]	Mean	SD	Median	*N*	*Z*	*p*[b]
All	Pre	4.65/9	1.59	4.50/9	62	−0.73	0.465
	Post	4.48/9	1.52	5.00/9			
Carbohydrates	Pre	2.29/3	0.81	2.00/3	63	−4.53	<0.001*
	Post	1.49/3	0.69	1.00/3			
MBP	Pre	0.85/3	0.90	1.00/3	62	−2.44	0.015*
	Post	1.29/3	0.84	1.00/3			
Biosensor	Pre	1.48/3	0.67	1.00/3	62	−1.36	0.173
	Post	1.69/3	1.02	2.00/3			

[a] See SI 1 and 2 for pretest and posttest questions. [b] Wilcoxon signed-rank test p value of ≤ 0.05 is considered significant, indicated with asterisks. The Wilcoxon signed-rank test was used due to a non-normal sample distribution.

Sixty-nine undergraduate students participated in the study (32 F, 28 M, and nine who did not indicate their gender). Participants were between 18 and 30 years old (mean = 19.56, standard deviation (SD) = 1.54 years). Approximately 51% of participants were Asian/South Asian, 16% were White, 1.5% each were Black/African American or Hispanic/Latinx, 4.5% were more than one race/ethnicity, and 3% identified themselves as another race/ethnicity, while approximately 23% did not indicate their race/ethnicity. All students were pursuing majors in the Biological and Chemical Sciences or Health Sciences. This study was granted an exemption by the Institutional Review Board, as it was based on a classroom activity at the authors' university. Prior to completing any of the study assessments, all participants were given information about the purpose of the study and assured that their responses would be anonymous and would have no impact on their course or lab grade. All participants gave their consent to participate in the study.

Implementation

Participants completed the activity during their scheduled lab section with up to 18 students in the same lab section and six students in the same VR environment. First, participants completed a pretest in Qualtrics to gauge their understanding of relevant concepts before the activity (see SI 1). The pretest had nine multiple-choice questions, divided into three groups. Each question group showed students a molecule with three questions. These sections corresponded to different types of content covered in the VR activity: carbohydrate structure, MBP structure and function, and components of the MBP-GFP biosensor. Most participants completed the pretest on their own smartphone, although a few used a tablet or laptop present in the lab room instead due to internet connectivity issues.

After completing the pretest, participants were given instructions about how to put on the VR headsets and navigate the VR environment. Participants were instructed that their task was to explore all five rooms in the virtual environment.

Participants engaged with the VR activity using Oculus Quest 1 or 2 VR headsets or could engage with the activity on a desktop computer if they experienced discomfort using the headsets. Each student navigated the virtual environment at their own pace, reading the content, watching the videos, and viewing and interacting with the 3D models. They were also able to interact with up to five classmates in the VR environment, so they were able to "walk" through the VR environment together and even play (e.g., tossing 3D molecules to one another). Graduate students and the professor from the UX/UI program (who worked on the VR development) were available to assist participants who had any technical difficulties. The Biochemistry course director who created the content for the VR environment was also present to answer content-related questions as participants navigated through the activity. Because this was a self-guided experience, it is possible that students engaged in the different activities to different degrees, but student questions indicated that, overall, students engaged in a variety of the activities available.

Participants were informed that once they had finished exploring the biochemistry content, they could navigate outside of the museum, where there was a laboratory-themed scavenger-hunt-style mini-game unrelated to the content.

After participating in the VR activity, participants completed a posttest (SI 2) and follow up survey (SI 3) in Qualtrics. The posttest was used to assess any enhancement in student understanding of the material after engaging in the VR activity. The format of the posttest was the same as that of the pretest, and the same three categories were assessed. Because the students took the pretest and posttest in the same lab session, similar questions using different molecules or protein conformations were used on the pretest and posttest to avoid potential problems related to students remembering the questions and their pretest answers. None of the images were taken from the VR activity directly, although the source material was the same.

The survey was used to assess students' thoughts and attitudes toward the activity. In the survey, participants rated 16 statements (SI 3) on a five-point scale from 1 ("strongly disagree") to 5 ("strongly agree"). Participants rated items such as how easy they thought the VR system was to use, how much they enjoyed the activity, their feelings of motivation, and to what degree they liked using technology in the classroom versus more traditional methods. Although the survey was created by the research team, items were informed by the literature.[14,15,21] Participants were also asked whether they had ever used a VR system before, responded to a few demographic questions, and were given the opportunity to include any other comments they wanted to share about the experience. As with the pretest, most participants completed the posttest and survey on their own smartphone, although some used a tablet or laptop present in the lab room.

■ RESULTS AND DISCUSSION

In the Spring 2022 semester, students participated in this self-paced web-based VR activity in person, in a classroom setting. One student completed the VR activity on a desktop computer after developing a headache while using the VR headset. This student was omitted from further analysis.

Pretest–Posttest Analysis

Five students did not complete either the pretest or posttest, or their pretest and posttest could not be matched and were therefore omitted from these analyses. One student completed only the carbohydrate structure section of the test and so was included in that analysis while omitted from the others.

Each of the three sections of the pretest and posttest (representing carbohydrate structure, MBP structure and function, and components of MBP-GFP biosensor) were analyzed individually to measure the effect of the VR activity on student comprehension in each of these laboratory topics. Table 1 shows relevant statistics for the full pretest and posttest as well as the section analyses for the Carbohydrate Structure section, MBP Structure and Function section, and MBP-GFP Biosensor section. As can be seen in Table 1, students performed about the same on the full posttest as they did on the full pretest, but these results obscure differences found in the individual sections.

In the Carbohydrate Structure section, students performed significantly worse on the posttest than they did on the pretest. For the section on MBP Structure and Function, students performed significantly better on the posttest than they did on the pretest. For the section on the MBP-GFP Biosensor, there was no significant difference in student performance between the posttest and pretest. These differences are useful for considering what parts of the VR activity were most helpful to students as well as determining any improvements that can be made to the design and assessment of the VR activity.

Carbohydrate Structure

For the assessment of carbohydrate structure, the pretest asked questions referring to an image of maltose, while the posttest asked questions referring to an image of sucrose. The questions asked students to determine whether the chemical structure presented was a monosaccharide or disaccharide, homo- or heterodisaccharide, and reducing or nonreducing. Students did very well on the carbohydrate structure portion of the pretest that focused on maltose but did significantly worse on the posttest questions that focused on identifying homo- versus heterodisaccharide and whether the structure shown was reducing or nonreducing. While sucrose should have been familiar from class and was mentioned briefly in the text displayed in one area of the VR activity, it was not a focus of the VR activity. This means that, on the posttest, this set of questions asked students to apply their knowledge about maltose (from class and reinforced in the VR activity) to a different molecule. It is possible that students were unable to apply their knowledge to a different molecule based on their experience with the VR activity.

Alternatively, it is possible that students assumed that the posttest structure was also maltose. In both of the other sections of the pretest and posttest, the question wording highlighted the given molecule (e.g., "This is the Maltose Binding Protein..."; see SI 1 and 2), but the wording in this section did not name the molecule specifically (e.g., "Is this sugar..."). Students were also responding using a small image on their smartphones (SI 4), which may have made viewing more difficult. It is possible that, after seeing maltose in the pretest and then engaging in an activity centered on maltose and MBP, students expected the posttest to ask about maltose again. In fact, the majority of students chose answers that would have been correct had the posttest asked about maltose instead. However, the other sections of the assessment (on MBP Structure and Function and the MBP-GFP Biosensor) asked students to work with new images of a molecule that was featured in the VR activity rather than a different molecule altogether.

In the future, the language in the assessment should help focus students' attention on the given molecule or make students aware that they need to apply knowledge to a new situation. Future assessments can also be given in a larger format or instructions could encourage students to zoom in on an image if needed. These changes may help tease apart these different explanations for students' performance on this section and may clarify whether knowledge acquired through these kinds of activities can be generalized to different molecules not covered in a given activity.

MBP Structure and Function

For the section on MBP Structure and Function, students showed the most improvement on the two questions that related most closely to the MBP room in the activity, which focused mainly on the structures of the open and closed conformations of MBP. Specific questions related to the conformation of MBP in the presented image, whether there was a ligand bound to the protein, and how many subunits the protein contained. This protein was the focus of a video, the two large 3D models, and the small 3D model in the MBP room. In this section, students did significantly better on the posttest than the pretest (Table 1).

For the question concerning subunits, students performed about the same on the pretest and posttest. The answer to this question was not directly related to the conformation of the protein and was not specifically covered by the VR activity, but levels of protein organization were covered in lecture. Students would have been able to use the 3D models to see for themselves how many subunits were present, using their knowledge from class, but their responses on the posttest for this question show that this did not occur. One possible take-away here is that showing students a protein or other structure in 3D or VR is not necessarily sufficient for increasing content knowledge. Prior work has shown that interactive activities that require manipulation of 3D structures in VR help students learn more than passive content that only asks students to view such structures.[22] In the present study, students had opportunities for learning through both passive (e.g., reading and viewing) and active (e.g., manipulating a structure) means within the museum. In this section, students showed increased content knowledge for information that was highlighted in the VR activity (through videos, text, and points of interest in 3D models) but may not have attended to other parts of the protein that they were not prompted to consider or interact with within the activity. Alternatively, this may be an issue of assessment. As noted here, one of the most useful aspects of VR is the ability for students to experience these molecules in 3D, as they actually exist; however, the images used in the assessment were 2D. Future work might consider assessing students in VR, allowing them to interact with 3D models as they problem-solve.

Students did show significant improvements with questions about determining the conformation of MBP from an image or whether a ligand was bound to the structure. The VR experience presented these topics in depth with annotated 3D models showing maltose bound to the active site of MBP, side-by-side 3D models of the open and closed conformations, and a video of the protein changing conformation. There was also a

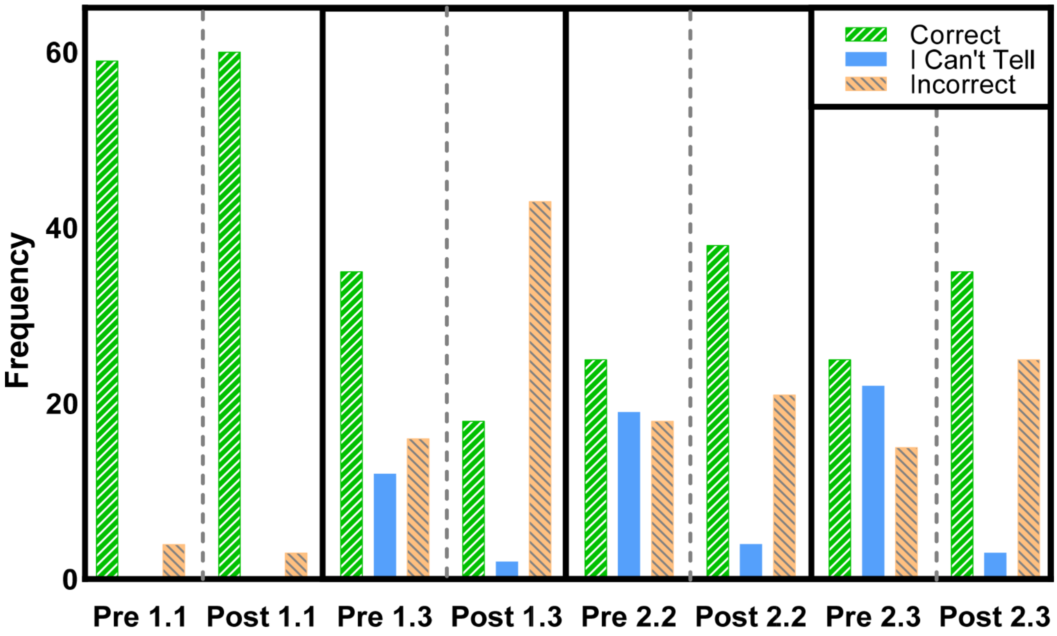


Figure 3. Student responses to pre- and posttest questions that included an answer choice of "I can't tell" (blue bars). The correct answer (green bars) and incorrect answer (orange bars) are also presented for each question. Questions can be found in SI 1 and 2.

significant reduction in the number of students choosing the "I can't tell" response when answering these questions on the posttest as compared to the pretest (Figure 3). Here, the VR activity proved effective at improving student understanding of the protein presented. Furthermore, students may have felt more confident in their ability to answer the question, as demonstrated by the reduction in students selecting "I can't tell" as an answer.

Components of the MBP-GFP Biosensor

For the section of the assessment on the MBP-GFP Biosensor, students again showed the most improvement on the two questions that were most closely related to the VR activity (identifying a ball-and-stick structure and its relation to the given protein). For the third question, students did very well on the pretest and much worse on the posttest (although a majority of students still chose the correct answer for this question on the posttest). This third question asked about an aspect of the structure that was not covered specifically in the VR activity (β-sheets vs α-helices) but was addressed in detail during lecture: students were asked to determine which secondary structure was most prevalent in the protein. Because of the differences between the proteins chosen for the pretest and posttest (GFP vs MBP, respectively), this question may have been more challenging on the posttest. GFP is often presented in biochemistry courses as an example of β-sheet and β-barrel structures. However, this question again underscores the need for the content in these types of activities to explicitly address any aspects of structure related to the learning goals. As discussed above, while VR is a helpful tool that allows students to interact with biomolecules in ways that are otherwise impossible, students may still need a guide through the material in order to reach educational goals, just as in other teaching methods. In this way, the use of VR is an additional tool—but not a replacement—for good teaching.

Comparison to Students without the VR Experience

One limitation of the previous analysis is the degree to which conclusions can be drawn from this analysis, given the use of different images in the pretest versus the posttest. To address this, in Fall 2022, 11 undergraduate students (7 F, 4 M) taking the same Biochemistry lab completed the same questions as in the pretest and posttest (combined as a single assessment) without participating in the VR activity. Although the class size here is much smaller, comparing the results of the group who had experienced the VR activity with a group who had not experienced this may provide additional information regarding whether the VR activity resulted in increased content knowledge, as we suggest the pretest and posttest results showed for the MBP section.

Participants in this group were between 19 and 23 years old (mean = 20.36, SD = 1.03 years). Approximately 54.5% of participants were Asian/South Asian, 27.3% were White, and 9.1% each were Hispanic/Latinx or another race/ethnicity. As before, all students were pursuing majors in the Biological and Chemical Sciences or Health Sciences and gave their consent to participate.

We report the results for the MBP section here, as the pretest−posttest analysis suggests an increase in content knowledge only for this section, although results for the other sections are available in SI 5. Specifically, we should expect that for the "pretest" questions, the group who had experienced the VR activity should perform comparably to the group who had not experienced this. However, we should expect that for the "posttest" questions in the MBP section, the group who had experienced the VR activity will have a higher score on this section. The Mann−Whitney U test was used due to the small sample size and the presence of a non-normal distribution. Comparison of MBP "pretest" questions for students who participated in VR and those who did not participate in VR revealed no significant differences between the groups ($z = -0.44$, $p = 0.659$). For MBP "posttest" questions, students who participated in VR scored higher than those who did not participate in VR, although this difference did not reach statistical significance ($z = -1.63$, $p = 0.052$). While this result was nonsignificant, contrary to the result of the pretest−posttest analysis, it is of note that the effect here was marginal and in the predicted direction. In light of the significant pretest−postest analysis and the extremely small sample size in the comparison group of the Mann−Whitney U test reported here, we find these results strongly encouraging and suggestive that the VR activity may have increased students' content knowledge for the MBP content.

Survey Analysis

Overall, students responded positively to the VR activity (Figure 4). The large majority of students rated the statement "I thought the VR activity was fun" as "strongly agree" (approximately 54%) or "somewhat agree" (approximately 29%) (Figure 4A). This is consistent with reports of students' experience from prior work.[14,20,23] Of note is that in Makransky et al.,[20] the research team found that students learned less in immersive VR compared to a simulation on a desktop computer. They argue that the enjoyment and fun of the activity may have been distracting or overwhelming to students, adversely affecting learning outcomes. This argument seems to contrast with our findings, as while students did find the activity to be fun, our pretest−posttest analysis suggests an increase in content knowledge by students, at least for some of the content. As each room of the museum was built similarly, it is unlikely that some rooms were more fun than others. Therefore, in the present study it seems more likely that the degree of interactivity and aspects of the assessment discussed above—and not students' enjoyment—account for whether students' content knowledge increased for different areas of content.

Students also reported feeling motivated to explore the VR activity (Figure 4C), with most students rating this item as "somewhat agree" (approximately 41%) or "strongly agree" (approximately 37%). This is consistent with prior work on VR use in educational settings.[14−17] In the present study, students were particularly excited to manipulate 3D structures in the environment and work collaboratively. Students also spent longer than we expected in the VR environment, likely due to their enjoyment of the activity and ability to interact with classmates.

Overall, students took a more neutral position with regard to whether they would prefer using the VR system in class or lab as compared to current teaching methods (Figure 4B). For this question, approximately equal numbers of students chose "neither agree nor disagree" and "somewhat agree" (approximately 33% and 32%, respectively). These ratings seem to reflect students' weighting of different priorities. One student commented in the survey that the VR activity "was fun but I think it would be difficult to use it for long periods of time". Similarly, one of the authors overheard students discussing the comparison of regular lab activities to the VR activity and commenting that they would not want to use VR all of the time, for instance as a full replacement of other lab activities. While prior work showed that students rated VR higher than traditional methods with regard to usefulness and motivation,[15] it should be noted that this was compared to methods such as reading and watching videos rather than the types of activities that would normally be a part of lab learning.

Finally, many students reported feeling like they learned something or understood something better because of the activity (Figure 4D), with students rating this item most often as "somewhat agree" (approximately 41% of responses). As the results suggest an increase in content knowledge for some of the content on the pretest−posttest assessment, this result shows that many students were aware of this improvement. This may also have contributed to the apparent increase in confidence students showed on the posttest for the questions with "I can't tell" answer choices, compared to the pretest. In the literature, there is some nuance regarding students' perception of their own learning using immersive VR, although this may be related to methodology. While one study found that medical students perceived increased learning with

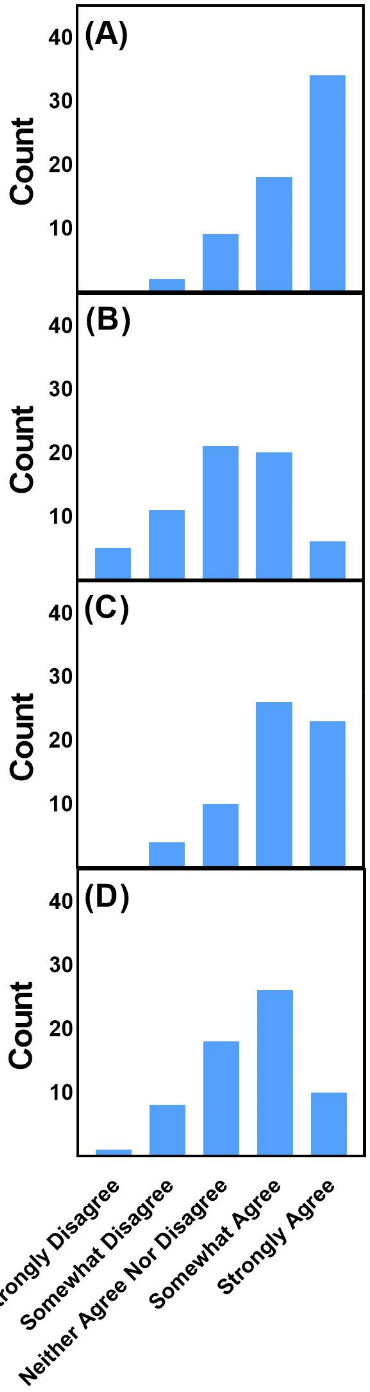


Figure 4. Students were asked to rate their agreement with the following statements after completing the VR activity: (A) I thought the VR activity was fun; (B) I would prefer using the VR system in class/lab (compared to your current teaching methods); (C) I felt motivated to explore the VR activity; and (D) I feel like I learned or understood something better because of the activity.

immersive VR (compared to text or video[15]), studies of elementary and college students found that students did not feel they learned more in immersive VR (compared to desktop VR[14,23]). However, qualitative analysis in Han[23] revealed two main themes that contributed to this: feelings of isolation in immersive VR, which were avoided in the present study by students' ability to collaborate in the VR environment, and the need for more guidance through complex material, echoing our comments above.

■ LIMITATIONS

While the present study suggests that students showed an increase in knowledge for the MBP content as well as that they enjoyed engaging in this activity, there are also limitations to the present study. Because of the short time frame between the pretest and posttest, we chose to use different images in the questions to prevent students from answering from memory. However, this complicated our ability to show clearer evidence supporting improvement in content knowledge in the pretest−posttest design. While the comparison of these data to those for a similar group who had not completed the VR activity are encouraging, the comparison group was underpowered and this analysis was marginal, not reaching statistical significance. Future research should assess this type of activity using a larger sample, preferably comparing students within the same class/semester, to better assess the effectiveness of VR content for increasing content knowledge (including best practices for content creation and assessment). In addition to the kinds of quantitative analyses completed here, qualitative analyses including think-aloud procedures can be used to gain further insight into students' thought processes and reactions. Further, while this activity was designed to be accessed via desktop or VR headset both in and out of the classroom, we tested this using headsets in a classroom setting. Future research should assess whether desktop presentation—as well as alternate settings like remote/hybrid use—is also effective.

■ CONCLUSIONS

In sum, students enjoyed this interactive, immersive VR activity, and results suggest increased understanding for students for some content based on their experience. To enhance student understanding and assessment, improvements can be made to the wording of questions and in the design of the VR content to ensure that student attention is drawn to the key features being presented. Importantly, instructors should not expect students to learn from passively viewing structures without prompts such as labeled points of interest, videos, text, and interactive models that can be directly manipulated.

While the present study reports results of this activity implemented in-person and as a self-paced, collaborative experience using head-mounted VR displays, the use of a web-based system would enable this kind of activity to be used differently, such as in remote or asynchronous settings, using a desktop or laptop computer, or with students working individually. The COVID-19 pandemic revealed the need for flexible learning tools to accommodate remote instruction, and activities such as this may continue to allow for students to better engage in course content both in and out of the classroom.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c01015.

Pretest, posttest, survey instrument, cell phone presentation, and comparison to students without the VR experience (PDF, DOCX)

■ AUTHOR INFORMATION

Corresponding Authors

Nicole Calma-Roddin − *Department of Behavioral Sciences, New York Institute of Technology, Old Westbury, New York 11568-8000, United States*; Email: ncalmaro@nyit.edu

Jacqueline Keighron − *Department of Biological and Chemical Sciences, New York Institute of Technology, Old Westbury, New York 11568-8000, United States*; orcid.org/0000-0003-4539-4122; Email: jkeighro@nyit.edu

Author

Kevin Park − *Department of Digital Art and Design, New York Institute of Technology, Old Westbury, New York 11568-8000, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.2c01015

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by New York Institute of Technology through a Teaching and Learning with Technology Grant. We thank Dr. Navin Pokala for his contributions to the experimental protocol, including the expression and purification of the MBP-GFP biosensor; Dr. Daniel Quigley for his support of the work; Lavin Amarnani, Kyle Diaz, Mohammed Irfan Shaik, Vaibhavi Deo, and Joey Vasikauskas for their work programing and testing the VR museum and their assistance facilitating student use of the VR headsets; Stephanie Alvarado, Meghan Dallas, Shifeng Li, and Shelby Tesoriero for assistance in literature search and contributing to an early version of the student engagement survey; and Anthony Ginez for contributing to an early version of the student engagement survey.

■ REFERENCES

(1) Reißer, S.; Prock, S.; Heinzmann, H.; Ulrich, A. S. Protein ORIGAMI: A Program for the Creation of 3D Paper Models of Folded Peptides. *Biochem. Mol. Biol. Educ.* **2018**, *46* (4), 403−409.

(2) Herman, T.; Morris, J.; Colton, S.; Batiza, A.; Patrick, M.; Franzen, M.; Goodsell, D. S. Tactile Teaching. *Biochem. Mol. Biol. Educ.* **2006**, *34* (4), 247−254.

(3) Chakraborty, P.; Zuckermann, R. N. Coarse-Grained, Foldable, Physical Model of the Polypeptide Chain. *Proc. Natl. Acad. Sci. U. S. A.* **2013**, *110* (33), 13368−13373.

(4) Gilbert, J. K. Models and Modelling: Routes to More Authentic Science Education. *Int. J. Sci. Math. Educ.* **2004**, *2* (2), 115−130.

(5) Pinger, C. W.; Geiger, M. K.; Spence, D. M. Applications of 3D-Printing for Improving Chemistry Education. *J. Chem. Educ.* **2020**, *97* (1), 112−117.

(6) Howell, M. E.; Booth, C. S.; Sikich, S. M.; Helikar, T.; Roston, R. L.; Couch, B. A.; van Dijk, K. Student Understanding of DNA Structure-Function Relationships Improves from Using 3D Learning

Modules with Dynamic 3D Printed Models. *Biochem. Mol. Biol. Educ.* **2019**, *47* (3), 303−317.

(7) Theisen, K. E. Two Active Learning Models of Protein Dynamics for Use in Undergraduate Biochemistry Courses. *J. Chem. Educ.* **2022**, *99*, 2245.

(8) Bhagat, K. K.; Liou, W. K.; Chang, C. Y. A Cost-Effective Interactive 3D Virtual Reality System Applied to Military Live Firing Training. *Virtual Reality* **2016**, *20* (2), 127−140.

(9) Portelli, M.; Bianco, S. F.; Bezzina, T.; Abela, J. E. Virtual Reality Training Compared with Apprenticeship Training in Laparoscopic Surgery: A Meta-Analysis. *Ann. R. Coll. Surg. Engl.* **2020**, *102* (9), 672−684.

(10) Pastel, S.; Petri, K.; Chen, C. H.; Wiegand Cáceres, A. M.; Stirnatis, M.; Nübel, C.; Schlotter, L.; Witte, K. Training in Virtual Reality Enables Learning of a Complex Sports Movement. *Virtual Reality* **2023**, *27* (2), 523−540.

(11) Misak, J. A (Virtual) Bridge Not Too Far: Teaching Narrative Sense of Place with Virtual Reality. *Comput. Compos.* **2018**, *50*, 39−52.

(12) Tsivitanidou, O. E.; Georgiou, Y.; Ioannou, A. A Learning Experience in Inquiry-Based Physics with Immersive Virtual Reality: Student Perceptions and an Interaction Effect Between Conceptual Gains and Attitudinal Profiles. *J. Sci. Educ. Technol.* **2021**, *30* (6), 841−861.

(13) Häfner, P.; Häfner, V.; Ovtcharova, J. Teaching Methodology for Virtual Reality Practical Course in Engineering Education. *Procedia Comput. Sci.* **2013**, *25*, 251−260.

(14) Makransky, G.; Lilleholt, L. A Structural Equation Modeling Investigation of the Emotional Value of Immersive Virtual Reality in Education. *Educ. Technol. Res. Dev.* **2018**, *66* (5), 1141−1164.

(15) Sattar, M. U.; Palaniappan, S.; Lokman, A.; Shah, N.; Khalid, U.; Hasan, R. Motivating Medical Students Using Virtual Reality Based Education. *Int. J. Emerg. Technol. Learn.* **2020**, *15* (2), 160−174.

(16) Stepan, K.; Zeiger, J.; Hanchuk, S.; Del Signore, A.; Shrivastava, R.; Govindaraj, S.; Iloreta, A. Immersive Virtual Reality as a Teaching Tool for Neuroanatomy. *Int. Forum Allergy Rhinol.* **2017**, *7* (10), 1006−1013.

(17) Makransky, G.; Borre-Gude, S.; Mayer, R. E. Motivational and Cognitive Benefits of Training in Immersive Virtual Reality Based on Multiple Assessments. *J. Comput. Assist. Learn.* **2019**, *35* (6), 691−707.

(18) Jambi, E.; Gardner, M.; Callaghan, V. A Generalized Pedagogical Framework for Creating Mixed-Mode Role-Play in Multi-User Virtual Environments. *Commun. Comput. Inf. Sci.* **2019**, *1044* (c), 158−171.

(19) Wu, B.; Yu, X.; Gu, X. Effectiveness of Immersive Virtual Reality Using Head-Mounted Displays on Learning Performance: A Meta-Analysis. *Br. J. Educ. Technol.* **2020**, *51* (6), 1991−2005.

(20) Makransky, G.; Terkildsen, T. S.; Mayer, R. E. Adding Immersive Virtual Reality to a Science Lab Simulation Causes More Presence but Less Learning. *Learn. Instr.* **2019**, *60*, 225−236.

(21) Youssef, M. Assessing the Use of *Kahoot!* In an Undergraduate General Chemistry Classroom. *J. Chem. Educ.* **2022**, *99* (2), 1118−1124.

(22) Jang, S.; Vitale, J. M.; Jyung, R. W.; Black, J. B. Direct Manipulation Is Better than Passive Viewing for Learning Anatomy in a Three-Dimensional Virtual Reality Environment. *Comput. Educ.* **2017**, *106*, 150−165.

(23) Han, I. Immersive Virtual Field Trips in Education: A Mixed-Methods Study on Elementary Students' Presence and Perceived Learning. *Br. J. Educ. Technol.* **2020**, *51* (2), 420−435.