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Impact of transition to a hybrid model of biochemistry course-based undergraduate research experience during the COVID-19 pandemic on student science self-efficacy and conceptual knowledge

Jing Zhang[1] · Heejeong Kim[1] · Limei Zhang[1]

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Abstract
The COVID-19 outbreak has had a significant impact on higher education worldwide. In-person courses had to be quickly transited to online, including lab courses embedded with Course-based Undergraduate Research Experiences (CUREs). In response to this challenge, we successfully converted a fully in-person biochemistry lab that integrated with a 6-week modular CURE (mCURE) into a hybrid CURE (hCURE) in Fall 2020, with support from the Malate dehydrogenase CUREs Community. The hCURE was structured to have in-person labs and online activities arranged on an alternating weekly basis, so that only half of the regular class size of students attended the hands-on labs at any given time to maintain proper social distancing. To evaluate the efficacy of the hCURE, student science self-efficacy and conceptual understanding of protein structure–function relationships were measured using pre-course and post-course surveys and tests, respectively. Our data showed a significant increase in student science self-efficacy and conceptual knowledge test scores. Furthermore, we compared the pre-lab quiz scores that assessed various biochemical concepts and skills across three different semesters, Fall 2019 with a fully in-person mCURE before the pandemic, Fall 2020 with the hCURE implemented during the pandemic, and Fall 2021 when the lab returned to the fully in-person mCURE following the pandemic. A significant decline in quiz scores from Fall 2019 to Fall 2020, and an even further decline from Fall 2019 to Fall 2021 were observed, suggesting that apart from the impact of course modality, the pandemic may have exerted a lasting adverse effect on student learning.

1 Introduction

The COVID-19 pandemic had a profound impact on almost every sector of our society, including higher education [1–4]. Educators had to rapidly pivot to emergency remote teaching, including lab courses that are integrated with Course-based Undergraduate Research Experiences (CUREs). CUREs are effective alternatives to the apprenticeship model of undergraduate research experiences at individual faculty research labs by incorporating essential research elements into a course [5]. The characteristics of a CURE include teaching scientific practices, engaging in projects with unknown outcomes that contribute to the broader scientific community, emphasizing collaboration and teamwork, and using an iterative approach to scaffold the learning process [6]. CUREs provide structured research experiences for students to learn the process of science, ranging from within a short span of weeks to across multiple semesters [7, 8]. This makes

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✉ Jing Zhang, jzhang24@unl.edu | [1]Department of Biochemistry, University of Nebraska-Lincoln, Lincoln, NE 68588, USA.

Table 1 Demographics of participating students from the Fall 2020 semester

Fall 2020 Hybrid CURE n = 41		
Level		
Junior	13	31.7%
Senior	28	68.3%
Major		
Biochemistry	30	73.2%
Chemistry	5	12.2%
Other Science Majors	6	14.6%

research experiences more accessible and equitable to diverse groups of students [9], resulting in enhanced student outcomes and increased persistence in the STEM fields [10–12].

The shifts from in-person lab courses to either online or hybrid mode during the pandemic have been reported across various disciplines, including physics, cell biology, chemistry, and biochemistry [13–18]. Many reports have focused on instructors' efforts to convert their courses to online or hybrid formats, sharing their experiences and lessons learned. Online labs, when well-designed, can result in comparable or better student outcomes than in-person labs in terms of gaining computer-based research skills and conceptual understanding [19, 20]. However, the most significant challenge of online labs is likely the lack of hands-on skill practice, particularly for instrumentation learning [13, 21]. Other notable difficulties include maintaining student engagement in the remote learning environment, diminished sense of community, reduced motivation [22, 23], and challenges with asynchronous communication and group work [24].

Hybrid labs, on the other hand, present advantages that combine the accessibility of online learning and the necessity of hands-on training. They can be more effective in improving conceptual understanding [25] and provide a cost-effective model compared to fully in-person labs [26]. Comparison of face-to-face, hybrid, and online CURE labs has yielded similar findings. Student self-reported gains in research skills [27] and knowledge gains on scientific content [28] were equivalent in hybrid CUREs to the fully in-person models, and no significant differences were detected in student perception of project ownership, science identity, or networking [29] between the hybrid and fully face-to-face modality [28], suggesting that CUREs can be effectively adapted to the hybrid mode. In comparison to in-person CUREs, however, literature on hybrid CUREs is limited to a handful of disciplines and the pandemic presented a unique opportunity for advancement in this critical area.

In this study, we reported the conversion of a biochemistry lab course incorporated with a 6-week modular-CURE (mCURE) on Malate Dehydrogenase (MDH) research to a hybrid CURE (hCURE) to comply with the pandemic regulation in the Fall 2020 semester. To evaluate the efficacy of this hybrid module, we surveyed student science self-efficacy and created a multiple-choice test to measure students' conceptual understanding of protein structure–function relationships. Moreover, we compared the pre-lab quiz scores across three semesters, Fall 2019 (fully in-person mCURE), Fall 2020 (hCURE), and Fall 2021(fully in-person mCURE), to gauge the impact of course modality and the pandemic on student learning. We are interested in the following research questions:

1. Is the hCURE effective in enhancing student self-efficacy and conceptual knowledge?
2. Are there changes in student conceptual knowledge, as measured using the pre-lab quizzes, compared to the pre-pandemic semester?

2 Methods

2.1 Participants

This study was approved by the Institutional Review Board #20583. Students enrolled in a biochemistry lab course at a public research-intensive university in the Midwest United States during the Fall 2020 semester. Most students are juniors and seniors majored in Biochemistry. There were two lab sections, each capped at 24 students. 41 students consented and completed the evaluative instruments. Student demographic data are shown in Table 1.

2.2 Course structure

Bioc 433/833 is a one-semester biochemistry lab course required for biochemistry and chemistry majors. It has a weekly 4-h lab and a separate 50-min lecture introducing biochemical concepts to prepare students for the lab activities. This lab course is integrated with a 6-week modular CURE (mCURE) (Fig. 1a) supported by the malate dehydrogenase (MDH) CUREs community (MCC) [30, 31].

During COVID-19 pandemic in Fall 2020, we pivoted to an hCURE to comply with the university safety policy. The redesigned hybrid model (Fig. 1b) followed the theme of the original mCURE and included most of the MCC CURE components such as scientific practice, relevance, discovery, hypothesis, collaboration, and presentation [32]. The first week of the class was an asynchronous pre-recorded overview of the course. The following weeks were alternated with

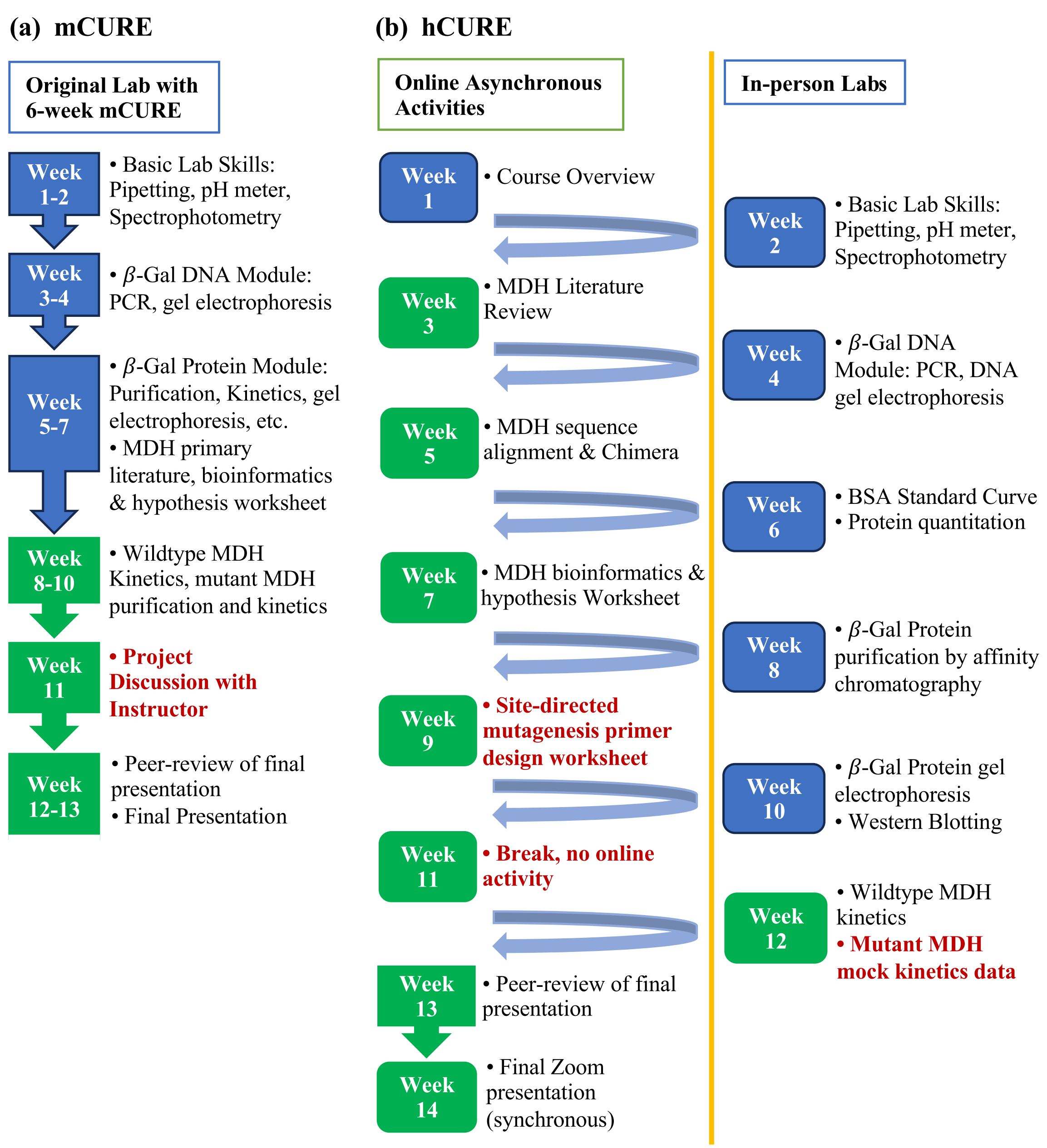

Fig. 1 Course structure of the original in-person lab and the hybrid CURE lab. **a**. The course structure of the pre-pandemic in-person lab incorporated a 6-week MDH mCURE. **b**. Re-structured hCURE lab with alternating weekly online asynchronous learning and in-person hands-on labs. The weeks highlighted in blue boxes described the regular lab content, while the weeks in green boxes contained CURE elements. Descriptions in red font indicated the components that were unique for each model

hands-on and online asynchronous activities accompanied with pre-recorded lectures. Students in each section were divided into two halves. When one-half of the class was doing the hands-on lab, the other half watched the pre-recorded lectures and worked on the assignments, and then the two groups swapped activities for the following week. The 50-min lecture component in the mCURE was replaced by the pre-recorded lectures in the hybrid mode.

Compared to the mCURE, the hCURE had the majority of the CURE components (Fig. 1, green boxes) arranged online so that the in-person lab time could be dedicated to hands-on practices. There were several design features unique to each model (Fig. 1, red descriptions). In the mCURE, one lab time was dedicated for students to meet with the instructor to discuss their CURE projects in small groups of 2–4 (Fig. 1a). It was unfeasible for in-person meetings during the pandemic, so students were given a break time from week 11 (Fig. 1b). In the hCURE, a site-directed mutagenesis primer design worksheet (Supplemental Information S1) was created as week 9's online assignment to link the design of mutants from the wildtype enzyme. Because there was not enough hands-on lab time for the purification of mutant MDH and measurement of enzyme activity, mock kinetics data of mutant MDH were provided for students to practice data analyses and interpretation (Fig. 1b).

2.3 Data collection

2.3.1 Science self-efficacy

A pre-course/post-course survey measures students' belief in their ability to perform research tasks. It includes eight statements (adapted from Ballen, et al. [33]) measured on a point scale ranging from 1 (not confident) to 4 (very confident). The pre-survey and post-survey were administered at the first week of the semester and near the end of the semester before the final presentation, respectively. Pre- and post-course survey scores were compared for each statement.

2.3.2 Knowledge assessment on protein structure–function

We created an assessment that included eight multiple-choice questions to assess students' conceptual understanding of protein structure–function relationships (Supplemental Information S2), a foundational concept area defined by the American Society for Biochemistry and Molecular Biology (ASBMB) [34]. This assessment was administered at the first week of the semester, and near the end of the semester before the final presentation. Pre- and post-course test scores were compared.

2.3.3 Pre-lab quizzes

There was a pre-lab quiz given at the beginning of each in-person lab. Each quiz comprised four questions and had a maximum of four points. These quizzes test general concepts related to biochemical knowledge and skills (Table 2) across the semesters, irrespective of the format of the labs. An example of quiz testing pH, pKa, and titration curve is provided in Supplemental Information S3. Therefore, we compared the average quiz scores of the hCURE in the fall of 2020 to the preceding Fall semester in 2019 and the subsequent Fall semester in 2021 to gauge the impact of hCURE and the pandemic on student learning.

Table 2 Concept areas of the pre-lab quizzes

Topic
pH, pKa, Titration Curve
Beer's Law, Spectrophotometry
Amino Acid Structures
Polymerase Chain Reaction
Restriction Digestion
DNA and Protein Gel Electrophoresis
Protein Purification, Affinity Chromatography
DNA and Protein Quantitation
Gene regulation (*lac* operon)
Enzyme Kinetics

2.4 Data analysis

Wilcoxon signed-rank test was used to compare the pre- and post-course scores for each of the eight science self-efficacy statements because the Likert scale used was categorical. Paired t-test was run for the protein structure–function assessment. One-way ANOVA was used to compare the pre-lab quiz scores between the three semesters (Fall 2019, 2020, 2021), and the Tukey post-hoc test was run to determine the significance of differences between the three semesters. Significance for statistical analysis was set at *$p < 0.05$, ** $p < 0.01$, ***$p < 0.001$.

3 Results

3.1 Science self-efficacy survey outcomes

The science self-efficacy survey measures students' belief in their ability to perform research tasks. Analysis of the pre- and post-course scores of each science self-efficacy statement indicated a significant increase in the post-course scores on six of the eight statements (Table 3). These skills included analyzing scientific primary literature, using molecular visualization program and proposing a hypothesis, performing hands-on experiments, analyzing data, presenting and writing scientific findings. While there was no significant change observed in designing a controlled experiment or using tables and graphs for data presentation, these data suggested that the hCURE was effective in developing student self-efficacy in multiple scientific practices pertaining to biochemistry lab work. Individual scores are attached in Supplemental Information S4.

3.2 Protein structure–function assessment outcomes

Based on the paired t-test analysis on the pre- and post-course scores, there was a significant improvement in students' conceptual understanding of protein structure–function relationships (Fig. 2, $p = 0.0002$), suggesting that the hCURE model was effective in fostering student learning on the foundational biochemical concepts. See Supplemental Information S5 for complete results.

3.3 Comparison of pre-lab quizzes

To further explore the impact of course modality on student conceptual knowledge, we compared the average pre-lab quiz scores across three semesters: Fall 2019 in-person mCURE, Fall 2020 hCURE, and Fall 2021 in-person mCURE post-pandemic. One-way ANOVA identified a significant difference ($p < 0.001$). A Tukey post-hoc test found a notable decrease in quiz scores from Fall 2019 to Fall 2020 (Fig. 3, $p < 0.05$), likely caused by both the pandemic and changes in course modality. Unexpectedly, an even greater decrease was observed in the following year when the class returned to the fully

Table 3 Wilcoxon signed-rank test on the Science Self-Efficacy survey

Statement	Total N	N for Test[†]	*p*-Value (two-tail)
Dissect and understand scientific primary literature	41	19	0.008**
Use primary literature and molecular visualization program to propose a meaningful hypothesis	41	28	0.002**
Design a controlled experiment to test a hypothesis	41	20	0.151
Perform hands-on experimentation to generate usable data	41	20	0.005**
Use tables and graphs to effectively organize and present the results of an experiment	41	17	0.093
Analyze experimental results and discuss the results to the work of others	41	25	0.019**
Present a research project to a broader audience using scientific terminology	41	21	0.004**
Explain the process of a research project in scientific writing	41	24	0.006**

Each of the eight statements was measured on a point scale ranging from 1 (not confident) to 4 (very confident)

[†] The number of students whose pre- and post-course scores were different that was used to calculate the test statistic

** $p < 0.01$

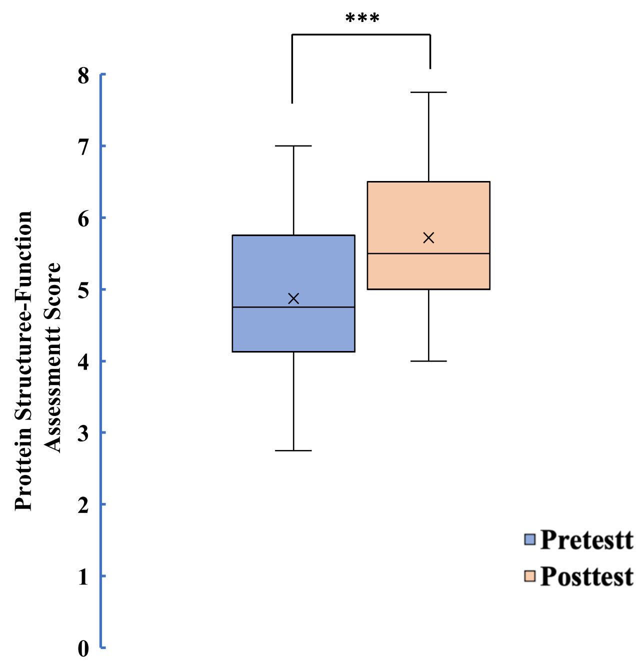

Fig. 2 Comparison of pretest and posttest scores in the protein structure–function assessment. Paired t-test was run to compare student pre- and post-course scores. There was a significant increase in the post-course score. ***$p < 0.001$

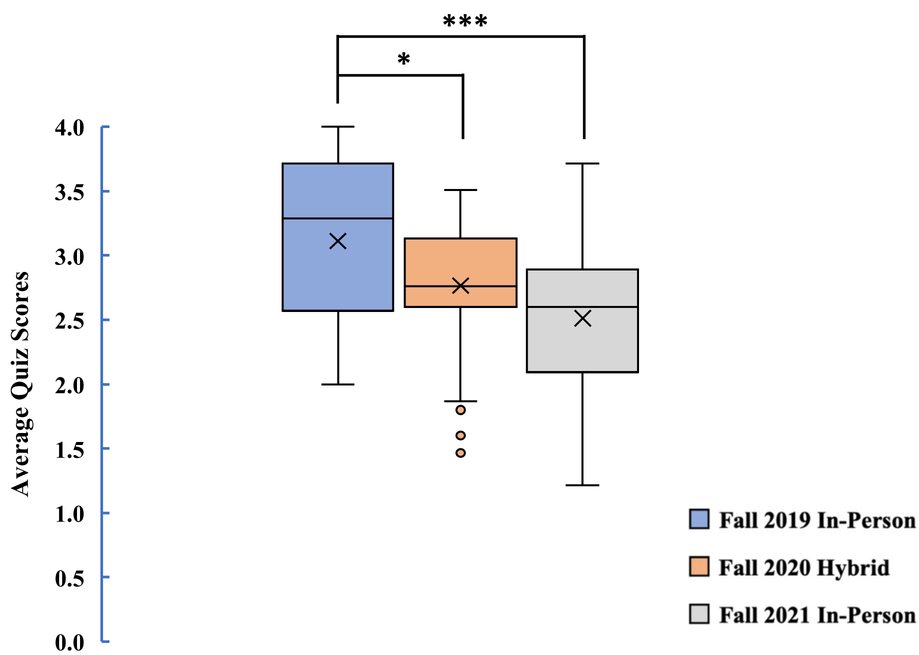

Fig. 3 Comparison of pre-lab quizzes across three semesters in Fall 2019, Fall 2020, and Fall 2021. One-way ANOVA analysis was run to compare the average quiz scores among the three semesters. A Tukey post-hoc test identified a significant decrease in quiz scores from Fall 2019 to Fall 2020, and a further decrease in the Fall 2021 semester. *$p < 0.05$, ***$p < 0.001$

in-person mCURE in Fall 2021 post-COVID ($p < 0.001$), suggesting that the pandemic may have posed a prolonged adverse effect on student learning apart from the impact of lab modality. See Supplemental Information S6 for complete results.

4 Discussion

4.1 Conversion of the original MDH mCURE to an hCURE

While transitioning from in-person to online labs within a constrained timeframe poses substantial challenges, the availability of support from the CURE communities can help alleviate these obstacles [16, 17, 35, 36]. We adapted the materials from MCC [31] and incorporated most of the core CURE elements [6, 32] into the online activities in our hybrid model (Fig. 1b). In comparison to the original fully in-person mCURE, similar levels of discovery and relevance to the broader science community could be achieved by reading primary literature, using bioinformatics tools for hypothesis development, and presenting and discussing project findings via online platforms.

However, a lower level of collaboration was observed in both online and in-person sessions. Because students were required to keep a 6-feet physical distance from the other students in the lab, the teaching assistant (TA) and the instructor, it hindered interpersonal interactions during the hands-on labs. Instead of working in pairs as in the normal time, students had to work individually to avoid close contact, which was particularly challenging for those who did not have prior lab experience. The online labs were designed in an asynchronous format using pre-recorded lectures and required submission of assignments to assess student self-paced learning. Because of the TA and the instructor's limited availability, these online activities were not closely monitored except for the graded assignment, which negatively affected collaboration and teamwork as also observed by other groups [22–24].

In the original mCURE, one week's lab was dedicated to small groups of 2–4 students to meet with the instructor to discuss the research project. These meetings also provided opportunities for the instructor to know students at a personal level. The pandemic presented a marked obstacle to in-person interactions, resulting in removing these meetings from the course design. Nevertheless, these direct interactions with the instructor not only improve student understanding of the project, but also increase student motivation and sense of belonging [37, 38]. If the hybrid format were to be repeated in the future, a potential solution could involve meeting through an online platform that offers greater flexibility in terms of time and location.

4.2 Impact of the hCURE on students' science self-efficacy

Self-efficacy is a person's belief in their ability to achieve a particular goal [39]. Science self-efficacy is a mediator of undergraduate research experience and science identity [40], which has been linked to student persistence in STEM [41, 42].

Students reported a significant increase in six of the eight science self-efficacy statements. One of the greatest improvements was in "Use primary literature and molecular visualization program to propose a meaningful hypothesis" (Table 3). The utilization of primary literature in undergraduate science courses is associated with a range of beneficial outcomes including improved content knowledge [43, 44], data analysis skills [45], critical thinking and experimental design skills [46]. The knowledge and skills acquired may facilitate motivated undergraduates' transitioning to graduate programs [47]. Concurrently, molecular visualization is an effective tool to improve student understanding of protein structure–function relationships, a fundamental concept in biochemistry education [48–50]. For the hypothesis development component, it was critical to visualize the three-dimensional (3D) structure of the protein for students to develop a better understanding of the project. In our hCURE, we used the 3D structure viewer Chimera developed by UCSF researchers [51, 52]. It was probably the first encounter with molecular visualization software for most students, which may account for the significant increase in this self-efficacy statement.

We did not observe a significant change in students' belief in their ability to "Design a controlled experiment to test a hypothesis" or "Use tables and graphs to effectively organize and present the results of an experiment" (Table 3). Students might not be familiar with the concept of a controlled experiment and more opportunities of designing such experiments may help improve their confidence in this area. Likewise, more practice in using tables and graphs may help students master these tools in presenting scientific data.

4.3 The hCURE improved students conceptual understanding of protein structure–function relationships

According to ASBMB standards [34], understanding the structure and function relationship of biomolecules is a core concept that should be included in a biochemistry curriculum. To evaluate student learning in this area, we created a multiple-choice test with five out of the eight questions having two or more correct answers (Supplemental Information S2). This design required students to select all the correct answers to receive full points, thus minimizing the impact of random guessing on the assessment [53]. Our data showed a significant increase in students' post-course scores (Fig. 2), indicating that the hCURE was effective in enhancing student learning in this concept area. However, the increase in the mean score from 4.87 to 5.72 indicated that students answered an average of one more question correctly in the posttest (Supplemental Information S5), which may not reflect the high significance indicated by the statistic ($p < 0.001$). Additional assessment may be required to validate this outcome.

4.4 The COVID-19 pandemic negatively affected student performance on pre-lab quizzes

Despite the fact that the hCURE was designed to closely align with the original mCURE, a notable decrease in quiz scores was identified compared to the Fall 2019 semester prior to the pandemic (Fig. 3). This implied that while the hybrid model improved student science self-efficacy and conceptual knowledge when comparing pre- and post-course scores within the same semester, it did not provide equivalent benefits as the fully in-person model as shown by the quiz scores. Enhancements in implementation, such as coordinating online activities and reintroducing small group meetings with the instructor, may be necessary to reduce the performance gap. To our surprise, a greater decline in quiz scores was observed in Fall 2021 when the lab returned to its fully in-person format, suggesting that the pandemic could have a persisting negative impact on student learning [54]. Hence, the decline in quiz performance could be a combined result of the pandemic and the differences in modality, indicating the need for further investigation.

5 Limitation

The data collected in this study were primarily from a single course during one semester, which limited the evaluation of the impact of the hCURE in comparison to the fully in-person mCURE, except for the analysis of pre-lab quiz scores. Because the design and implementation of the hCURE were conducted within a restricted timeframe, further improvements are necessary, which may require several iterations. Consequently, the student data may not accurately reflect the effectiveness of the hCURE.

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Author contributions JZ directed the project and prepared the manuscript. LZ created the multiple-choice test for structure–function assessment. HK and JZ created the pre-lab quiz assessments. All authors revised the manuscript, approved the version to be published, and agreed to be accountable for all aspects of the work. All authors read and approved the final manuscript.

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Data availability De-identified datasets from this study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval and consent to participate The research protocol was approved by the University of Nebraska—Lincoln Institutional Review Board (IRB) #20583. Informed consents were obtained from all participants or approved by IRB #20583 for using retrospective data.

Competing interests The authors declare no conflicts of interest.

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