AMERICAN SOCIETY FOR MICROBIOLOGY | JMBE Journal of Microbiology & Biology Education

Check for updates

| Research Article

Student performance and perceptions in a hybrid laboratory model: an exploratory study of interactive virtual simulations and in-person integration in a foundational microbiology course

Vanessa Ayer Miller,[1] Timothy Marks,[1] Dorothea K. Thompson[1,2]

AUTHOR AFFILIATIONS See affiliation list on p. 12.

ABSTRACT Interest in virtual laboratory simulations as a pedagogical tool continues to grow, given the advantages of flexibility, scalability, technology integration, and interactive visualizations. We developed a laboratory model that integrates virtual lab simulations (VLS) and traditional in-person (IP) lab experiences for targeted skill development. In this study, we aimed to compare the effectiveness of VLS versus IP labs in the promotion of procedural, conceptual, and critical thinking levels of understanding. A second research objective was to explore students' perceptions in using VLS compared to IP labs in an undergraduate microbiology course. Study participants comprised students (n = 49) enrolled in a foundational microbiology course at a private university in the Fall semesters of 2022 and 2023. Identical quizzes were administered to assess learning performance of students who received the VLS first and those who completed the IP lab first. Focus group discussions were conducted, and participant responses were audio recorded for accuracy purposes, transcribed, and analyzed thematically using open and axial coding. The results indicated differences in performance scores between the VLS and IP groups were not statistically significant, suggesting both lab modalities are effective in enhancing learning. Overall, students expressed positive perceptions of VLS, noting detailed explanations, repetition, time management, and visual learning as primary benefits. Furthermore, students indicated an interest in using VLS in a hybrid structure as either a pre-laboratory exercise or a supplemental lab. These findings support the utility of a hybrid laboratory model in a foundational microbiology course for training pre-clinical students.

KEYWORDS hybrid laboratory model, virtual lab simulator, VLS, in-person labs, IP, microbiology, student perceptions and learning

Laboratory training constitutes an essential component of science curricula in higher education because it allows students to apply conceptual and theoretical knowledge through hands-on experiences (1, 2). Experiential learning provides opportunities for students to develop key skills in analysis, problem-solving, and critical thinking (3). The public health restrictions imposed by the COVID-19 pandemic challenged the traditional model of face-to-face, onsite laboratory instruction, forcing educators to implement other course-delivery mechanisms that permitted the achievement of similar student learning outcomes (4–7). As a result, digitally-based pedagogical modalities, such as virtual laboratory simulations (VLS) and immersive technologies like virtual reality (VR) and augmented reality, have become increasingly utilized in the teaching of basic sciences (7–11) and for clinical skills training in healthcare programs (12–16). Some noted advantages of interactive computer-based simulations and VR technology include allowing students to explore otherwise unobservable phenomena, the testing of hypotheses through multiple dry lab experiments in a short time and providing adaptive

Editor Jack Wang, The University of Queensland, Brisbane, Australia

Address correspondence to Vanessa Ayer Miller, vayermiller@campbell.edu.

The authors declare no conflict of interest.

Received 1 November 2024
Accepted 11 February 2025
Published 6 March 2025

guidance (1). Furthermore, virtual laboratories afford flexibility, allowing both instructors and students to balance the frequency and duration of each simulation to optimize learning experiences and accommodate individual differences in learning strategies (17, 18).

VLS are becoming more prevalent in educational contexts, necessitating further research to evaluate their effectiveness compared to traditional physical labs in enhancing student learning, engagement, and performance. Several studies have shown VLS increased student knowledge, self-efficacy, and intrinsic motivation, particularly when used in combination with traditional physical labs (17, 19–22). Students with lower pre-test knowledge demonstrated the greatest gains in learning and self-efficacy in a simulation-based virtual learning environment (19). Others have found computer-based simulations do not adversely affect student learning (23), and students who participated in a "blended lab" attained similar learning outcomes as students taking the equivalent lab in-person (IP) only (6). Students who completed virtual laboratory cases had more confidence in operating laboratory equipment but were not more motivated to engage in virtual labs compared to traditional IP labs (24). Furthermore, VLS, when used to supplement hands-on laboratories, aid students in connecting conceptual knowledge with practice (21) and may help medical students transfer theory to the clinical setting (19). Virtual modalities are generally a well-accepted pedagogical approach in the context of undergraduate medical education, surgical procedural training, emergency and pediatric emergency medicine, and basic medical sciences (25).

Reimagining laboratory-based science education by integrating different learning modalities is vital to meeting the curricular needs of diverse learners preparing for careers in healthcare. To enhance biomedical training for pre-clinical students, authors D.K.T. and T.M. developed a hybrid foundational microbiology laboratory model that integrates a three-dimensional (3D) VLS, Labster, and IP labs for targeted technical skill development. The incorporation of Labster in educational contexts has been described previously (4, 7, 17, 19–21, 24). Labster is a digital platform that creates a 3D interactive learning environment allowing students to interact with simulated lab equipment and perform lengthy experiments in a realistic case context while fostering theoretical understanding. Labster can be used on any platform including tablets, computers, and VR headsets. By strategically integrating both VLS and IP approaches, the hybrid laboratory design has the potential of capitalizing on the strengths of each modality to optimize student learning outcomes. De Jong et al. (1) concluded that a combination of virtual and physical experiments provides students with a more nuanced and robust understanding of scientific phenomena and inquiry. However, studies remain limited (6, 26–28), and the efficacy and student perceptions of a hybrid laboratory experience require further investigation.

Through the current study, we explored the following research questions (RQ):

RQ1. Are there differences in efficacy in the use of VLS versus IP labs in the promotion of procedural, conceptual, and critical thinking levels of understanding in microbiology?

RQ2. What are students' perceptions and preferences in using VLS compared to IP labs in an undergraduate microbiology course?

Quiz-based assessment data and qualitative response data from student focus groups were collected to examine student learning and student perceptions of a hybrid laboratory model integrating VLS and IP labs. We hypothesized that the inclusion of VLS is as effective in promoting student learning as traditional IP labs. The primary expected outcome of this study is the generation of data that will inform evidence-based teaching practices and curricular adjustments that will benefit students.

METHODS

Participant eligibility and recruitment

The course described in this study is a 4.0-credit-hour lecture/laboratory, 200 level clinical microbiology course offered at Campbell University (Buies Creek, North Carolina) in the College of Pharmacy & Health Sciences. The course is required for undergraduate students majoring in Pharmaceutical Sciences or Clinical Research and fulfills the general microbiology requirement for admission into the Doctor of Pharmacy program. Prerequisites for the course include general biology and general chemistry. This seated course was team-taught by authors T.M. and D.K.T. Participants eligible for inclusion in this exploratory study were undergraduate students enrolled in the Fall semesters of 2022 and 2023. Informed consent, including explanation of the research aims and methodology, was provided at the start of the course by author V.A.M., who was not an instructor for the course. Consent for and facilitation of onsite focus group discussions was also carried out by author V.A.M. Participation was voluntary, and those who chose to participate were required to complete the IRB-approved consent forms and FERPA Authorization. The Campbell University IRB approved this project (IRB Protocol #758).

Study schema

The course directors created a hybrid model consisting of computer-based laboratory simulations and targeted IP laboratory activities. The VLS platform used was Labster (https://www.labster.com), a computer-based laboratory simulation platform with interactive 3D animations. Labster simulations were seamlessly integrated with the course learning management system, Blackboard, and the study ran concurrently with the course. Two Labster simulations were used in this study, both of which align with ASM core competencies for undergraduate microbiology (4, 7): *Polymerase Chain Reaction* (PCR) and *The Gram Stain: Identify & Differentiate Bacteria*. All students were asked to complete the *Lab Safety* and *Gel Electrophoresis* Labster modules prior to the PCR lab to facilitate familiarity with the VLS platform. VLS and IP labs were completed throughout the course. Only the two specified labs were analyzed for this study. VR headsets were not used for simulations. Figure 1 presents the study schema. For the two pre-determined labs an IP lab and a VLS were given to all students. The information covered in both labs was the same. The two lab sections were randomly assigned to either Section A or Section B. For the first lab (PCR), Section A completed the VLS version first, and the same lab in person after completion of the assessment. Section B completed the IP version first and then given access to the VLS after completion of the assessment. This process was reversed for the second lab (Gram Stain). The same quiz assessment was given to both sections after the first time the lab was completed, whether virtually or in person. Students were given a single chance to complete the IP lab and two chances to complete the VLS to represent VLS capability to be repeated. Students were invited to participate in a focus group following the completion of both lab modalities.

Data collection and analysis

Quizzes were used to quantitatively assess the learning effectiveness of the VLS compared with traditional IP labs in promoting procedural, conceptual, and critical thinking levels of understanding. Multiple-choice questions were used to assess relevant procedural and conceptual knowledge, and short-answer questions tested students' ability to think critically from both procedural and conceptual perspectives. The quiz for each laboratory consisted of two procedural questions, two conceptual questions, and one critical thinking question. The definition of the types of questions and the questions developed by the course directors are provided in Table S1. Quizzes were administered on paper, timed, and proctored in class. Students were not permitted access to notes or the internet during the quiz. Assessments were blinded and scored, with each question being evaluated as either "correct" or "incorrect." Scores were compiled and compared for each lab as a percentage of students getting at least one of two questions correct and as a percentage of students getting both questions correct in each category. A confidence interval (CI) of 95% was used to statistically compare the results between VLS and IP lab modalities. SAS Software System version 9.4 (SAS Institute Inc., Cary, North Carolina) was used for statistical analysis.

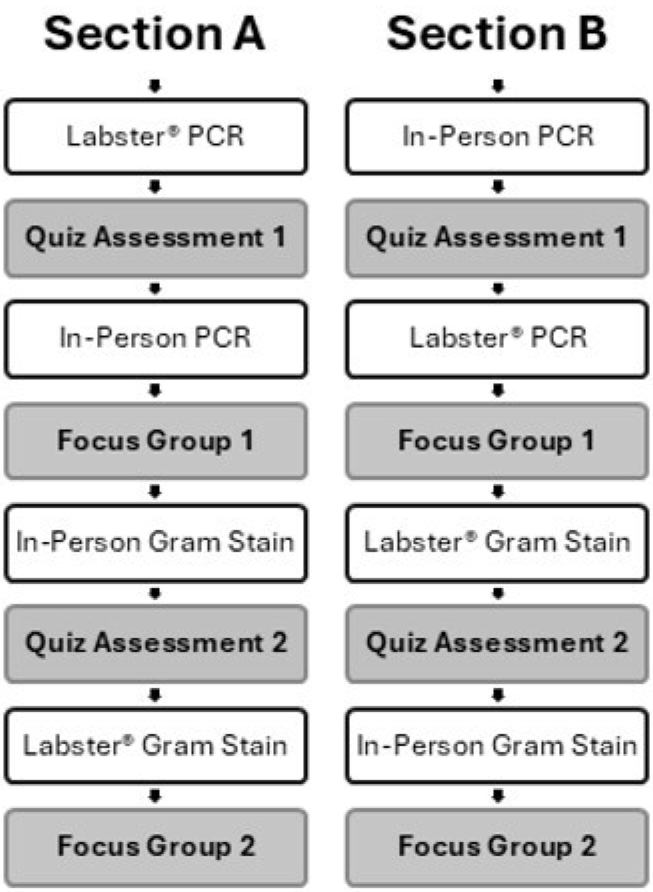

FIG 1 Study schema.

To explore students' thoughts and preferences in using VLS compared to IP, focus group discussions were conducted at the conclusion of each pair of lab modalities. Each student could participate in two focus groups. A semi-structured guide consisting of open-ended questions (see Table S2) was used to gather information about students' opinions on the critical thinking skills developed in each lab setting, their ability to learn the materials provided in the lab, the ease and convenience of the lab, and the pros and cons of the VLS and IP environments. Focus group discussions were held during the scheduled class period to ensure equitable access. A $10 gift card was given for focus group participation. Consent was solicited at the beginning of each focus group session and included the consent to be recorded. All focus group sessions were audio-recorded. The content of the recorded responses was then transcribed and coded using the software ATLAS.ti (version 9). Open and axial coding of the transcripts was performed to identify key themes. Codes were grouped into themes based on the similarity of the content provided by participants and relevance to the research questions. Thematic saturation was determined when no new prevalent themes or codes emerged within the discussions and data began to be repeated, rendering any further data collection redundant.

RESULTS

A total of 49 students participated in this study. Students were not asked to provide demographic information; however, the overall student body composition of Campbell University is 52% female, 58% Caucasian, 16% Black or African American, 13% Hispanic, 2% Asian, and 11% other or unknown.

Quantitative comparison of student learning: VLS versus IP labs

We analyzed the performance of two cohorts, where traditional laboratory experiences were integrated with VLS. To investigate Research Question 1, a 95% CI was used to statistically compare the results between VLS and IP lab modalities. Statistical significance of the differences in sample percentages was inferred if the CI did not contain zero. Tables 1 and 2 summarize the results of this study comparing the assessment performance of students completing either the VLS or IP lab for PCR and Gram Stain, respectively. Each assessment question type was evaluated based on the number of correct answers per student, the percentage of students achieving at least one correct answer, the percentage correctly answering both questions, and the difference in performance between lab modalities. In certain cases, the VLS section performed better, demonstrating a 3.7% higher rate of getting one question correct and a 15.4% higher rate of getting both questions correct when compared to the IP section for the PCR conceptual questions (Table 1). In contrast, the IP lab section had a 7.2% higher rate of getting both questions correct than the VLS group for the PCR procedural questions (Table 1). The results indicate mixed performance for students between VLS and IP lab modalities across different learning levels. VLS students generally performed better or similarly for questions assessing procedural and conceptual knowledge. Critical thinking assessments show varied results, with VLS students sometimes performing better and sometimes worse compared to IP lab students. In all instances, differences in assessment performance can be inferred to be not statistically significant based on 95% CI values, suggesting both lab modalities were equally effective in promoting higher-level learning (Tables 1 and 2).

Student experiences and perceptions of VLS and IP labs

Eight individual focus groups were held. Major themes queried included positive experiences, negative experiences, and future use of a VLS modality. Positive and negative experiences were analyzed based on IP or VLS delivery. Focus group discussions elicited a number of themes within the positive and negative experiences, including (i) students' perceptions of their knowledge gained from the lab (*knowledge*); (ii)critical thinking skills gained from the lab (*critical thinking*); (iii) ability (*error*) or inability (*no error*) to make or learn from an error; (iv) detailed explanations given or absent during the lab (*explanation*); (v) support of kinesthetic learning (*kinesthetic learning*); (vi) the ability to repeat all or part of a lab (*repetition*); (vii) the ability to control when, where, and the time it takes to complete the lab (*time management*); (viii) unforeseen equipment, software, or manipulation issues (*technical issues*); and (ix) the support of visual learning (*visual learning*). Table 3 provides representative quotes for the predominant themes that emerged in the focus group discussions.

Theme 1: positive experiences

Using open and axial coding, analysis of the qualitative response data revealed 115 instances where students associated the VLS with a positive experience (Fig. 2). Positive experiences focused on the detailed explanations provided by the VLS, the opportunity for repetition, time management, and enhancement of visual learning (Fig. 3). Students associated their positive VLS experience with their ability to control where, when, and the time needed to complete the VLS with 38 instances where student statements referred to time management positively. Repetition, often associated with time management, was also expressed 17 times by students in statements like:

> *"… we like it because you can do it from home at your time and [it] repeats, and we like it because we don't have to be in a lab."*

Participants also appreciated the capacity of the VLS to visualize experimental processes that occur at microscopic and molecular levels, which helped provide more

TABLE 1 Assessment of differences in quiz performance for undergraduate students completing the VLS PCR versus the IP PCR lab across different learning categories

Assessment question type	No. of correct answers/student	*N* (%) of VLS students (*n* = 20)	*N* (%) of IP students (*n* = 23)	IP–VLS (%)	95% CI[a] for IP%–VLS%
Procedural	At least one answer correct	19 (95.0)	18 (78.3)	(−16.7)	[−35.5, 5.6]
	Both answers correct	9 (45.0)	12 (52.2)	(7.2)	[−22.0, 35.1]
Conceptual	At least one answer correct	19 (95.0)	21 (91.3)	(−3.7)	[−20.4, 14.6]
	Both answers correct	17 (85.0)	16 (69.2)	(−15.4)	[−38.2, 10.6]
Critical thinking (procedural)	At least one answer correct	14 (70.0)	17 (73.9)	(3.9)	[−22.4, 30.1]
	Both answers correct	13 (65.0)	14 (60.9)	(−4.1)	[−31.4, 24.2]
Critical thinking (conceptual)	At least one answer correct	2 (10.0)	2 (8.7)	(−1.3)	[−20.8, 17.5]
	Both answers correct	1 (5.0)	1 (4.34)	(−0.7)	[−17.1, 15.0]

[a]CI, confidence interval.

detailed explanations. Of the positive statements collected, 19 were for visual learning and 17 were for detailed explanations (Fig. 3; Table 3).

By contrast, approximately 68% of student statements regarding positive IP labs centered around their association of kinesthetic learning and detailed explanations provided by faculty, particularly when experimental errors occurred (Fig. 4). Students expressed the benefits of tactile learning by going through the process of pipetting samples in an agarose gel (Table 3). They also appreciated the support provided by the course directors during the lab.

> *"He asked a list of questions, what do we need for this and the other? What do we need for the DNA to synthesize?"*

Theme 2: negative experiences

Students' negative experiences were linked to the inability to make errors when progressing through the VLS and the lack of explanation provided by the VLS as to potential outcomes should an error be made or why the experiment could not be done as attempted (Fig. 3). Participants also noted the lack of support for kinesthetic learning as a negative aspect of VLS labs. Negative IP experiences focused on technical or experimental errors that caused unobservable results or delays in completing the lab.

Theme 3: future use of VLS in an undergraduate microbiology course

Future use of the VLS was analyzed in terms of five categories: a hybrid approach using a combination of VLS and IP (*hybrid*), make-up labs (*make-up lab*), review for a lab or lecture exam (*review*), pre-lab before an IP lab (*pre-lab*), or adjunct for a lecture, lab, or both (*supplement*). When asked how they would like to see a VLS component implemented in the course, students expressed an overwhelming preference for a hybrid-style approach (Fig. 5):

TABLE 2 Assessment of differences in quiz performance for undergraduate students completing the VLS Gram Stain versus the IP Gram Stain lab across different learning categories

Assessment question type	No. of correct answers/student	*N* (%) of VLS students (*n* = 23)	*N* (%) of IP students (*n* = 20)	IP–VLS (%)	95% CI[a] for IP%–VLS%
Procedural	At least one answer correct	21 (91.3)	19 (95.0)	(3.7)	[−14.6, 20.4]
	Both answers correct	17 (73.9)	9 (45.0)	(−28.9)	[−53.8, 0.7]
Conceptual	At least one answer correct	23 (100.0)	20 (100.0)	(0.0)	[−69.3, 69.3]
	Both answers correct	22 (95.7)	19 (95.0)	(−0.7)	[−17.1, 15.0]
Critical thinking (procedural)	Question answered correctly	14 (60.9)	6 (30.0)	(−30.9)	[-55.5,−0.8]
Critical thinking (conceptual)	Question answered correctly	7 (30.4)	5 (25.0)	(−5.4)	[−30.8, 21.4]

[a]CI, confidence interval.

TABLE 3 Focus group reflection themes

Category	Theme	Representative quotes
Positive IP lab experience	Overall view	"I think part of what makes in-person so much more interesting is you created yourself in-person instead of doing it virtually where it's you but not really you. I think you feel more proud of your results or no results or whatever, when you do in-person because you did it. You went and took your time and effort to do it." … "I enjoyed using all the equipment … and being able to see how everything worked."
	Kinesthetic learning	"For me, it helps me remember because I actually did this rather than somebody else doing it and talking about it." "When you actually do it, you have to sit there and pipetting everything and you have to put it in the gel and everything. It helps you remember the process and what's supposed to happen and why this happens and then if you don't get results, it kind of helps you go back, 'This is why it didn't work.'"
	Detailed explanations provided by faculty	"I feel like we talked about that. She asked that question in lab yesterday, and that's why I remembered the answer." "He helped guide us as far as questions and then the procedure and stuff like that."
Negative IP lab experience	Errors leading to non-viewable results	"I didn't go into the lab assuming I wouldn't see anything but like everybody would have something, so to see that only one group did was kind of like, 'Wow!'"
Positive VLS experience	Time management	"We had to look at something under a microscope … and I'm done in 20 minutes, and I already know what's going on. And I'm not sitting there twiddling my thumbs and wasting my time at 8:00, 8:30 at night." "I think it just saves a lot of time, but it also, whenever you're doing the different steps, it gives a description of what each thing is sometimes."
	Repetition	"I also like how [Labster] shows you video, then it shows me the video again while asking you the questions." "It was repetitive. Drilled it into your head."
	Visual learning	"It actually had the cell wall layers, and you could see the model, and you had to stack it correctly. So, I actually [was] able to see it because it's not like we could see that on a molecular level, I guess, or a detailed level like that, in person." "And with the DNA replication videos and how it shows you on a microscopic level the things that you can't see in lab. I think that was really helpful in terms of being able to comprehend the content of the lab."
	Detailed conceptual explanations	"I think the information given to us in the Labster was really good and it helped me, and I think I understand everything more."
	Personal view	"I was one of those kids where I didn't get any labs from high school, so even virtual labs still feel really new to me and like I'm experiencing a lot of things for the first time, and especially the first Labster was kind of interesting."
Negative VLS experience	Inability to make errors with little explanation	"It's not necessarily that practical in real life because you probably are going to forget to add that one thing at least once and then knowing what the possible outcomes would be if you were to do it wrong or not all of them obviously, but at least a couple common mistakes that people make."

FIG 2 Relationship of positive and negative experiences between IP and VLS labs. Students in the Fall 2022 and Fall 2023 focus groups had generally positive impressions of the hybrid-style microbiology lab experience compared to negative impressions. Numbers represent the times student statements fell within a code category. Sankey diagram was generated using ATLAS.ti qualitative data analysis tool.

> *"Well, personally I would like the mix because in lab you can do the actual experiment but for intricate really small details, Labster also helps you with [visualizing] that."*
>
> *"I think a hybrid definitely seems like the easiest go-to option just because I think we definitely need to be able to sit there, hold the pipette, use the pipette, but on those long waiting portions, a video of what was happening in the machine would be really cool to see."*

Participants specifically recommended utilizing the VLS as a pre-laboratory activity or supplement to the IP lab:

> *"I recommend doing Labster before the real lab, because you're doing the Labster first. You're getting all the virtual reality stuff. You get the specific things you need to know."*
>
> *"Having a Labster to help reinforce the basic knowledge that you need to understand what's actually happening would be beneficial for also the lecture portion too."*

DISCUSSION

This study aimed to compare the efficacy of VLS vs traditional IP labs in the promotion of student learning in a foundational microbiology course. Additionally, we explored how students perceive their learning experiences while participating in a hybrid laboratory integrating VLS and IP activities. Through this analysis, our objective was to gain insight into how best to implement and improve hybrid-style teaching labs to maximize student learning and enjoyment.

The first research question examined whether there are differences in the effectiveness of VLS and traditional IP labs in enhancing procedural, conceptual, and critical thinking levels of learning. The quantitative data indicated students who participated in the VLS first performed similarly or better than students who received the IP version on questions assessing procedural and conceptual knowledge. Differences in scores were not statistically significant based on 95% CI, suggesting both modes of teaching are effective in promoting knowledge acquisition in basic microbiology. This finding is consistent with previous studies that assessed the learning effectiveness of VLS compared with traditional, physical labs (17, 20, 23). The extant literature analyzing the impact of virtual lab modalities on educational effectiveness reports mixed results and

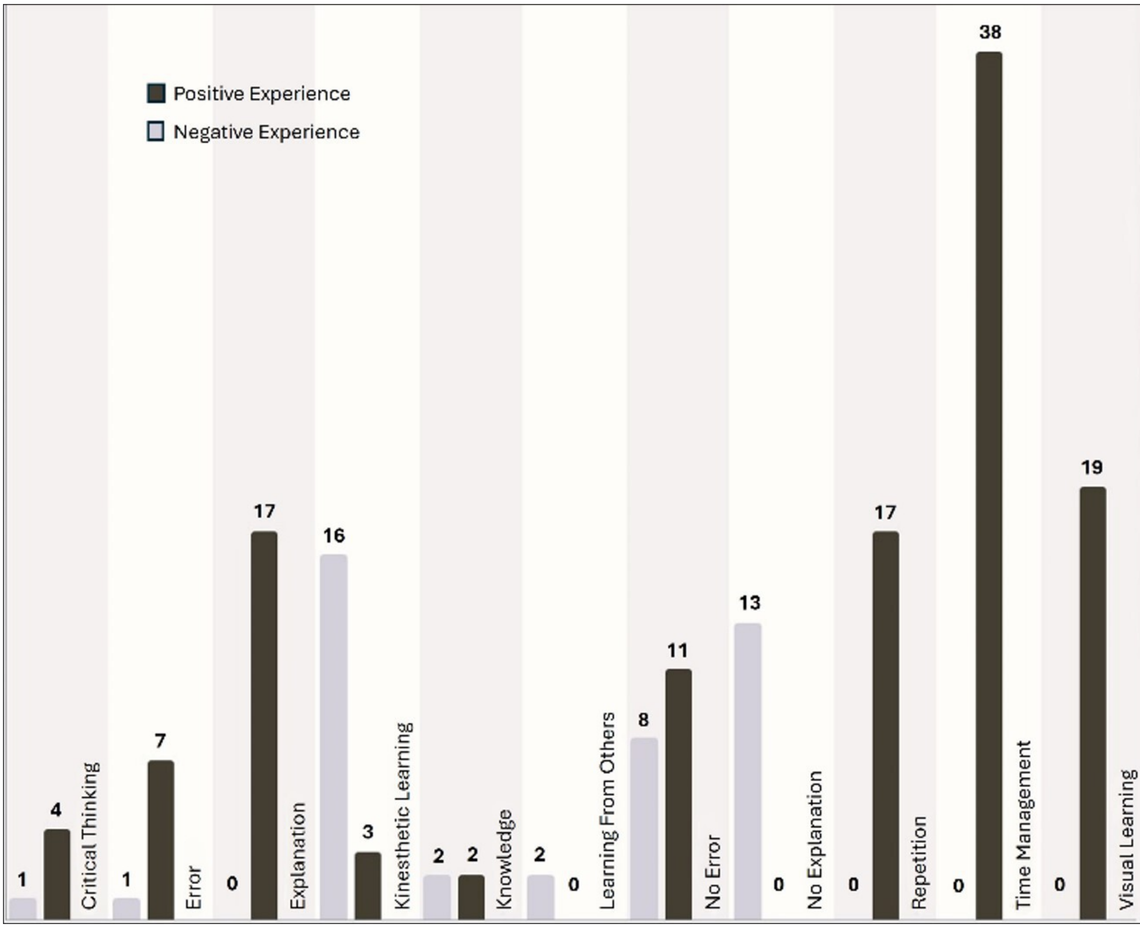

FIG 3 Bar graph of positive and negative student perceptions of VLS experience. Focus group participants provided detailed perceptions on these code categories: critical thinking, error, explanation, kinesthetic learning, knowledge, learn from others, no error, no explanation, repetition, time management, and visual learning. Numbers represent the times student statements fell within a code category.

remains limited. Other studies demonstrated the integration of immersive VR technology into traditional lab settings improved student understanding of anatomical structures and their spatial relationships (14) and biochemical topics such as the citric acid cycle (29), as well as enhanced the knowledge and skill performance of students in nursing (30). Our assessment results support versatility in the use of different teaching modes in the microbiology laboratory without compromising student learning.

The second research question explored participants' perceptions and preferences in using VLS vs IP labs in an undergraduate microbiology course. In coding the reflections from focus group discussions, student perceptions after engaging with the VLS were predominantly positive (115 instances vs 58) in our study and other studies (8, 22, 31). Student impressions of their IP lab experience were more evenly distributed between the positive and negative categories (43 vs 30, respectively). Overall, our analysis of open-ended qualitative responses showed students' positive experiences with VLS are mainly associated with time management. Students appreciated the opportunity to complete the VLS on their schedule and at their own pace without the time constraints associated with physical labs. Other themes emerged as positive features of VLS including visual learning, repetition, and detailed explanations. Virtual simulations can depict molecular interactions, like the amplification of DNA in PCR, that are not directly observable in IP labs, allowing complex concepts to be visually represented. This primary affordance of VLS has been reported in the literature (1, 31). VLS also allows students to engage more deeply with the laboratory topic by revisiting abstract concepts as needed.

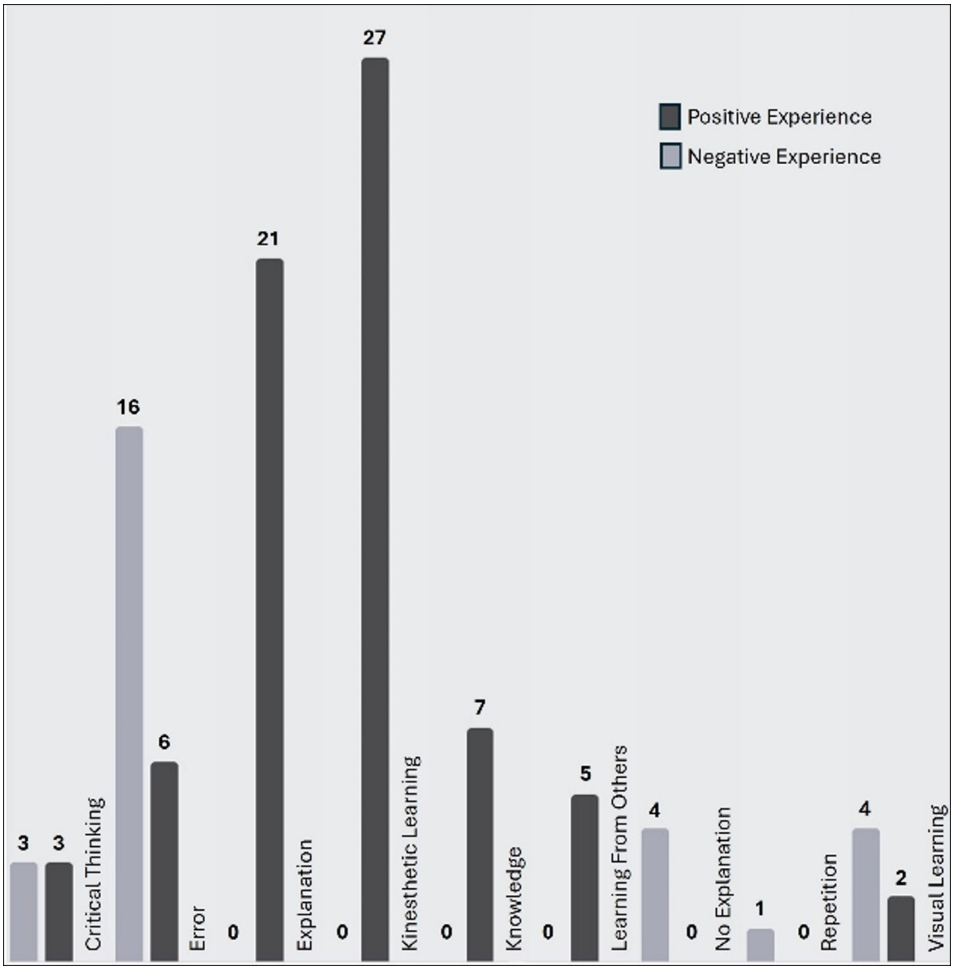

FIG 4 Bar graph of positive and negative student perceptions of IP lab experience. Focus group participants provided detailed perceptions on these code categories: critical thinking, error, explanation, kinesthetic learning, knowledge, learn from others, no explanation, repetition, and visual learning. Numbers represent the times student statements fell within a code category.

Conversely, participants perceived the lack of support for kinesthetic learning as a negative aspect of VLS, noting the tactile experience of handling specimens and equipment in a physical IP lab is important to student learning. Focus group participants also perceived the direct supervision and personalized feedback provided by the instructor as a positive feature of IP labs. Students expressed dissatisfaction when errors made in the VLS were not explained. Students' negative impressions of VLS aligned with an earlier qualitative study in which participants perceived the social interaction of traditional IP labs and the ability to ask questions and receive feedback from instructors as enhancing their understanding of course content (32). Further research is needed to fully understand the possible negative impacts of implementing VLS in education.

We also queried participants about the potential future use of VLS in laboratory education. Participants expressed an overwhelming preference for a hybrid structure that strategically integrates both IP and virtual lab experiences. A similar finding was evident in a study that investigated student perceptions of employing a combination of online practical sessions followed by hands-on laboratory sessions (33). While we did not specifically evaluate the effectiveness of the hybrid model in terms of student learning, research by Pollock (28) comparing face-to-face (F2F), hybrid, and online lab styles in student performance on practical grades and overall grades in anatomy and physiology found attendance, student satisfaction, and performance scores were higher among

FIG 5 Sankey diagram of the future use of virtual labs. Focus group participants provided their opinions on how they would use virtual labs in the course. Categories included using VLS in a *hybrid* format, as a *pre-lab*, *replacement lab*, *review*, or *supplemental* lab. Sankey diagram was generated using ATLAS.ti qualitative data analysis tool.

hybrid lab students, but students who participated in the F2F laboratory outperformed students from both the online and hybrid laboratory styles (28). These differences may be course-dependent and due to the specific implementation method used. By contrast, other studies found that students participating in a "blended" microbiology laboratory mastered learning outcomes as well as students taking the equivalent lab in person (6). Future work should further validate the utility of combining both modalities strategically for the optimization of student learning outcomes, engagement, study motivation, and enjoyment.

Study participants indicated a preference in using VLS in a mixed-use capacity including its incorporation as a pre-laboratory exercise or as supplementation of IP learning experiences. Our results align with previous studies that support the use of VLS as an effective preparation tool for a physical IP lab activity (7, 9, 17, 24) and to a lesser extent, as a supplement to IP experiences (11, 21). VLS appear to facilitate a learner's ability to connect theory to practice in the physical laboratory (21). Moreover, as Dyrberg et al. (24) concluded, students receiving virtual pre-laboratory instruction complete the hands-on procedures faster and ask higher-level questions compared to unprepared students. Most participants in this study did not prefer utilizing virtual simulations as a substitute or safer alternative to traditional IP labs. A few participants suggested VLS be used for a lab review or as a replacement lab but only for those not expected to perform similar labs as part of their future career.

This exploratory study provides insights into student performance at different knowledge levels and participant perceptions of a hybrid VLS-IP lab model; however, the study had some limitations that should be considered when interpreting the results. First, the study population consisted of a limited number of participants enrolled in a single undergraduate microbiology course at one private university. This may prevent the determination of the true nature behind the lack of statistical significance and affect the generalization of the findings to other scientific disciplines and institutional contexts. Focus group findings may not reflect the perceptions of students at other institutions. Furthermore, because our study population was derived from students enrolled in a specific course, we were not able to ensure a reflection of the university's student population in terms of gender and ethnicity. Future investigations should expand the sample population, increasing the number and diversity of participants to better understand the effectiveness of a hybrid lab model in various educational settings. Another limitation was the small number of questions used to assess students' procedural and conceptual knowledge and ability to critically think following the completion of a VLS and IP lab. Nevertheless, we attempted to strengthen the reliability of our results and reduce potential bias from single-cohort performance anomalies by evaluating student performance data collected over two separate semesters. Finally, we did not control for other potential confounding variables such as students' prior knowledge of the lab topics, knowledge gained from the course lectures, and previous experience with VLS.

ACKNOWLEDGMENTS

We thank Michael Jiroutek, PhD, for statistical guidance and calculations. Additionally, we are grateful to all students who participated in the study.

No source of financial support was received for this work.

AUTHOR AFFILIATIONS

[1]Department of Pharmaceutical and Clinical Sciences, College of Pharmacy & Health Sciences, Campbell University, Buies Creek, North Carolina, USA
[2]Department of Pharmaceutical Sciences, South College School of Pharmacy, Knoxville, Tennessee, USA

AUTHOR ORCIDs

Vanessa Ayer Miller http://orcid.org/0000-0001-7614-1959
Timothy Marks http://orcid.org/0000-0001-7444-469X
Dorothea K. Thompson http://orcid.org/0000-0002-6017-8359

AUTHOR CONTRIBUTIONS

Vanessa Ayer Miller, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing | Timothy Marks, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing | Dorothea K. Thompson, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing

ETHICS APPROVAL

This study was approved by Campbell University's Institutional Review Board, protocol number IRB-758.

ADDITIONAL FILES

The following material is available online.

Supplemental Material

Supplemental Tables 1 and 2 (jmbe00203-24-s0001.docx). Table S1 (Definitions and questions included in assessments) and Table S2 (Focus group question guides).

REFERENCES

1. de Jong T, Linn MC, Zacharia ZC. 2013. Physical and virtual laboratories in science and engineering education. Science 340:305–308. https://doi.org/10.1126/science.1230579
2. Waldrop MM. 2013. Education online: the virtual lab. Nature New Biol 499:268–270. https://doi.org/10.1038/499268a
3. Hofstein A, Lunetta VN. 2004. The laboratory in science education: foundations for the twenty-first century. Sci Educ 88:28–54. https://doi.org/10.1002/sce.10106
4. Alvarez KS. 2021. Using virtual simulations in online laboratory instruction and active learning exercises as a response to instructional

challenges during COVID-19. J Microbiol Biol Educ 22:22.1.58. https://doi.org/10.1128/jmbe.v22i1.2503
5. Baid S, Hefty PS, Morgan DE. 2022. A CURE for the COVID-19 era: a vaccine-focused online immunology laboratory. J Microbiol Biol Educ 23:e00311-21. https://doi.org/10.1128/jmbe.00311-21
6. Guzman-Cole C, García-Ojeda ME. 2022. An upper-division, remote microbiology laboratory that blends virtual and hands-on components to promote student success during the COVID-19 pandemic. J Microbiol Biol Educ 23:e00328-21. https://doi.org/10.1128/jmbe.00328-21
7. Tripepi M. 2022. Microbiology laboratory simulations: from a last-minute resource during the Covid-19 pandemic to a valuable learning tool to retain-a semester microbiology laboratory curriculum that uses labster as prelaboratory activity. J Microbiol Biol Educ 23:e00269-21. https://doi.org/10.1128/jmbe.00269-21
8. Chitra E, Mubin SA, Nadarajah VD, Se WP, Sow CF, Er HM, Mitra NK, Thiruchelvam V, Davamani F. 2024. A 3-D interactive microbiology laboratory via virtual reality for enhancing practical skills. Sci Rep 14:12809. https://doi.org/10.1038/s41598-024-63601-y
9. Donner L, Imhoff M. 2022. Development of online clinical microbiology laboratory unknowns: active learning for online, hybrid, and in-person courses. J Microbiol Biol Educ 23:e00071-22. https://doi.org/10.1128/jmbe.00071-22
10. Majewska AA, Vereen E. 2023. Using immersive virtual reality in an online biology course. J STEM Educ Res 12:1–16. https://doi.org/10.1007/s41979-023-00095-9
11. Tandon I, Maldonado V, Wilkerson M, Walls A, Rao RR, Elsaadany M. 2024. Immersive virtual reality-based learning as a supplement for biomedical engineering labs: challenges faced and lessons learned. Front Med Technol 6:1301004. https://doi.org/10.3389/fmedt.2024.1301004
12. Boyanovsky BB, Belghasem M, White BA, Kadavakollu S. 2024. Incorporating augmented reality into anatomy education in a contemporary medical school curriculum. Cureus 16:e57443. https://doi.org/10.7759/cureus.57443
13. Liao ML, Yeh CC, Lue JH, Chang MF. 2024. Implementing virtual reality technology to teach medical college systemic anatomy: a pilot study. Anat Sci Educ 17:796–805. https://doi.org/10.1002/ase.2407
14. Neyem A, Cadile M, Burgos-Martínez SA, Farfán Cabello E, Inzunza O, Alvarado MS, Tubbs RS, Ottone NE. 2024. Enhancing medical anatomy education with the integration of virtual reality into traditional lab settings. Clin Anat. https://doi.org/10.1002/ca.24213
15. Saghiri MA, Vakhnovetsky J, Nadershahi N. 2022. Scoping review of artificial intelligence and immersive digital tools in dental education. J Dent Educ 86:736–750. https://doi.org/10.1002/jdd.12856
16. Vihos J, Chute A, Carlson S, Shah M, Buro K, Velupillai N. 2024. Virtual reality simulation in a health assessment laboratory course. Nurse Educ 49:E315–E320. https://doi.org/10.1097/NNE.0000000000001635
17. Makransky G, Thisgaard MW, Gadegaard H. 2016. Virtual simulations as preparation for lab exercises: assessing learning of key laboratory skills in microbiology and improvement of essential non-cognitive skills. PLoS One 11:e0155895. https://doi.org/10.1371/journal.pone.0155895
18. Smetana LK, Bell RL. 2012. Computer simulations to support science instruction and learning: a critical review of the literature. Int J Sci Educ 34:1337–1370. https://doi.org/10.1080/09500693.2011.605182
19. Makransky G, Bonde MT, Wulff JSG, Wandall J, Hood M, Creed PA, Bache I, Silahtaroglu A, Nørremølle A. 2016. Simulation based virtual learning environment in medical genetics counseling: an example of bridging the gap between theory and practice in medical education. BMC Med Educ 16:98. https://doi.org/10.1186/s12909-016-0620-6
20. Bonde MT, Makransky G, Wandall J, Larsen MV, Morsing M, Jarmer H, Sommer MOA. 2014. Improving biotech education through gamified laboratory simulations. Nat Biotechnol 32:694–697. https://doi.org/10.1038/nbt.2955
21. de Vries LE, May M. 2019. Virtual laboratory simulation in the education of laboratory technicians-motivation and study intensity. Biochem Mol Biol Educ 47:257–262. https://doi.org/10.1002/bmb.21221
22. Spencer D, McKeown C, Tredwell D, Huckaby B, Wiedner A, Dums JT, Cartwright EL, Potts CM, Sudduth N, Brown E, Albright P, Jhala A, Srougi MC. 2024. Student experiences with a molecular biotechnology course containing an interactive 3D immersive simulation and its impact on motivational beliefs. PLoS One 19:e0306224. https://doi.org/10.1371/journal.pone.0306224
23. Wiesner TF, Lan W. 2004. Comparison of student learning in physical and simulated unit operations experiments. J Eng Edu 93:195–204. https://doi.org/10.1002/j.2168-9830.2004.tb00806.x
24. Dyrberg NR, Treusch AH, Wiegand C. 2017. Virtual laboratories in science education: students' motivation and experiences in two tertiary biology courses. J Biol Educ 51:358–374. https://doi.org/10.1080/00219266.2016.1257498
25. Wu Q, Wang Y, Lu L, Chen Y, Long H, Wang J. 2022. Virtual simulation in undergraduate medical education: a scoping review of recent practice. Front Med 9:855403. https://doi.org/10.3389/fmed.2022.855403
26. Png CW, Goh LI, Chen YK, Yeo H, Liu H. 2024. A comparison of students' preferences for face-to-face and online laboratory sessions: insights from students' perception of their learning experiences in an immunology course. J Microbiol Biol Educ 25:e0018123. https://doi.org/10.1128/jmbe.00181-23
27. Klages JE, Baid S, Giri EG, Morgan DE, Hotze EM. 2023. Hybrid inquiry-based laboratory curriculum highlights scientific method using bacterial conjugation as a model. J Microbiol Biol Educ 24:e00237-22. https://doi.org/10.1128/jmbe.00237-22
28. Pollock NB. 2022. Student performance and perceptions of anatomy and physiology across face-to-face, hybrid, and online teaching lab styles. Adv Physiol Educ 46:453–460. https://doi.org/10.1152/advan.00074.2022
29. Barrow J, Hurst W, Edman J, Ariesen N, Krampe C. 2024. Virtual reality for biochemistry education: the cellular factory. Educ Inf Technol 29:1647–1672. https://doi.org/10.1007/s10639-023-11826-1
30. Huai P, Li Y, Wang X, Zhang L, Liu N, Yang H. 2024. The effectiveness of virtual reality technology in student nurse education: a systematic review and meta-analysis. Nurse Educ Today 138:106189. https://doi.org/10.1016/j.nedt.2024.106189
31. Byukusenge C, Nsanganwimana F, Tarmo AP. 2022. Effectiveness of virtual laboratories in teaching and learning biology: a review of literature. Int J Learn Teach Edu Res 21:1–17. https://doi.org/10.26803/ijlter.21.6.1
32. Stuckey-Mickell TA, Stuckey-Danner BD. 2007. Virtual labs in the online biology course: student perceptions of effectiveness and usability. J Online Learn Teach 3:105–111. https://jolt.merlot.org/vol3no2/stuckey.pdf.
33. Salter S, Gardner C. 2016. Online or face-to-face microbiology laboratory sessions? First year higher education student perspectives and preferences. Creative Educ 07:1869–1880. https://doi.org/10.4236/ce.2016.714189