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Communication

A Desirable Combination for Undergraduate Chemistry Laboratories: Face-to-Face Teaching with Computer-Aided, Modifiable Program for Grading and Assessment

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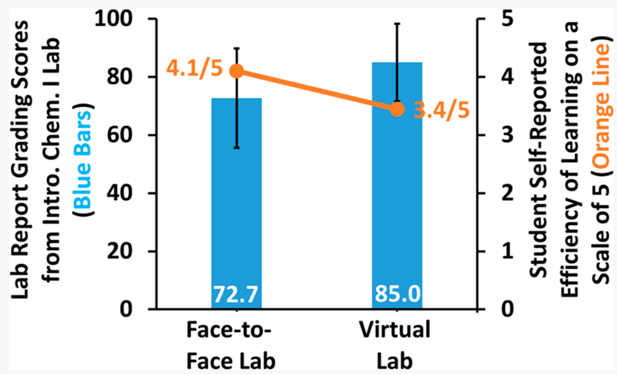
ABSTRACT: The COVID-19 outbreak has altered chemistry laboratory instruction and forced us to reconsider the balance between face-to-face and online teaching. Our students preferred face-to-face teaching (score 4.1/5 on a Likert-like scale) to virtual laboratory exercises (3.4/5) despite the fact that their performance score was actually lower in face-to-face laboratories (72.7/100) than that obtained through online classes (85.0/100) in Introduction Chemistry I Lab. Student performance in virtual biochemistry laboratories in spring 2020 (94.3 ± 1.6/100) was close to that from similar face-to-face exercises done in the fall 2017 (90.4 ± 0.9/100). Students viewed virtual laboratories as more approachable and appeared to master the underlying content better than in face-to-face laboratories although their responses regarding the effectiveness of online teaching were mixed. A combination of face-to-face teaching with a computer-aided, modifiable program for grading and assessment would have a promising future.



KEYWORDS: *First-Year Undergraduate/General, Upper-Division Undergraduate, Laboratory Instruction, Computer-Based Learning, Distance Learning/Self Instruction, Hands-On Learning/Manipulatives, Internet/Web-Based Learning, Reactions*

■ INTRODUCTION

Learning science through virtual laboratories is often perceived as an addition to traditional hands-on experiences, although computer-based simulations and instructions have been practiced for decades.[1−4] Virtual experiments have several advantages over face-to-face laboratories, including lack of safety issues, opportunities for enhanced instruction through visualization technology,[5] and manipulation of variables that are difficult to use in physical experiments to aid conceptual understanding (e.g., electrons, heat, and light).[6] Though the evidence basis for laboratory teaching is still inconclusive,[7,8] the value of physical laboratories is well recognized. The National Science Teaching Association (NSTA) recommends scientific laboratory investigations for all K-16 students.[9] The National Research Council (NRC) discourages the use of computer simulations and teachers' classroom demonstrations as a substitute for physical laboratory investigations.[10] Similarly, the American Chemical Society Committee on Professional Training (ACS-CPT) views laboratory experiences as inquiry-driven and open-ended investigation. ACS-CPT certification requires 400 h of laboratory experiences beyond freshmen chemistry, which may not include virtual or simulated experiences for bachelor's degree programs.[11] In general there is limited research on the advantages and disadvantages of digital platforms for learning chemistry.

The COVID-19 pandemic lockdown ushered in an opportunity for online teaching and learning. On March 11, 2020, the coronavirus outbreak caused all SUNY institutions (over 2 million students from 64 campuses) to cease face-to-face instruction. In the following week, faculty and staff at SUNY Old Westbury, one of the 64 SUNY campuses, were asked to switch from face-to-face to online teaching, including redesign of curricula, selection of online platforms, planning for virtual lectures, sharing data with students for laboratory report writing, attending Blackboard workshops, preparing handouts, writing exams, etc. This unexpected school closure adversely affected students as well in terms of logistics, evacuation from campus, cancellation of events, and concern about meeting academic goals. Such a hasty change forced us to reconsider the balance between face-to-face and online teaching. We herein aim to gather information about the practice of face-to-face and online teaching, from the viewpoints of both instructors and students.

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Table 1. Chemistry Laboratory Exercises in Spring 2020

Laboratories	Introductory Chemistry I Lab	Biochemistry Lab
Face-to-face	Hands-on (5 Laboratories): Experimental Error: Accuracy and Precision,% H_2O in a Hydrated Salt, Empirical Formula, Limiting Reagent, Writing Workshop	Hands-on (5 Laboratories, compared to the same hands-on exercises used in fall 2017): Making Plates and Inoculation, Bacterial Transformation, Protein Purification, SDS-PAGE and Protein Concentration Determination, Western Blotting
Online	Virtual (5 Laboratories): Gas Laws,[15] Reactions in Solution,[15] Calorimetry,[15] Quantitative Analysis,[15] Beer's Law,[12] and Copper Chemistry (Kitchen Lab, see handout in Supporting Information)	Virtual (5 Laboratories, compared to the similar hands-on exercises used in fall 2017): Protein Structure Exploration,[14] Enzyme Kinetics,[13] Equilibrium Study of a Ligand Binding[a], Protein Stability[a], Polymerase Chain Reaction[13]

[a]Instructor-generated data.

INTRODUCTION OF UNDERGRADUATE CHEMISTRY LABORATORIES IN SPRING 2020

Two Introductory Chemistry I Laboratories for freshmen and one Biochemistry Lab for juniors and seniors were involved in this study. Laboratory instruction can be described by two distinct scenarios: face-to-face teaching before, and online teaching after, the COVID-19 outbreak. The virtual laboratories used were selected from various sources, including the University of Colorado PhET site,[12] Biochemistry simulation laboratories from Labster ApS,[13] viewing and manipulation of protein structures from the molecular graphics program Swiss Pdb-Viewer (DeepView),[14] and LearnSmart Lab series from McGraw Hill.[15] The selection of each virtual program is indicated in Table 1. Students submitted laboratory reports within 1 week after completion of face-to-face laboratories. The laboratory report included traditional sections: Objective(s), Introduction, Procedure, Results, Discussion, Conclusion(s), Safety Consideration, and Guiding Questions. A grading rubric was provided to and discussed with students at the beginning of the semester (See rubric in Supporting Information). For online teaching, students had several options. They were able to collect virtual data and submit laboratory reports to the publisher's Web site for automatic grading or use the virtual data to write traditional laboratory reports. Instructors met students at regular class time and held 20−60 min of prelaboratory lecture explaining experiments, answering questions, and demonstrating experimental setups or software operation. Online meetings were conducted using Blackboard Collaborate Ultra, a component of our campus Blackboard Learning Management System. Prior to the shutdown, students used an in-house laboratory manual. Instructions for the newly adopted virtual laboratories were uploaded onto Blackboard in advance (see an example in Supporting Information.). The detailed components of each course involved in this study are given in Table 1. Course assessments were done through student postlaboratory surveys, instructors' observations, and grading of laboratory reports. This research was approved by the institutional review board at SUNY College at Old Westbury. Students enrolled in the NSF-IUSE-supported chemistry laboratory courses voluntarily signed consent forms and anonymously participated in surveys.

ASSESSMENT AND DISCUSSION

Instructors' Evaluation and Student Feedback

McGraw Hill's LearnSmart Lab series engage students through two scenarios: laboratory simulation and conceptual learning that is composed of multiple choice or matching questions. These virtual laboratories allow students to access tutorial help and repeat problems in the core concepts when they experience difficulty. Once students have completed a LearnSmart Lab, a performance report on experimental operation and conceptual mastery is generated for them to view. Instructors can also configure the assignment to allow students to improve their scores at any time before submission. Moreover, we found that many questions had only a few discrete answers, making it easy to choose correctly. We believe that these characteristics contributed to better student performance in virtual laboratories (85.0/100), compared to face-to-face laboratories (72.7/100) in Introductory Chemistry I Lab (blue bars in Figure 1). On average, freshmen spent 1.5 ± 0.8 h on each virtual laboratory as recorded by the computer program, which is consistent with their self-reported weekly study hours spent on this course during the COVID-19 outbreak (Figure 2). In Biochemistry

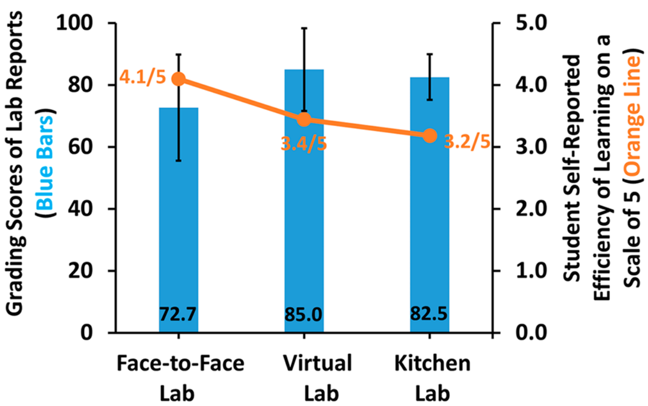

Figure 1. Student performance scores on five face-to-face, five virtual, and one kitchen laboratories (n = 43, blue bars), and student self-reported teaching and learning efficiency from those laboratories, respectively (n = 23) from Introductory Chemistry I Laboratories, spring 2020.

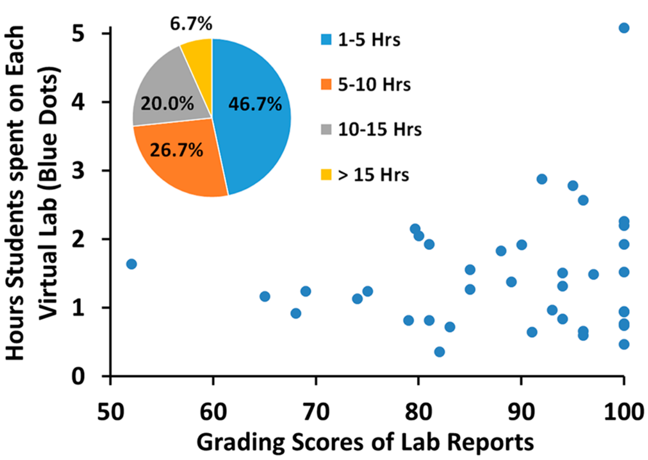

Figure 2. Hours individual students spent on each virtual lab versus score obtained in Introductory Chemistry I Laboratories, spring 2020 (blue dots, n = 16 students × 4 virtual laboratories (reactions in solution, gas law, calorimetry, and lab skills) = 64; (inset) student self-estimated weekly study hours spent on this class.

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Lab, the grading score from four virtual laboratories (Protein Structure Exploration, Enzyme Kinetics, Equilibrium Study of a Ligand Binding, and Protein Stability) done in spring 2020 (94.3 ± 1.6/100, n = 10 students × 4 laboratories = 40) was only slightly higher than that from similar face-to-face exercises completed in fall 2017 (90.4 ± 0.9/100, n = 12 students × 4 laboratories = 48). However, considering enhanced performance by 7.4% over the past two years (87.8 ± 5.3/100 in fall 2017 with n = 12 students × 5 laboratories = 60 and 94.6 ± 1.7/100 in spring 2020 with n = 10 students × 5 laboratories = 50 on the same five hands-on laboratories listed in Table 1), we would conclude that there was not much difference in grading scores between face-to-face and virtual laboratories in Biochemistry Lab.

To examine how instructors' grading relates to students' view of the effectiveness of teaching and learning, the following three postcourse survey questions were asked of freshmen on a scale of 1 to 5, with 5 being the most: (1) Please rate how efficient was face to face teaching in chemistry laboratories; (2) Please rate how efficient was virtual laboratory exercises using software; and (3) Please rate how efficient was learning through kitchen chemistry laboratory. Students rated the efficiency to be 4.1/5 for face-to-face teaching, 3.4/5 for virtual exercises, and 3.2/5 for kitchen laboratory (orange line in Figure 1). It is interesting to learn that undergraduates enrolled in Introductory Chemistry I Lab valued face-to-face teaching the most despite the fact that their grades (72.7/100) were actually lower than those obtained via online teaching (85.0/100 for virtual laboratories and 82.5/100 for kitchen laboratory in Figure 1), showing that scores were not their only consideration when evaluating teaching and learning. It is worth noting that the actual exercises in virtual laboratories are quite different from those in face to face laboratories. Our intention was to understand student perspectives toward the two pedagogical approaches, which should not be considered as a robust comparison of student performance. Written comments from students revealed some details for their preference of face-to-face teaching. Students identified various reasons, including learning to use real equipment, being able to use the library at school, closer interaction with instructors and peers for questions, and absence of internet or software issues. Their responses regarding online teaching were mixed. Some commented that virtual laboratories were really helpful in teaching content, and were much clearer and simpler to understand; while others thought it was extremely difficult to achieve 100% mastery even with multiple attempts, and were frustrated with bugs and software glitches. Similarly, varied postcourse responses were obtained about the kitchen copper chemistry laboratory. Some students enjoyed doing experiments at home with family members around, while others were concerned about acquiring suitable supplies, experimental errors, independence, and less safety protection. It is worth noting that these empirical observations are based upon a single kitchen chemistry laboratory and should not be used as a comprehensive assessment about kitchen chemistry experiments. For juniors and seniors enrolled in Biochemistry Lab (n = 10), 67% of students were extremely satisfied with the remote learning experience, while 33% were neutral when being asked about their experience with virtual laboratories. Compared to face-to-face teaching, the majority of students in biochemistry laboratory rated virtual laboratories extremely effective (17%) or somewhat effective (50%) while others not so effective (33%). Correspondingly, widespread reactions were seen when asking "In your opinion, which teaching method is more efficient for lectures?" Face-to-face teaching was ranked at the top by a majority of freshmen (66.7%), while 13.3% preferred online teaching through Blackboard Collaborate Ultra and 20% favored a combination of both methods

We also sought students' suggestions for teaching and learning should the COVID-19 situation continue in the Fall 2020 semester. Their responses were surprisingly congruent with instructors' thoughts. For instance, students preferred that their own instructors were involved with virtual experiments, while faculty-created videos in a real laboratory setting are currently under discussion in our department. An excerpt from student responses describes well the experiences our faculty heard, as reported in a "Lessons Learned" meeting held after the close of the semester: "If this pandemic continues into the fall semester, my biggest advice to professors would be to have patience with their students. Many students at Old Westbury share devices with their family members, are continuing to work, and have become teachers to their children while working and finishing their degree. Because of this they may need to have extra time on assignments and other course materials."

Pros and Cons of Teaching Chemistry Laboratories Online

Some virtual chemistry laboratories (e.g., McGraw Hill's LearnSmart series) include an automatic grading function, allowing students to closely monitor and improve their performance. Such an automatic grading system also makes the itemized assessment of key concepts easy and efficient, thus releasing instructors from tedious grading, and allowing them to spend more time on valuable work. Many instructors had been reluctant to use technology in the classroom due to lack of digital expertise, frustration in troubleshooting, and limited availability of appropriate experiments and equipment. It is even more challenging to use digital technology in chemistry laboratories, where hands-on experiments are expected. This situation, however, has been changed by the COVID-19 pandemic. We all must now adopt alternative instructional modalities, which involves more than simply selecting a new device. When we manage to overcome our hesitation toward distance teaching, we also better understand our abilities as well as students' in handling complex circumstances, thus improving curriculum design in the future. In addition, virtual laboratories can always be used as a substitute for "institutions facing disruptions to their normal course offerings"[16] such as those caused by Hurricane Florence,[17] or now by the COVID-19 crisis. It goes without saying that virtual laboratories offer benefits in safety outcomes and cost of supplies.

Our findings are consistent with those of others who conducted more extensive comparisons of virtual and face-to-face laboratories. Grove and co-workers compared hybrid laboratory teaching to the traditional one with one group using both face to face and McGraw Hill's LearnSmart Laboratories, while others experienced only traditional face-to-face teaching.[16] They observed the development in students' cognitive and psychomotor skills but an affective decline toward chemistry with hybrid teaching in General Chemistry I laboratory. By using the ACS online laboratory assessment, the Meaningful Learning in the Laboratory Instrument, and instructors' grading, they found that replacing half of the face-to-face experiments with corresponding virtual laboratories did not have a negative impact on students' cognitive understanding of acid/base chemistry, calorimetry, or stoichiometry. Students in the hybrid laboratory, however, reported significantly higher expectations of being confused or frustrated by their work and felt that the material they were learning would be less useful in their daily lives. Barbera et al. assessed affective differences between a McGraw Hill's LearnSmart and a traditional Beer's Law laboratory focusing on students' anxiety, attitude, and interests.[18] They found that students in the virtual laboratory demonstrated significantly higher anxiety and more negative sentiments about affective aspects, including "emotional satisfaction, intellectual accessibility, usefulness of the lab, and equipment usability for the virtual students." They also concluded that the affective outcomes could be influenced much more by the instructor than by the environment in which the experiment was performed.

Chemistry is an experimental science. A potential drawback with training merely based on virtual laboratories is that students are deprived of hands-on skills in college. In virtual laboratories, they do not learn how to set up an apparatus for heating, how to adjust instruments, how to wash and handle glassware, how to transfer solutions with a pipet, how to lift, wash, and wipe a pH electrode, where to dispose of chemical wastes and when goggles and gloves must be worn, etc. With the few choices of data offered by the virtual laboratory platforms we used, all experimental errors are simply ignored, which is far different from real laboratory practice.

CONCLUSIONS

COVID-19 has altered chemistry laboratory instruction in unforeseen ways. Faculty and staff at SUNY Old Westbury went through this challenge and learned how to strike a balance between face-to-face and online teaching. While it is clear that chemistry majors need authentic laboratory experiences if they are to gain the knowledge and skills to participate in the profession, our experience with virtual laboratories did have a positive side including efficient grading and assessment for instructors and explicit training for students. In addition, both instructors and students benefitted by acquiring digital skills using these laboratories. Students viewed virtual laboratories as more approachable and appeared to master the underlying content as well as or better than in face-to-face laboratories although more negative responses were received from freshmen. It would be desirable to combine face-to-face teaching with a computer-aided, modifiable program for grading and assessment.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.0c00634.

- Grading rubric (PDF)
- Student handouts for virtual laboratory of calorimetry (PDF)
- Student handouts for the virtual copper chemistry kitchen laboratory (PDF)
- Instructor notes for the virtual copper chemistry kitchen laboratory (PDF)

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Notes

The authors declare no competing financial interest.

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