Using a Library Immersive Classroom to Support Visual Literacy and Collaboration in Undergraduate STEM Students

Jenny Coffman, North Carolina State University at Raleigh

I am a Research Librarian for Engineering at North Carolina State University and liaison to Computer Science, Electrical and Computer Engineering, and Chemical and Biomolecular Engineering departments. Before obtaining my MI at Rutgers I was also a Chemistry PhD candidate at Emory and received a B.S. in Forensic Science at Penn State. My current research interests include knowledge management, AI, data management, and visual/spatial literacy.

Lejla Š Biberić, North Carolina State University at Raleigh

I received my B.S. in Biochemistry from the University of Oregon, followed by an M.S. in Applied Mathematics and an M.S. in Physical Chemistry from the University of Washington. I am currently a Ph.D. candidate in Chemical Engineering at NC State University. My research interests focus on leveraging computational approaches to study and advance biomimetic materials.

Courtney Hewett, North Carolina State University at Raleigh

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Introduction

Visual and spatial literacy is a crucial and often underdeveloped element of engineering and science education. These skills are essential for students to effectively interpret and understand complex data, concepts, and systems prevalent in fields such as biology, engineering, and computer science. Visual literacy enables students to visualize, comprehend, and communicate data and information presented in visual form, while spatial literacy allows them to understand and manipulate the spatial relationships between objects. These are vital skills for problem-solving and innovation in STEM disciplines. As libraries expand and explore the boundaries of their services and programming, data and visualization has become a popular area of support [1]. Typical offerings include data management and statistical/data science services but there is also room to engage in support around visual-spatial literacy. Even with advances in virtual reality (VR)/augmented reality/extended reality and graphics to support visual-spatial literacy, significant gaps still exist [2], [3]. Library spaces and expertise offer strong opportunities for collaboration with faculty in this area.

Developing the visual-spatial literacy required to navigate complex, multidimensional representations of abstract concepts such as molecular, chemical, and mechanical systems that cannot be viewed in real life is a persistent challenge [4]. This challenge is further amplified by traditional classroom setups that are ill-equipped to fully display visualizations and facilitate collective problem-solving. Instruction has historically relied on lecture-based and static two-dimensional representations, supplemented by laboratory experiences. While these approaches can be effective, they do not address the wide variation in students' visual-spatial abilities. Research has shown that deficits in spatial thinking can negatively impact retention, performance and confidence in STEM courses [5]. These challenges become especially important in collaborative learning environments, where students must not only interpret complex visual information individually but also communicate and troubleshoot their reasoning with peers. As a result, instructional approaches that support both individual and collaborative spatial reasoning are increasingly needed. Visual and spatial literacy continues to be a significant challenge in undergraduate engineering education and requires innovative research approaches to effectively develop and improve these skills.

This paper addresses these challenges by examining how NC State University Libraries' immersive classroom technology supports spatial-visual literacy through enhanced collaboration, troubleshooting and perceived learning. Specifically, we describe the design and implementation of an immersive learning experience in an undergraduate biotechnology course using virtual screening for drug discovery. With specialized molecular visualization software, laptops and the Teaching and Visualization (T&V) Lab, a shared immersive environment was created. Figure 1 displays the T&V Lab. The space allowed up to 8 students to project their work on an 85-foot, 217-degree smooth screen. This setup supports collective visualization of molecular docking and drug design processes that are traditionally difficult to visualize with theory and single screens alone. The successful implementation of this class in T&V Lab highlights the need for further research on this immersive classroom's impact on spatial visual literacy, collaboration and troubleshooting.

Figure 1: Teaching and Visualization Lab at the Hunt Library at NC State University. Up to 8 projections of independent content can be displayed simultaneously.

Literature Review

Previous research has demonstrated that immersive visualization tools are especially beneficial for students with weaker spatial skills. Merchant et al. [6] showed that spatial reasoning of molecular chemistry improved in students taught in 3D VR environments as compared to traditional 2D representations. This finding aligns with broader evidence that spatial thinking is a foundational skill in STEM and associated with improved retention and performance across

STEM disciplines [5]. Immersive technologies like large domes and VR can complement traditional instruction and improve student outcomes [7], [8]. These media succeed at integrating the abstract concepts and visuals of the curriculum into accessible modes for students. In chemistry education specifically, immersive instruction has been shown to support student learning by explicitly connecting macro-, micro- and symbolic levels of representation [9]. By strengthening these connections, immersive environments provide deeper conceptual understanding as opposed to rote memorization. Similar benefits have been observed across STEM courses where VR and other immersive classrooms consistently enhance students' ability to visualize complex structures and processes that are difficult to grasp with static images alone [10], [11].These findings suggest that immersive visualization not only improves comprehension but also promotes deeper conceptual coherence.

Perceived Learning and Collaboration

Evaluating immersive visualization tools requires attention to how students perceive their own learning within these environments. In parallel with these cognitive challenges, students' perceptions of their learning environment play a critical role in engagement, motivation and persistence. As education institutions increasingly adopt new technologies, understanding how students perceive their own learning has become an important factor. Technologically enhanced learning environments have been shown to improve student learning outcomes compared to traditional classrooms [12], motivating further exploration of immersive and interactive instructional modalities. Perception of learning influences motivation, engagement, and satisfaction. It has become a widely used measure in studies of educational innovation [13]. In laboratory and technology-rich environments, students often form expectations early in the semester that strongly shape their engagement and attitudes [14]. Research indicates that technologically enhanced learning environments can positively influence these perceptions, contributing to improved learning outcomes [12].

Collaboration is closely linked to both perception of learning and peer learning. Collaborative learning environments that promote peer-to-peer interaction have been shown to improve engagement and understanding across STEM disciplines [15]. Some of the benefits of peer learning and collaboration is the development of troubleshooting skills. Teaching effective troubleshooting techniques to STEM students is an active area of research [16], [17]. A case study on engineering students' troubleshooting skills noted how the immersive learning environment and approach enabled students to employ multiple diagnostic studies at the same time through teamwork [18]. Immersive environments create shared visualization and collective problem-solving which makes them particularly well suited to support collaborative learning.

Immersive Environments

VR for learning is a well-researched form of an immersive educational environment. VR learning environments have been widely studied as tools for enhancing visualization, engagement and conceptual understanding in STEM education. Studies consistently report positive cognitive and motivational outcomes associated with VR-based instruction [19], with a recent systematic review confirming overall positive effects of VR in STEM education [11]. Its practicality makes it particularly interesting. Qin et al. [13] reported the successful implementation of a VR-based biochemistry laboratory in a 200-student course, providing a low-cost and safe alternative to traditional labs, while maintaining high student satisfaction and perceived learning. Other studies reported students in VR-based learning environments outperformed desktop-based peers on recognition and retention tasks [20]. The success of immersive environments as demonstrated through VR methods, encourages the exploration of other mechanisms of immersive learning.

Beyond VR, large-scale immersive environments such as giant screens and digital domes offer additional benefits, particularly for collaborative learning. Giant screens display at least five meters in length and dome environments create shared immersive experiences which can enhance recall and engagement [7]. Johnson-Glenberg et. al. [21] found that exposure to giant screens and dome formats increased students' interest in science and for some, their desire to pursue scientific careers. Museum attendees reported high levels of immersion, interest and perceived helpfulness when engaging with dome projections [22]. These findings suggest that immersive classrooms can influence not only learning and collaboration, but attitudes toward STEM.

Building on this body of work, this paper describes how an investigation into immersive classroom environments can support spatial and visual literacy. Collaboration, troubleshooting and perceived learning are of particular interest. The T&V Lab learning environment enables shared visualization as demonstrated through a lab focused on molecular docking and virtual screening for drug design. This approach allows students to collaboratively diagnose errors, compare models and refine their understanding of drug discovery workflows.

Background

Project Overview:

NC State University Libraries has developed a comprehensive effort across many departments to make experiential learning a core component of our offerings. Previous to this project, within the Libraries' department Collections and Research Engagement (CoRE), liaison subject librarians had begun an initiative through discussions with the NC State College of Engineering to expand and improve library programming and support of visual and spatial literacy. Thus, a project was devised to bring these efforts together and integrate them into a project centering our high-tech space T&V Lab that exists in the Library.

Our Collaborative Visualization Project aims to elevate students' engagement and learning experiences through the use of visualization software and experiential learning in our T&V Lab. By incorporating visualization software already being utilized in undergraduate STEM curriculums at NC State University into our high-tech spaces, we created immersive learning experiences that help students grasp the visualization of complex protein systems from their course more effectively. Visualization software, such as PyMOL [23], plays a pivotal role in this context. PyMOL is instrumental in molecular visualization, enabling students to explore, manipulate, and analyze 3D structures of proteins, thus deepening their understanding of molecular biology and biochemistry and preparing them for applications in protein engineering research. Leveraging the expertise around this visualization software was critical to the success of this project.

Additionally, our high-tech spaces, particularly T&V Lab, have been seeking increased engagement from NC State College of Engineering, so utilizing this space was advantageous. By leveraging its multi-source mode (simultaneous display of up to 8 devices) the space can serve as powerful tools to help students process, understand, and learn about complex systems in STEM. We sought out faculty to partner with us to adapt their course-based activities (using PyMOL and other analysis/visual software) to T&V Lab.

Project Goals:

1. Development of Protein Visualization Demos:
    - Created and designed advanced software demos for protein system visualizations in T&V Lab.
    - Developed use cases to showcase to faculty the diverse options and capabilities available.
2. Instruction in Protein Visualization with PyMOL:

    - Developed and taught a workshop titled "Protein Visualization with PyMOL," utilizing the unique immersive features of T&V Lab.
3. Adaptation of Instructional Visualization Activities:
    - Collaborated with faculty to adapt existing instructional visualization activities to the T&V Lab space.
    - Implemented these activities into course-based instruction to enhance learning outcomes.
4. Support for Visualization Experiential Learning:
    - Contributed to the development of the CoRE departments' strategies and support systems for visualization experiential learning activities in T&V Lab
    - Built a framework for sustained engagement and support in visual and spatial literacy initiatives.

This paper focuses on our collaboration with faculty to adapt existing instructional visualization/computational activities to the T&V Lab space. The first step towards this goal was to select a class to pilot this project with. The pilot class we chose to do that with was "Cancer Drug Discovery and Development" which already had a component to the class of learning PyMOL. In this class, 11 multi-disciplinary engineering and science students complete a molecular docking activity using several software tools to explore how drug-like molecules interact with a protein linked to human tumors. The activity focuses on binding these molecules (called ligands) to the protein and estimating how strongly they interact. PyMOL visualization software is used to examine how different ligands fit into the protein's structure or binding "pocket". By comparing binding strengths, students explore how molecular shape and chemical properties influence the intermolecular forces that drive binding. Figure 2 demonstrates students visualizing different ligands bound to the protein in the T&V Lab. The activity introduces computational molecular docking and reinforces core ideas about intermolecular interactions in biological systems. For documentation and a complete explanation of the docking activity please reference their paper "Design and Implementation of an Accessible and Open-Sourced *In Silico* Drug Screening Activity for Cancer Drug Discovery" [24]. The project brought together several critical milestones and moving parts that all needed to align on the day of the event to create a meaningful experiential learning opportunity for students. These included setting up the necessary technology infrastructure, hiring and supporting a graduate assistant instructor, recruiting faculty participants, adapting activities, and ultimately executing those activities successfully.

Figure 2. Multiple students simultaneously visualizing ligand-protein interactions in PyMOL within the T&V Lab space.

Technology Infrastructure Set Up

Planning, managing and organizing the technology necessary for this project was a critical and time intensive aspect of the project. The two key pieces of technological infrastructure we used was theT&V Lab with its immersive screen and classroom set up and laptops with the software needed for the activity pre-installed. The testing, tweaking, and coordinating with T&V Lab was easier and more straightforward and the process of using the space is highlighted in the high-tech spaces section. However, the laptops were a new addition to the space. We worked with Library IT to acquire, set up and install the necessary software on the laptops. The software required for the activity was AutoDock Vina [25], AutoDockTools [26], Strawberry Perl [27], and PyMOL [23], all of which are free, open-source software, though we used a multi-seat license for PyMOL that the library already supported. Each of these steps involved technical challenges and collaborating with library IT to ensure everything was set up to work seamlessly between the lab, laptops, and software.

Graduate Assistant Instructor Hiring

The librarian knew that this project would require more subject matter expertise and work than could be provided by the librarian and identified and applied for a funding source to hire a graduate student. The librarian was awarded funding through the Libraries Pentair Fellowship to hire a chemical engineering PhD candidate to support the project for about 10 hours per week. After the first year further funding for the graduate assistant instructor was provided through the librarian’s home department. The purpose of the graduate assistant instructor was to help act as an extra liaison between the librarian, other library collaborators, and the course instructors to improve understanding of needs and tasks on both sides and to help with completing tasks that required more advanced knowledge of PyMOL and molecular docking than the library team possessed. This meant that there was less burden on the faculty collaborator and made participating in the project more appealing. An example of a task the graduate student completed that demonstrates how essential they were to this project was running through the activity numerous times after different adjustments were made to the technology set up to make sure everything was set up and working properly, because the student's activity was beyond the skills of the librarian.

Faculty Recruitment:
For the initial pilot it was important to keep the scope and workload reasonable so we identified one course to pilot. Criteria we were looking for was small class size, software use that had a highly visual element to it, and instructors invested in pedagogy.

While we had interest in being able to support the visual literacy of many different concepts and disciplines, the Librarian had past experience using the software PyMol and knew it was used on campus because the Libraries had acquired a license for it. We knew of disciplines using it but did not know about exact courses, so we did a search in Web of Science using the keyword "PyMOL" and then filtered the results to just our institution to be able to find literature on courses at our institution using PyMOL. We found a publication detailing a course that was a great candidate: small class size, highly visual activities, and run by a faculty instructor and guest instructor who liked to experiment and innovate in their classroom and had research experience in using immersive technologies. We sent an outreach email, gave them a tour of the space while we pitched the project. Once they indicated they were interested we onboarded them to the project. There were minimal adaptations necessary as they already had a molecular docking activity that fit what we were trying to facilitate.

It was initially appealing to the faculty for several reasons. They thought using the space would engage students by creating a more motivating immersive experience to do the lab in. The larger screen real estate was also appealing because they struggled in their existing lab environment with a small lecture screen and laptops for the students.

Activity Adaptation
After the faculty agreed to adapt their existing activity to the T&V Lab immersive environment we had multiple consultations to get them acquainted with the space and work on the technical aspects of conducting the activity in an engaging and immersive way. One consideration was pacing how we switched between different screen modes. We needed to accommodate periods of lecture mode for the instructor which involved displaying multiple windows from one laptop to the immersive screen simultaneously. However there were also periods of the course in activity mode when the students were actively working and collaborating which involved displaying from multiple student laptop sources to the main immersive screen. Additionally, we assisted the instructors with planning the flow of activities and check-ins where instructors review progress in the activity, ask guiding questions, and facilitate group communication using the visual real

estate of the screen. Alongside the technical aspects, we considered the type of furniture and placement of technology that would be necessary for an effective computational lab class. Up to four students were placed at a table. Each table group (we had 4 groups) could connect to two projectors through use of an HDMI cord. These cords allowed anyone at the table to connect to the screen and project a laptop screen. The tables and chairs used in the activity had wheels to accommodate movement as students would rotate to view or present different parts of the work.

Interdisciplinary Collaborators

Librarian

Though the librarian identified the opportunity to start this project, planned out the initial stages, and applied for funding for the graduate student instructor, the project was encouraged by library management and fits in with broader departmental and library-wide initiatives. There were several advantages to this being a librarian initiated project. The librarian understood the link between department cultures on campus, pathways to identifying collaborators, the connections between library wide strategic goals, and the connections with departmental initiatives. The positioning of the librarian as liaison allowed them to identify the needs, resources, and people to be able to execute this project. The librarian also acted as the project manager coordinating between everyone involved in the project across library units and faculty, which they often do in other capacities as a liaison librarian. Sometimes they were a technology fixer, a hiring manager, scheduler, mentor, or collaborator. The librarian managed and worked extensively with the graduate assistant instructor to carry out the goals of the project.

Graduate Assistant Instructor

The graduate assistant instructor served as a critical pedagogical and technological bridge within the immersive learning environment. In addition to assisting during the classroom setup, this role required liaising between course instructors and library staff. The graduate assistant instructor focused on understanding the learning objectives and how they could be supported with the technology in the T&V Lab. Working closely with library staff, these objectives were communicated to design an optimal technologically aided learning experience. Each decision, from format of screens to use of hardware was intentionally chosen for each learning goal. The design of the space and technology was communicated and demonstrated to course instructors along with how these setups could promote the learning objectives.

Course Instructors

The course instructors had pre-designed the lecture and lab activity but worked with us to adapt it to the space. They led those conversations and the learning objectives of the activity were their vision. The space and our actions were there to support them, we did not dictate or drive the direction of how they used the technology or the space.

High-tech Spaces Consultants

The high-tech spaces consultants carried out the high tech spaces support modeling detailed in the next section.

High-tech space support model

The success of the NC State University Libraries' high-tech spaces (and the campus community members working in those spaces) is dependent upon a small team of Libraries staff. The high-tech spaces (HTS) team includes 3 librarians, a University Library Specialist, and a Graduate Assistant (different from graduate assistant instructor), each of whom is a member of the Collections and Research Engagement department (CoRE). The HTS team also works closely with multiple Libraries Departments to keep the spaces maintained and able to support a full schedule of presentations, events, and workshops each semester, including Information Technology (IT), Operations, Logistics, & Services (OLE), and Learning Spaces & Services (LSS).

General work-flow for reserving the spaces

Any NC State University affiliate with plans to utilize the immersive technology in the spaces is able to request a reservation for their presentation, dissertation, class, or workshop. The HTS team receives the request as soon as it is submitted and makes the reservation based on fit, availability of the space, staff, and the specifics of the request. This often includes additional negotiation and coordination with the requestor. A member of the HTS team is assigned to be the lead for each new reservation or project. When appropriate, subject specialists with specific interests in, or connections to, the particular campus unit or subject area are also brought into the collaboration.

The assigned consultant is responsible for setting up the initial in-person meeting with the requestor in the space. During this consultation, they discuss content creation, day-of logistics, and technology needs. The consultant will also use this time to share user design templates for the spaces and schedule times to work on and test content. This is the most crucial step in our workflow. It is vital that the presenter spend time editing their work in the space itself. Content created for the HTS is not accurately represented on standard computer screens, so testing content ahead of time is the best way to ensure smooth day-of presentations and avoid unwanted surprises on screen.

BIT 455/555 Support

The consultation process described above also applies to lab sessions hosted in the high-tech spaces. When planning the Libraries' PyMOL lab sessions, the HTS team worked closely with IT and members of CoRE to ensure the lab session materials displayed properly in the lab and met faculty expectations. The most critical piece of this puzzle was dedicating 11 laptops pre-loaded with the PyMOL software and educational licenses. These laptops were able to be logged into by anyone with a NC State Unity ID, and each had full-sized HDMI outputs compatible with the T&V Lab's floorbox inputs.

Day-of Support in the High-Tech Space

A member of the HTS team is present for each high-tech spaces reservation. Typically, they will stay in the space for the duration of the reservation to troubleshoot the myriad issues that come with using 8 projectors and a complex AV system. Because users also find it challenging to use the 85 foot wide screen, the consultant handles navigating the PC and pulling up content to ensure a smooth experience for presenters and attendees.

Having staff on site to address any technology issues as they arise keeps the classes, presentations, workshops, or events running smoothly and creates the best experience for users. Often campus community members have not been to the NC State Hunt Library before, in which case the consultant also serves as a point person to help attendees and presenters have a seamless experience. This may include assistance with arranging the proper accessibility accommodations, navigational help, providing access to adapters or equipment, and anything else that might arise. Users have also reported positive experiences with having a consultant there on the day-of to provide a calm and capable presence during what is often a high-stakes presentation or workshop in an intimidating and unfamiliar space.

In the case of the PyMOL lab sessions, the consultants serve in all of these roles in addition to providing extra technical support to the students who are unfamiliar with how to properly use and display the software. The laptops dedicated to PyMOL lab sessions are housed and maintained in the libraries by IT and CoRE faculty/staff.

Results

This project aimed to enhance the student learning experience by moving beyond the limitations of a traditional computer lab environment. In previous semesters before doing the lab in this space the students would complete the lab on laptops and instructors would have a small lecture screen to teach off of. The immersive classroom breaks the norms of a traditional computer lab students are accustomed to and brings them into an entirely new space. Students mentioned that they appreciated the atmosphere of the T&V Lab which added to the novelty and engagement levels of the students. The instructors mentioned that the students were able to complete the lab session much faster and noticed their focus was much better in this space. This is consistent with previously reported results comparing different immersive and collaborative learning environments [5], [6], [7], [8].This is likely due not just to being more engaged, having improved learning, and being able to visualization real time in the session but also that the set up of the classroom and the projection of their screens. It likely also kept them focused, helping them not get distracted with other tasks or windows on the laptop. Other VR environments have also demonstrated improved concentration on tasks based on lack of external distractions [28]. Students said that the lecture was easier to follow as the adaptations made for the big screen allowed the instructor to display the software, lecture info, and lab documents simultaneously without sacrificing the window size, text size or size of the visuals. Both PyMOL visualization and desktop file organization are presented in tandem in figure 3. Overall the oversized and curved nature of the screen adds a lot of flexibility and real estate to display content which supports a more engaged seamless lecture and helps the instructor draw upon information and demonstrate visual concepts in tandem (figure 4). These results were corroborated by [29] which showed the benefits of more screen space.

Figure 3. A student and teaching assistant interaction with screens displaying the docking interaction on one screen and a different screen showing which files are needed for the docking activity.

A central objective of this project was to foster meaningful collaboration among students during the lab sessions. Past iterations where students were working from laptops meant that students did not collaborate during the lab sessions. In the T&V Lab session, students were able to compare results, share in the experience of the lab, and have a sense of their progress as compared to other students. Having their screens displayed realtime up on the big screen as they worked allowed for better discussions and made being able to compare the protein interactions with the small molecule variants much easier between students (figure 4). Break points were specifically inserted in the course of their docking activity for formal student interactions. Here, students talked through their results and which ligands were the best drug candidates for the protein of interest. Students and instructors alike agreed that they were able to interact and benefit from the collaboration the space facilitated.

Figure 4. Curved display of the Teaching and Visualization Lab allows multiple projections and facilitates positive student-instructor interactions.

An additional and particularly impactful outcome of using the T&V Lab was the improvement in troubleshooting and instructional support. Many times issues or questions came up that the students needed help from the instructor or peers. This environment facilitated the ability for students and instructors to troubleshoot issues and seemed like the strongest benefit that the instructors emphasized to us (figures 3 and 4 show student-instructor interactions). Troubleshooting from a student's small laptop screen is difficult and limits the viewership. Projecting the laptop screen increases visibility to other students and decreases the need for instructors to repeat troubleshooting steps. Additionally, instructors were able to follow along with the progress of the students naturally. Instructors noted they were able to proactively see when students were running into issues and could address the issues on the shared screen with the class quickly. Collective troubleshooting became much easier and we observed peer-to-peer troubleshooting naturally occurring. Having their work visible by everyone also seemed to break down the anxiety barrier of asking questions.

Conclusion

Overall, this project has been a successful exploration of using an immersive classroom space in Hunt Library to support students' visual and spatial learning. Improving their concentration and execution of their lab and supporting collaboration and troubleshooting through a computational activity is a unique offering that not many library spaces are able to provide. Student and instructor feedback has been overwhelmingly positive and reinforces the need to continue this project. We have repeated this activity in the space once more.

This was an exploratory and experimental project. Support and flexibility was provided to us by library leadership to test ideas in a low stakes way. The nature of the project did not impose rigid expectations and allowed flexibility to observe the effects of T&V Lab on a lab class. We had many challenges with the technology and we received plenty of moral and tangible support as we sought solutions. High impact experiential learning is an important strategic priority at the Libraries and library leadership was extremely supportive.

In the future we plan to continue doing this lab session in T&V Lab. We also have done outreach to other engineering courses and have been gathering interest in bringing more interactive and collaborative activities that promote visual learning into T&V Lab. The goal is to expand the variety and applications of the space to new science and engineering visual learning objectives.

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References

[1] M. S. Zakaria, “Data visualization as a research support service in academic libraries: An investigation of world-class universities,” *The Journal of Academic Librarianship*, vol. 47, no. 5, p. 102397, Sep. 2021, doi: 10.1016/j.acalib.2021.102397.

[2] A. Martín Erro, S. Nuere Menéndez-Pidal, R. Díaz-Obregón Cruzado, and A. Acitores Suz, “A framework for visual literacy competences in engineering education,” *Journal of Visual Literacy*, vol. 41, no. 2, pp. 132–152, Apr. 2022, doi: 10.1080/1051144X.2022.2053820.

[3] M. Gittinger and D. Wiesche, “Systematic review of spatial abilities and virtual reality: The role of interaction,” *Journal of Engineering Education*, vol. 113, no. 4, pp. 919–938, 2024, doi: 10.1002/jee.20568.

[4] T. Tseng and M. Yang, “The Role of Spatial-Visual Skills in a Project-Based Engineering Design Course,” presented at the 2011 ASEE Annual Conference & Exposition, Jun. 2011, p. 22.1501.1-22.1501.16. Accessed: Jan. 19, 2026. [Online]. Available: https://peer.asee.org/the-role-of-spatial-visual-skills-in-a-project-based-engineering-design-course

[5] D. H. Uttal *et al.*, “The malleability of spatial skills: A meta-analysis of training studies,” *Psychological Bulletin*, vol. 139, no. 2, pp. 352–402, 2013, doi: 10.1037/a0028446.

[6] Z. Merchant, E. T. Goetz, W. Keeney-Kennicutt, L. Cifuentes, O. Kwok, and T. J. Davis, “Exploring 3-D virtual reality technology for spatial ability and chemistry achievement,” *Journal of Computer Assisted Learning*, vol. 29, no. 6, pp. 579–590, Dec. 2013, doi: 10.1111/jcal.12018.

[7] J. Jacobson, “Digital dome versus desktop display:learning outcome assessments by domain experts,” *International Journal of Virtual and Personal Learning Environments*, vol. 4, no. 3, pp. 51–65, 2013, doi: 10.4018/jvple.2013070104.

[8] R. S. Muthyala and W. Wei, “Does space matter? Impact of classroom space on student learning in an organic-first Curriculum,” *Journal of Chemical Education*, vol. 90, no. 1, pp. 45–50, Jan. 2013, doi: 10.1021/ed3002122.

[9] R. van Dinther, L. de Putter, and B. Pepin, “Features of Immersive Virtual Reality to Support Meaningful Chemistry Education,” *Journal of Chemical Education*, vol. 100, no. 4, pp. 1537–1546, Apr. 2023, doi: 10.1021/acs.jchemed.2c01069.

[10] M. Roopaei and E. Klaas, “Immersive Technology in Integrating STEM Education,” presented at the 2021 11th IEEE Integrated STEM Education Conference, ISEC 2021, Institute of Electrical and Electronics Engineers Inc., 2021, pp. 159–164. doi: 10.1109/ISEC52395.2021.9764112.

[11] T. Tene, J. A. Marcatoma Tixi, M. de L. Palacios Robalino, M. J. Mendoza Salazar, C. Vacacela Gomez, and S. Bellucci, “Integrating immersive technologies with STEM education: a systematic review,” *Frontiers in Education*, vol. 9, 2024, doi: 10.3389/feduc.2024.1410163.

[12] D. C. Brooks, “Space matters: The impact of formal learning environments on student learning,” *British Journal of Educational Technology*, vol. 42, no. 5, pp. 719–726, Sep. 2011, doi: 10.1111/j.1467-8535.2010.01098.x.

[13] T. Qin, M. Cook, and M. Courtney, “Exploring Chemistry with Wireless, PC-Less Portable Virtual Reality Laboratories,” *Journal of Chemical Education*, vol. 98, no. 2, pp. 521–529, Feb. 2021, doi: 10.1021/acs.jchemed.0c00954.

[14] K. R. Galloway and S. L. Bretz, “Measuring Meaningful Learning in the Undergraduate Chemistry Laboratory: A National, Cross-Sectional Study,” *Journal of Chemical Education*, vol. 92, no. 12, pp. 2006–2018, Sep. 2015, doi: 10.1021/acs.jchemed.5b00538.

[15] N. Apkarian, C. Henderson, M. Stains, J. Raker, E. Johnson, and M. Dancy, “What really impacts the use of active learning in undergraduate STEM education? Results from a national survey of chemistry, mathematics, and physics instructors,” *PLoS ONE*, vol. 16, no. 2 February, Feb. 2021, doi: 10.1371/journal.pone.0247544.

[16] B. Diong, C. Chin, S. Das, A. Tekes, and W. Thain, “Enhancing Engineering Students’ Troubleshooting Skills,” in *2021 ASEE Virtual Annual Conference Content Access Proceedings*, Virtual Conference: ASEE Conferences, Jul. 2021, p. 37083. doi: 10.18260/1-2--37083.

[17] C.-A. Koh, “Promoting Systems Thinking and Active Problem Solving Skills,” in *Proceedings of the 6th International CDIO Conference*, École Polytechnique, Montréal, 2010. [Online]. Available: https://cdio.org/knowledge-library/documents/promoting-systems-thinking-and-problem-solving-skills-through-active
[18] D. Lui, D. A. Fields, and Y. B. Kafai, “Collaborative Troubleshooting in STEM: A Case Study of High School Students Finding and Fixing Code, Circuit and Craft Challenges in Electronic Textiles,” *Cognition and Instruction*, vol. 42, no. 3, pp. 359–398, Jul. 2024, doi: 10.1080/07370008.2024.2334697.
[19] I. Maheshwari and P. Maheshwari, “Effectiveness of Immersive VR in STEM Education,” presented at the 2020 7th International Conference on Information Technology Trends, ITT 2020, Institute of Electrical and Electronics Engineers Inc., Nov. 2020, pp. 7–12. doi: 10.1109/ITT51279.2020.9320779.
[20] B. Brucker *et al.*, “How Learners’ Visuospatial Ability and Different Ways of Changing the Perspective Influence Learning About Movements in Desktop and Immersive Virtual Reality Environments,” *Educational Psychology Review*, vol. 36, no. 3, Sep. 2024, doi: 10.1007/s10648-024-09895-w.
[21] M. C. Johnson-Glenberg, M. Kosa, and H. P. O’Rourke, “STEM learning, science identity and immersivity: Giant screen films comparing 2D, 3D, and dome formats including a videogame assessment,” *Frontiers in Education*, vol. 7, Jan. 2023, doi: 10.3389/feduc.2022.1096889.
[22] N. Umezu and S. Horie, “Immersive Dome Projection: Skywalking Through Iconic Global Destinations,” presented at the Proceedings - 2025 IEEE International Conference on Artificial Intelligence and eXtended and Virtual Reality, AIxVR 2025, Institute of Electrical and Electronics Engineers Inc., 2025, pp. 327–330. doi: 10.1109/AIxVR63409.2025.00062.
[23] *schrodinger/pymol-open-source*. (Jan. 20, 2026). C. Schrödinger, Inc. Accessed: Jan. 20, 2026. [Online]. Available: https://github.com/schrodinger/pymol-open-source
[24] A. G. Fikes and M. C. Srougi, “Design and Implementation of an Accessible and Open-Sourced In Silico Drug Screening Activity for Cancer Drug Discovery,” *J. Chem. Educ.*, vol. 100, no. 10, pp. 4125–4130, Oct. 2023, doi: 10.1021/acs.jchemed.3c00307.
[25] *ccsb-scripps/AutoDock-Vina*. (Jan. 19, 2026). C++. Center for Computational Structural Biology. Accessed: Jan. 20, 2026. [Online]. Available: https://github.com/ccsb-scripps/AutoDock-Vina
[26] mgl-admin, “mgltools,” mgltools. Accessed: Jan. 20, 2026. [Online]. Available: https://ccsb.scripps.edu/mgltools/
[27] *StrawberryPerl/Perl-Dist-Strawberry*. (Jan. 20, 2026). Perl. StrawberryPerl. Accessed: Jan. 20, 2026. [Online]. Available: https://github.com/StrawberryPerl/Perl-Dist-Strawberry
[28] J. Kim, K. Kim, and W. Kim, “Impact of Immersive Virtual Reality Content Using 360-Degree Videos in Undergraduate Education,” *IEEE Transactions on Learning Technologies*, vol. 15, no. 1, pp. 137–149, Feb. 2022, doi: 10.1109/TLT.2022.3157250.
[29] J. Lanir, K. S. Booth, and K. Hawkey, “The benefits of more electronic screen space on students’ retention of material in classroom lectures,” *Computers & Education*, vol. 55, no. 2, pp. 892–903, Sep. 2010, doi: 10.1016/j.compedu.2010.03.020.