| Ref. | Cohort Comparison | Activity Comparison | Sample | Context | Performance Evidence | Performance Results | Competency Evidence | Competency Results | Engagement Evidence | Engagement Results |
|------|------------------|---------------------|--------|---------|----------------------|--------------------|------------------|------------------|--------------------|--------------------|
| 56   | Same             | At-school vs. at-home hands-on labs | Preservice teacher training in nonmajors general chemistry with 20 students at California State Polytechnic University-Pomona, USA during Spring 2020 | Students did a series of simple at-home, hands-on kitchen labs and follow-up creative assignments which built on the lab results. The course's core experimental learning objectives appeared unchanged. | Lab grades before vs. during remote learning in that semester. Grades dropped a little but not by much. Quality of lab assignments. Students interpreted data correctly. Instructor believed hands-on labs are valuable for student learning. | Most students continued submitting assignments. Students reported that, with more heads-up, they could have obtained all the materials and done the labs. |
| 35   | Same             | At-school vs. at-home hands-on labs | Introductory high school organic chemistry with 7 students at the University of Chicago Laboratory Schools, USA during Fall 2020 | Students used a DIY lab kit made by the instructor to complete several hands-on labs at home with a mix of laboratory supplies and household materials. | Quality of lab work. Students mostly successfully executed the experiments and appeared to learn the desired information. They could accurately predict outcomes of procedures, interpret results, and troubleshoot experiments. | Student feedback via non-anonymous mid-semester and end-of-semester surveys (86% response rate for each) and exit interviews. Parent feedback during Parent-Teacher Conferences. Students and parents were happy to have hands-on labs to end the course. Students valued the labs and saw nuances between what the lab and the lecture contributed to their learning. Students mostly reported preferring hands-on labs over other popular alternatives. |
| 34   | Same             | At-school vs. at-home hands-on labs AND Hands-on labs vs. videos | Introductory high school general chemistry with 59 students in 3 class sections at the University of Chicago Laboratory Schools, USA during Spring 2020 | Students did (1) a lab at school before closure and then analysis at home, (2) a classroom lab at home with school-provided supplies, and (3) a kitchen lab at home with home supplies. Students had the option of doing a parallel video-based alternative assignment instead of the hands-on, wet labs, but all students answered the same post-lab questions. The lecture component did not differ much other than the new remote modality. Averages and standard deviations for lab assignment grades between (1) hands-on vs. video groups and (2) different labs. Completing the labs (vs. the video alternative) appeared to result in better grades for lab assignments; hands-on lab grades were comparable to earlier in the semester. The standard deviation for the video alternative assignments was much higher than for the labs. Indicating a possible performance gap between strong and weak students who did the video alternative. Student feedback from multiple anonymous and non-anonymous surveys (65%, 81%, and 85% response rates) and class discussions in focus group format. Students commented that it helped them to learn with their hands. Submission rates of hands-on-lab vs. alternative video assignments. Supply distribution of lab materials. Historical grade distribution of students who chose hands-on vs. video assignments. Student feedback from multiple anonymous and non-anonymous surveys (response rates and class discussions in focus group format). Lack of supplies appeared to drive student selection to do the alternative video assignment more than student choice did. Labs appeared to be viewed favorably and boosted morale. At-risk students were more likely to not complete the lab and to do the video assignment instead. Students and instructor reported pros and cons of at-home, hands-on labs, but the positives outweighed the negatives for both students and instructor. |
| 48   | Same             | At-school vs. at-home hands-on labs AND At-school hands-on labs vs. at-home videos | IT Academy Project with 20 middle and high school general chemistry teachers at different institutions and 78 of their students in Slovakia during Fall 2020 | Teachers had been receiving training on using data logging equipment for inquiry-based experiments. Most teachers implemented their training during remote learning but made different decisions as to how to do labs in remote learning. 10 teachers showed pictures with captions, 11 showed videos, 10 did live demos, and 11 had students conduct at-home, hands-on experiments. Teacher feedback on non-anonymous survey. Student feedback on anonymous survey paired with teacher (average 13 students per teacher responded for 17 teachers) Teachers felt that experiments increased student interest but did not make up for personal contact with students. 26% of students disliked remote learning, but 84% preferred working at home. 46% said that experiments were what they missed most about in-person learning. 100% of the students who did hands-on, at-home labs reported missing experiments whereas 34% of students who didn’t do labs reported missing labs (presumed that the absence of labs during remote learning made them think less about doing the labs). 10% did not like online experimentation due to lower “coolness” relative to in-person labs. 38% missed interacting with teachers and classmates. Teacher feedback on non-anonymous survey. Student feedback on anonymous survey paired with teacher (average 13 students per teacher responded for 17 teachers) Teachers felt that experiments increased student interest but did not make up for personal contact with students. 26% of students disliked remote learning, but 84% preferred working at home. 46% said that experiments were what they missed most about in-person learning. 100% of the students who did hands-on, at-home labs reported missing experiments whereas 34% of students who didn’t do labs reported missing labs (presumed that the absence of labs during remote learning made them think less about doing the labs). 10% did not like online experimentation due to lower “coolness” relative to in-person labs. 38% missed interacting with teachers and classmates. |
| 59   | Same             | At-school hands-on lab proposals vs. at-home hands-on labs | Introductory undergraduate food chemistry course at the College of the Ozarks, USA during Spring 2020 | Students had learned the course content knowledge and proposed two experimental projects each before the transition. The instructor developed three at-home, hands-on labs for students to do instead, or the students could develop their own at-home procedures. Each student did two labs of their choice. Student notebooks. Student-instructor email correspondence. Students actively worked on their projects and frequently contacted the instructor to troubleshoot experimental issues. Students generated creative projects and procedures instead of just following the provided procedures. Perceived student attitude. The instructor reflected that students appeared interested and invested in their projects. | | |
| 72 | Same | At-school hands-on labs vs. remote control of hands-on labs | Introductory noncredit optional supplemental high school course for 17 students at Sekolah Pelita Harapan School, Indonesia through Covenant College, USA during Summer 2020 | The instructor did any wet benchwork live during the class while student volunteers used their computers to control the instructor's computer and run software programs to operate instruments. | Background survey after day 1 (100% response rate). Attendance records. End-of-course survey (response rate unspecified). | A third of the students had not taken chemistry before. Students valued taking real-time measurements using the remote sensors and seeing the data appear as it was collected. 98% attendance rate was excellent, possibly due to attendance requirements for receiving the financial deposit back afterward. Students enjoyed the course and felt it increased their interest in chemistry. Students were fascinated by the ability to run experiments remotely. Students did not feel lost during the class sessions and felt that their connection to collecting the data was important. Students also reported that they felt more involved and interested when their peers were collecting the data rather than when an instructor collects data. |
| 46 | Same | At-home mobile app vs. hands-on dry simulation | Upper-level undergraduate materials science course with 23 students at the Hochschule Bremen–City University of Applied Sciences, Germany during Spring 2020 | Students investigated the structures of metals using a smartphone AR mobile app and manually building mock unit cells from table tennis balls at home. Pre/post-quiz grades. Students performed statistically significantly better on quiz questions at the end of the lab than before. | Student feedback on anonymous survey at end of lab (74% response rate). | Students were evenly split as to whether the app helped them build the models. Only 9 students agreed that using the app helped them understand the concept, although 13 students agreed that building the model helped (remainder were neutral or disagreed). Only 7 students felt the hands-on activity helped them do better on the quiz, and only 8 students felt the app helped (remainder were neutral or disagreed). Students overwhelmingly agreed that the app was easy to use and cited visualization and interaction as the most important features for AR. Student feedback on anonymous survey at end of lab (74% response rate). | Students expressed gratefulness for and enjoyment of the hands-on activity. |
| 118 | Same | At-school hands-on labs vs. at-home modeling | Upper-level undergraduate biochemistry course with 56 students, graduate bioinformatics course with 15 students, and summer high school course with 24 students at Kean University, USA during Spring | After the transition, all labs were remote as students conducted bioinformatics analyses and modeling of the COVID-19 virus. Grades for the activities in the undergraduate course. The activity grades were considered satisfactory. | Student feedback (methods unspecified). | Students reported favorably on the experience, and several high school students expressed interest in minoring in Bioinformatics in the future. Students overwhelmingly agreed that the at-home labs gave the greatest educational growth compared to remote. Students overwhelmingly felt that in-person labs gave the greatest emotional satisfaction whereas remote labs gave the greatest anxiety. |
| 78 | Same | At-school hands-on labs vs. at-home videos, simulations, data | Introductory undergraduate general chemistry course with 26 students in 2 class sections at St. John’s University, USA during Spring 2020 | Before the transition, student groups planned their own experiments but, after the transition, collected data through simulations and experimental videos. The final course project challenged students to address how science could be used to address COVID-19 social issues. Student feedback after end of course (38% response rate). | Student feedback after end of course (38% response rate). | Students were either neutral or agreed somewhat that the simulations and activities during remote learning were effective at promoting their learning. Students overwhelmingly felt that in-person labs gave greater educational growth compared to remote. Students overwhelmingly felt that in-person labs gave the greatest emotional satisfaction whereas remote labs gave the greatest anxiety. |
| Reference | As-school hands-on labs vs. at-home videos, simulations, data | Department of Chemistry faculty and their undergraduate students in various chemistry courses at Davidson College, USA during Spring 2020 | The department faculty surveyed students to inform how they would transition to remote learning, and each faculty member did something different with their course. However, none of them made at-home, hands-on labs, instead focusing on the thought process of experimentation. Students read procedures, watched videos, attended lab lectures about techniques or theory, recorded observations, analyzed sample data, did computational and thought experiments, used modeling, and/or wrote reports. | Quality of student work in class. Synchronous lab sessions seemed to help students conduct data analysis. | Student feedback on surveys from multiple courses (methods unspecified). Attendance records. Peer tutor feedback from informal conversations. Students responded negatively to asynchronous lab work. Students enjoyed the creative remote lab assignments but still missed hands-on labs. |
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| Same | As-school hands-on labs vs. at-home videos, simulations, data | Introductory undergraduate nonmajors general biochemistry course with 73 students in 4 class sections at New York University, USA during Spring 2020 | Four f2f labs into were adapted into remote group activities, and two virus-related activities were added. Students watched experimental videos, did simulations, collected and analyzed simulated data, watched and wrote about a documentary, and analyzed genome sequencing data. Students who lived outside the New York time zone were permitted to do asynchronous work instead of synchronous. | Student feedback on anonymous end-of-semester survey (91.8 % response rate). Each remote activity was rated as useful for learning by a majority of students, and ratings were consistent across the activities. | Attendance records. Student survey about time zones. Student feedback on anonymous end-of-semester survey (91.8 % response rate). 71 % of students outside the New York time zone chose to participate in the optional-for-them synchronous group lab activities. Students preferred the virus-related documentary and genome sequencing activity the most. Students commented that they preferred hands-on labs to remote but also appreciated the structure and content of the remote labs. |
| Same | As-school hands-on labs vs. at-home videos, simulations, data | Upper-level undergraduate/graduate biopharmaceuticals course with 73 students at Columbia University, USA during Spring 2020 | Student groups had completed 3 of 8 lab modules (different from other groups due to a rotation schedule) before closure. 12 f labs were replaced with fully virtual exercises: modeling, simulations, experimental videos and photographs, literature reviews, additional lecture, and analyzing shared student data from groups who had completed other modules. Students completed different tasks depending on which modules they had to finish. Grades of (1) individual prelab quizzes and (2) formal group lab reports from before vs. during remote learning in that semester. | Performance on quizzes and lab reports were consistent with earlier in the semester. Quality of lab reports - The quality of data interpretation in lab reports suggests that students struggled with handling and understanding the data that they did not collect. | - |
| Same | As-school hands-on labs vs. at-home videos, simulations, data | Introductory undergraduate analytical chemistry course at Lander University, USA during Spring 2020 | For 2 labs, students watched experimental videos and were provided with sample data from past students to analyze for lab reports. For the next 2 labs, students did simulations and gathered simulated data to analyze. | Student-instructor discussions. Students appeared confused about the data, where it came from, what it meant, and how to analyze it when simply provided with it; students did not appear as confused for the simulated data. | Student feedback on survey (response rate unspecified). Students said the simulation “helped build their experimental design skills and that mistakes had fewer consequences than they would have had in the real world. Students also learned that statistical analysis of data is important. The most common miscomprehensions related to how enzymes work and the relationship to the data. |
| Same | As-school hands-on lab vs. at-home simulations, data | Introductory undergraduate biochemistry course with 180 students at the University of Oxford, UK during Spring 2020 | Students completed a Michaelis-Menten enzyme kinetics simulation instead of the corresponding hands-on lab. Students planned and conducted their simulated experiment, gathered data, and generated conclusions about their assigned enzyme. | Student feedback on survey (response rate unspecified). Quality of assignment responses. | Student feedback on survey (response rate unspecified). Students responded negatively on the simulation, saying that it was enjoyable. |
| Same | As-school hands-on labs vs. at-home simulations, data | Introductory undergraduate biochemistry course with 96 students at the University of South Australia, Australia during Spring 2020 | 60 of 96 students had already completed 2 of the 3 labs before the transition. Students were provided with 5 simulations and sample data to analyze to complete worksheets. Before the semester ended, restrictions were eased so that students could choose to come in to school to do hands-on labs. Worksheet grade averages and standard deviations for the first and second labs. | There was very little difference between the worksheet grades for the f2f vs. simulation students. | Optional hands-on lab attendance. Student feedback (methods unspecified). 12 students choose to come in to do hands-on labs. Students appeared to highly value getting the chance to do hands-on work. |
| Same | As-school hands-on labs vs. at-home simulations, data | Introductory undergraduate organic chemistry course with 24 students at Alfred University, USA during Spring 2020 | Students had completed their standard labs at school and were planning a final research project. Instead of doing the project, students did five-stick through "Choose Your Own Adventure" games to virtually conduct a set of standard experiments. The games featured safety, preparation, choosing proper steps, handling mistakes, and receiving data to analyze. | Simulation statistics, including number of clicks, time stamps, and selected answers. Student reflection responses | Students appeared to repeatedly make the same errors both within and across labventures and struggled to determine how to fix mistakes. Students very rarely completed a labventure in the optimal decision pathway. Students appeared to overwhelmingly struggle with making proper experimental decisions (such as deciding in what order to do steps and which analytical techniques to use) and interpreting data/observations provided. |
| Same | As-school hands-on labs vs. at-home simulations, data | Introductory undergraduate general chemistry course with 131 students at Rice University, USA during unspecified semester (presumably Spring 2020) | Students completed a prelab quiz, watched lecture and experimental videos, and made procedural decisions that led to new experimental videos showing the expected results stemming from those decisions. Pre/post-test (reduced number of answer options and different grading policies between the pretest and post test). Students' scores improved dramatically after the virtual lab. |  |
| Same | As-school hands-on labs vs. at-home simulations, data | Cross-disciplinary students used multiple simulations of analytical techniques, kept lab notebooks, and conducted data analysis in synchronous class sessions. |  |
| Same | As-school hands-on labs vs. at-home simulations, data | Upperlevel undergraduate forensic biochemistry/analytical chemistry course with 56 students at Sheffield Hallam University, UK |  |
| Same | As-school hands-on labs vs. at-home simulations, data | Upperlevel undergraduate forensic biochemistry course in the spring and an upperlevel undergraduate forensic biochemistry course and upperlevel graduate forensic biology course in the fall at Towson University, USA during Spring and Fall 2020 | Students were given pre-recorded lectures in a flipped classroom model. In the spring, students watched experimental videos, made observations, wrote reports, and analyzed a mock case using a decision-dependent PowerPoint. In the fall, most students were in person, but a few were remote. All students continued in the flipped classroom model, but in-person students conducted hands-on labs when at school. Remote students analyzed pictures and data from the experiment. Students used simulations for several labs, interacted with a live-stream video for one lab to direct the instructor's actions (if remote - in person students did the lab themselves), and reported the results in a final paper and a mock criminal trial. | Quality of lab notebooks. The quality of lab notebooks was comparable between the F2F and the remote students in the fall, although there were very few remote students to compare. |  |
| Same | As-school hands-on labs vs. at-home simulations, data | Upper-level undergraduate experimental physical chemistry with 95 students in 5 class sections at Pennsylvania State University, USA during Spring 2020 | After 7 F2F labs before closure, 3 remaining labs were replaced with short experimental videos, lectures connecting theory with data, prelab quizzes, graded notes, graded during-lab questions, and raw sample data to analyze. Students answered questions and wrote reports based on the provided data. The end-of-semester research projects were eliminated. Paired sample t test comparison of lab report grades before vs. during remote learning in that semester. | Quality of lab reports. Students did not fully understand the experiments. They copied mistakes out of the lab manual, even when the experiment in the video differed from the manual. |  |
| Same | 50 | At-school hands-on labs and at-home videos, data |
|------|----|------------------------------------------------|
| Introductory undergraduate analytical chemistry course with 51 students in 3 class sections at Ohio State University, USA during Spring 2020 |
| Students did 2 remote labs and were given notebook pages which included sample data and details about the procedural set-up. They watched explanatory prelab videos and completed prelab quizzes. They wrote a lab report for the first lab but, based on student feedback, did a short answer-style assignment focused on data analysis and discussions for the second lab. |
| Grades for both labs and a t-test analysis |
| Students performed better on the short answer-style assignment than the lab report. |
| Student feedback mid-semester survey (21 % response rate). |
| 90 % of 11 respondents preferred the short answer assignment over the lab report, and 7 either said the short answer was easier for them or didn’t provide a comment about its difficulty. Students commented that the procedure, analyzing the data, considering sources of error, and writing the lab report to be very challenging without having conducted the experiment themselves. Students suggested using more experimental videos in future remote iterations, but some comments emphasized that students believe labs could never be effectively taught remotely. |

| Same | 84 | At-school hands-on labs vs. at-home videos, data |
|------|----|------------------------------------------------|
| Introductory undergraduate analytical chemistry courses with 188 students in 2 class sections and for food science careers with 118 students at Complutense University, Spain during Spring 2020 |
| The pharmacy students had completed all labs already, but the food science students had not and so did four labs during remote learning (except the students repeating the food science course). These students read procedures, watched experimental videos, attended lectures, and were assigned more homework. Students received sample data, answered questions, and gave presentations about the data. |
| Grades on post-lab discussion questions between class sections |
| Students did well overall on answering the post-lab questions, although there was noticeable differences in performance between sections. |
| Quality of post-lab discussion question responses. Student feedback from post-lab survey (response rate unspecified). |
| Students felt that the virtual lab and resources helped improve their understanding of polymer chemistry, which they were previously unfamiliar with. Students met expectations for answering conceptual, reasoning, and calculation questions but showed some difficulty in interpreting the UV-Vis spectra for the experiment, although they had learned about UV-Vis analysis and Beer’s Law. |
| Student feedback from post-lab survey (response rate unspecified). |
| Students reported positively on the virtual lab experience. Several students comments indicated that they fall in was cool to watch the experiment video. They were interested in the real-life applicability of polymers and looked forward to doing similar hands-on labs in the future. Students liked being in breakout rooms with peers and TAs to answer the questions. |

| Same | 86 | At-school hands-on labs vs. at-home videos, data |
|------|----|------------------------------------------------|
| Introductory undergraduate general chemistry course with 88 students in 2 class sections at Missouri University of Science and Technology, USA during Spring 2020 |
| Students watched synchronous, live-streamed videos of the instructor doing the labs without any editing and including any mistakes that may have occurred naturally. Students made observations, recorded data, and worked with peers on data analysis. Attendance was incorporated into the overall grade. |
| Grades on post-lab discussion questions between class sections |
| Students did well overall on answering the post-lab questions, although there was noticeable differences in performance between sections. |
| Quality of post-lab discussion question responses. Student feedback from post-lab survey (response rate unspecified). |
| Students felt that the virtual lab and resources helped improve their understanding of polymer chemistry, which they were previously unfamiliar with. Students met expectations for answering conceptual, reasoning, and calculation questions but showed some difficulty in interpreting the UV-Vis spectra for the experiment, although they had learned about UV-Vis analysis and Beer’s Law. |
| Student feedback from post-lab survey (response rate unspecified). |
| Some students commented that the labs were well-done despite the occasional video blurriness but that the videos did not substitute for hands-on labs in training chemists. Many students did not appear to continue paying attention to the class session after checking in for attendance. |

| Same | 108 | At-school hands-on labs vs. at-home videos, data |
|------|----|------------------------------------------------|
| Introductory undergraduate honors general chemistry course with 128 students in 7 class sections at Duke University, USA during Fall 2020 |
| Near the end of the semester, students were given prelab resources and watched a pre-recorded video of a polymer lab experiment. Students used observations, data, and a published article to answer post-lab questions. |
| Grades on post-lab discussion questions between class sections |
| Students did well overall on answering the post-lab questions, although there was noticeable differences in performance between sections. |
| Quality of post-lab discussion question responses. Student feedback from post-lab survey (response rate unspecified). |
| Students felt that the virtual lab and resources helped improve their understanding of polymer chemistry, which they were previously unfamiliar with. Students met expectations for answering conceptual, reasoning, and calculation questions but showed some difficulty in interpreting the UV-Vis spectra for the experiment, although they had learned about UV-Vis analysis and Beer’s Law. |
| Student feedback from post-lab survey (response rate unspecified). |
| Students reported positively on the virtual lab experience. Several students comments indicated that they fall in was cool to watch the experiment video. They were interested in the real-life applicability of polymers and looked forward to doing similar hands-on labs in the future. Students liked being in breakout rooms with peers and TAs to answer the questions. |
| 97 | Same | At-school hands-on labs vs. at-home videos, data, literature reviews and readings | Upper-level undergraduate chemical engineering courses with 104 students and 20 instructors at the National Institute of Science and Technology of Toulouse, France during Spring 2020 | At first, instructors sent students class materials to read ahead, then later sent videos of lectures, then later sent audio-commented slideshows, then later hosted virtual class meetings. For labs, students worked in small groups on literature reviews, data analysis of existing or sample data, and/or unspecified projects. Some labs were abandoned. | Student feedback on end-of-semester survey (85% response rate). | Student feedback on end-of-semester survey (85% response rate). | Students did not like solely teaching materials, considered an instructor more beneficial, and felt that synchronous classes were helpful with live Q&A. Students reported that the personal interaction with live sessions was helpful and encouraged them to stay at the session. Motivation and participation in groupwork were felt to be unequal. Students appeared to feel more positively about short-term, low-stakes groupwork than larger projects. Some students were frustrated to not do hands-on labs whereas others appreciated the greater emphasis on theory. 33.3% students agreed with cancelling some labs, 31.1% were neutral, and 29.6% disagreed. Students felt that trying to continue labs was exhausting and time consuming, even without experiments. |
| 71 | Same | At-school hands-on labs vs. at-home videos, data, procedure writing | Introductory undergraduate organic chemistry CUREs (7 students) with 3 instructors at the University of New England, USA during Spring 2020 | The organic chemistry students had reviewed literature and finished their first research project; the second experimental project was replaced with an instructor-selected research question. Students revised the question as a class, designed experiments for the instructor to run, watched the instructor’s filmed videos of their designed experiments, analyzed the data, presented posters, and did peer review. | Student feedback on surveys (methods unspecified). | Student feedback on surveys (methods unspecified). | Students reported various types of frustrations surrounding not being able to do their own experiments at school. Many of the students and instructors were burnt out by the end of the semester. |
| 106 | Same | At-school hands-on labs vs. at-home data | Upper-level undergraduate biochemistry course with 12 students at College of St. Benedict/St. John’s University, USA during Spring 2020 | Students watched prelab videos and analyzed real and simulated ELISA data. | Pre/post-lab quiz grades (before vs. end of semester). | Student feedback on surveys (methods unspecified). | Students self-reported that they understood chemical principles and the steps of the ELISA afterward but struggled with the math. |
| 128 | Same | At-school hands-on lab vs. at-home data, presentations | Introductory undergraduate analytical chemistry course with 87 students in 5 class sections at the University of Wisconsin – Madison, USA during Spring 2020 | Students performed an extraction and analyzed data via HPLC for a project before the transition. The second experimental portion of the project was replaced with a more in-depth statistical analysis of the class’s pooled data. Groups presented their results orally and provided peer feedback. | Student feedback on end-of-semester survey (response rate unspecified). | Student feedback on end-of-semester survey (response rate unspecified). | Students liked that the remote activities related to their previous work in the project. Some students liked determining their group’s work schedule. Students appeared connected to their groups. The majority of students enjoyed the project, were satisfied with their group members, and felt they accomplished their goals. |
| ID | Same | A-school hands-on labs vs. at-home literature reviews, data presentations | Upper-level undergraduate synthetic chemistry course with 16 students at Georgia Gwinnett College, USA during Spring 2020 | Students were conducting experiments to modify literature reactions before the transition. Further experimentation was abandoned, and students instead attended mini-lectures, searched literature, and completed guided-inquiry assignments. Students analyzed data they collected earlier in the semester and data from published sources to evaluate environmental impacts and lifecycles. Students kept notebooks, wrote papers, and made a poster. | Student feedback at start of remote learning (methods unspecified) and on end-of-semester survey (56.3 % response rate) and final exam questions. | Groups did not appear to communicate well with each other. Students struggled to write lab reports for their incomplete projects, make predictions about experiments, and make assumptions from literature precedents. | Attendance rate. Estimated in-class participation rate. Student feedback at start of remote learning (methods unspecified) and on end-of-semester survey (56.3 % response rate) and final exam questions. | 91 % of students attended class. 50 % participated in class by speaking or using the chat box, but students did not turn on their video. Students wished they could have completed their experiments, but they still reported positive experiences with the course overall. |
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| 127 | Same | A-school hands-on labs vs. at-home literature reviews, data, procedure writing, outreach | Upper-level undergraduate biochemistry course at Southwestern University, USA during Spring 2020 | Students had already completed technique-building labs, reviewed literature, and generated a research project hypothesis in small groups. The hands-on lab projects were then replaced with more literature reviews, investigating methods, proposed a protocol for solving a presented research question, and orally presented their final protocol. Students generated publication-level figures from data and analyzed raw sample data provided from original research. Students made public outreach projects related to the pandemic. | Student feedback (methods unspecified). | The instructor reported that students indicated they learned a lot during remote learning. | Student feedback (methods unspecified). Student self-reflection assignment. | The instructor reported that students showed increased levels of pride and confidence in their ideas. Students reported enjoying the public outreach project. |
| 130 | Same | A-school hands-on lab vs. at-home literature reviews, procedure writing | Unspecified (presumed introductory undergraduate chemical engineering course at Graz University of Technology, Austria during either Spring or Fall 2020) | Students searched the literature and proposed their hypothetical procedure. They did not conduct their proposed procedure. | Student feedback (methods unspecified). | Students reported positive experiences with the course. Students felt the experience was valuable for their education. Students felt it took more work than they initially expected it would, and they were overwhelmed at first. | Student feedback (methods unspecified). | Students reportedly gave positive feedback by the end and felt the experience was valuable for their education. Students felt it took more work than they initially expected it would, and they were overwhelmed at first. |
| 76 | Same | A-school hands-on labs vs. at-home literature reviews | Introductory undergraduate organic chemistry course with 82 students at Wesleyan University, USA during Spring 2020 | Students worked in small groups to write and make presentations about a published paper's techniques but not familiar with some of the paper's techniques but not universally so. | Student feedback on survey at end of project (91 % response rate). | The class was split evenly regarding their past experience with symposium-styled presentations. Many students reported the general, chemistry, organic chemistry, and assorted biology courses were helpful for completing the project. 88 % agreed the project increased their awareness about the pandemic; 92 % agreed it helped them correlate concepts to the real-world, and 83 % agreed the project was relevant to the course. Students were fairly familiar with some of the paper’s techniques but not universally so. Many students utilized the university’s independent mentoring service for practicing presentations. Students reported improvement in public speaking and connecting concepts to the real world. 59 % felt they learned more during the f2f labs vs. the remote project. | Student feedback on survey at end of project (91 % response rate). | 91 % agreed they enjoyed the project. Students reported positively on the project experience. 68 % felt they were more engaged. |
At the end of the course (having done simulations until then), students wrote and conducted a procedure at home to determine amylase activity on starch in multiple substances. They were given guidance on a general protocol and relative ratios to consider using with household supplies. Students watched a video to learn how to use a computer program to analyze results.

Grades were comparable between prior f2f lab and at-home lab. Discussions during office hours. Historical comparison of quality of lab reports and data. Discussion board activity. Pull about time workload (27 % response rate).

Students wanted a procedure that provided specific amounts of material that should be used. Resources from the f2f lab version and a video about dilutions was thought to be helpful by the instructors. Students struggled to write the experimental section of the lab reports and couldn’t directly compare to other students since they wrote separate procedures. Students struggled to analyze and interpret data properly; less than half were perceived to understand why they were analyzing the linearity of their plot. Students appropriately recognized multiple experimental limitations caused by the at-home format. The lab took the standard amount of time as a f2f lab.

Student feedback (methods unspecified).

Students valued the hands-on lab experience despite the challenges.
| Course | Type | Student Engagement | Data Collection | Comparison | Feedback | Reflection |
|--------|------|-------------------|----------------|------------|----------|----------|
| Introductory biophysics course with 1-100 students at the University of Bologna, Italy during Spring 2020 | Data collection | Students completed hands-on labs about kinematics and optics in their homes using household supplies. Those who could not obtain supplies were given sample data to analyze. | Student feedback on anonymous end-of-semester survey (response rate unspecified). | Some students commented that the hands-on labs were helpful for learning and reinforcing the lecture concepts. | Submission rates. Historical comparison of student feedback on end-of-semester survey (response rate unspecified). | Approximately 94% of the students did the hands-on labs. 78% of students gave positive feedback about the course compared to 81% from the previous year. |
| Introductory forensic science course with 43 students at Teesside University, UK during Fall 2020 | Data collection | Students collected forensic data from their local environment and compared data from other sources. Students also conducted other activities such as simulations. | Historical comparison of final exam grades. | Students in the upper-level course achieved a higher average exam grade than the prior two years of students, although statistical analysis was not provided. | Student feedback (methods unspecified). | Students appreciated the hands-on work. More students engaged with the hands-on activities than the non-hands-on activities (method of measurement not specified). |
| Undergraduate forensic biology course, and upper-level graduate forensic biology course in the fall at Virginia Commonwealth University, USA during Spring and Fall 2020 | Data collection | Students in the upper-level forensic science students had one final, major lab remaining which they did at home by creating and analyzing a crime scene. In the fall, students in the forensics course did the option to conduct a supplemental virtual simulated forensics lab on PowerPoint in a choose-your-own-adventure style. In the forensic biology course, students analyzed sample data. In the graduate forensic biology course, students watched a screenshare to remotely see how to use a program usually done in a computer lab at school. | Historical grade comparison on various assessments. | Students did better on certain assessments compared to prior years, but it was very obvious there was widespread cheating going on. Cheating was a huge, flagrant problem for some courses. | Student feedback via serology survey (60% response rate). | Students felt the virtual serology lab was very helpful for their understanding of how to do the lab. A few students said it was just like doing the hands-on lab, which they also did at school. |
| Undergraduate general chemistry course with 43 students and biochemistry course with 10 students at SUNY College at Old Westbury, USA during Spring 2020 | Data collection | For each course, after completing 5 hands-on labs (hands-on kitchen labs and simulations) to replace the originally planned experiments. Students collected simulated data and wrote lab reports. | Historical comparison of lab report grades for remote vs. earlier in the semester and past years. | General chemistry students received better grades on remote lab assignments compared to labs earlier in the semester. Instructors attribute this improvement to the use of easier questions for the remote assignments. Biochemistry students received slightly better grades on remote lab assignments compared to similar labs from past years. | Student feedback on anonymous end-of-semester surveys (53% response rate for general chemistry). Historical comparison of self-reported study hours vs. computer logs of time spent on remote assignments. | General chemistry students rated off labs as more efficient for learning (4.1/5 Likert) compared to remote (3.4/5) and hands-on kitchen labs (3.2/5). Freshmen spent about the same amount of time on assignments as before. Students commented positively on the ability to use real equipment and interact closely with people for off labs, but also appreciated the simpler and clearer structure to remote labs. The majority of biochemistry students rated the remote labs as effective. | Student feedback on anonymous end-of-semester survey. | The majority of biochemistry students reported satisfaction with their remote learning experience. |
| Same | AND | Different |
|------|-----|-----------|
| **At-school hands-on labs vs. at-home videos** | **Introductory undergraduate general chemistry course with 430 students and 18 TAs** | **At-home simulations** |
| **General chemistry students had no prior exposure to remote lab course, and the academic year had not yet started. The physical learning objectives for both courses were abandoned and focus was placed on data analysis, theory, concepts of techniques, and safety. Students in both courses watched experimental videos and analyzed provided sample data from past students** | **Students watched videos and did simulations online to collect data. TAs facilitated breakout room sessions to foster peer-to-peer learning (based on prior experiences in Spring 2020).** | **Introductory and accelerated undergraduate general chemistry courses (2 different tracks) with 154 students combined at Georgia Institute of Technology, USA during Summer 2020** |
| **Student feedback from general chemistry students on mid-quarter and post-quarter surveys (79 % response rate). TA feedback from general chemistry TAs on mid-quarter and post-quarter surveys (100 % response rate).** | **Student feedback from organic chemistry students on mid-quarter survey (84 % response rate). TA feedback from organic chemistry TAs on mid-quarter and post-quarter surveys (84 % mid-quarter, 82 % post-quarter response rate).** | **Cognitive learning scores were similar between the two groups and with other, previously reported uses of the MLLI.** |
| **General chemistry students struggled with the electronic laboratory notebook. Organic chemistry students felt it was easier to ask questions when remote.** | **Organic students felt the lab lecture was helpful and thought it was similar to f2f lab lectures. TAs felt the labs required less time when remote. TAs felt students required more guidance to analyze data than in previous courses but discussed the theory and concepts more. TAs struggled to assess gaps in student learning.** | **For the standard course, the average affective score was noticeably lower than the accelerated course. The accelerated course had almost no decrease in student participation. TAs felt there was an overall decrease in student participation even though some students increased and contacted TAs more. Overall, students, TAs, and instructors felt the remote transition was a success.** |
| **TA feedback was given informally during synchronous sessions.** | **TA feedback was given informally.** | **Demographics of student populations.** |
| **Communication and expectations were established by higher activity on the discussion board than in the previous year. Students attended TA office hours much more than when f2f. General chemistry TAs worried they had fewer personal connection to students regardless of higher office hour attendance rates. TAs felt insufficiently prepared for office hours, where students primarily asked about grading rather than theory.** | **TA feedback was given informally.** | **For the accelerated course, there were more low-scoring affective items, and the average affective score was noticeably lower than the standard course. The accelerated course had almost no decrease in student participation. TAs felt there was an overall decrease in student participation even though some students increased and contacted TAs more. Overall, students, TAs, and instructors felt the remote transition was a success.** |
Halfway through the course, students had already done many experiments with most of the techniques and equipment before the transition occurred. The procedure design and observation activities were abandoned, and students instead attended prelab lectures, watched experimental videos, and analyzed the provided raw sample data from the instructor.

Instructors reported student performance was comparable to previous years (methods unspecified). Students struggled to write realistic procedures, understand literature experimental sections, engage in experimental design, make appropriate practical decisions, and predict the expected raw data. Students drew heavily on examples of published data and experimental sections, although students who followed the rubric guidelines had fewer instances of Turn-It-In percent-matches and appeared to understand the procedures and data better. The quality of the manuscripts, posters, and presentations appeared unchanged. Students reported learning that hands-on bench work is only one part of the research process.


different between the two groups, although the CURE group scored a little higher on average. There were no significant differences between the pre/post survey responses (given at start and end of course) on modified CLASS-Chem instrument to evaluate expert-like thinking for both CURE and traditional lab (~90 % response rate).

Semistructured focus group interviews (n ≥3 for each course). Two-tailed paired t test with equal variances analysis of pre/post-survey responses (given at start and end of course) on modified CLASS-Chem instrument to evaluate expert-like thinking for both CURE and traditional lab (~90 % response rate). The demographic composition of the CURE and traditional lab sections were roughly comparable except for the ratio of 1st generation students. The instructors suspect that scheduling mostly drove registration into one or the other. CURE students discussed their morale more than traditional students did.

Students overwhelmingly contrasted f2f labs and remote learning in terms of the ability to manually perform experiments and gain hands-on experience. But the majority also reported the videos and Zoom data discussion sessions were helpful and provided a much-needed license of normality, motivation, and accountability.


different between the two groups, although the CURE group scored a little higher on average. Two-tailed paired t test with equal variances analysis of pre/post-survey responses (given at start and end of course) on modified CLASS-Chem instrument to evaluate expert-like thinking for both CURE and traditional lab (~90 % response rate).

Semistructured focus group interviews (n ≥3 for each course). Two-tailed paired t test with equal variances analysis of pre/post-survey responses (given at start and end of course) on modified CLASS-Chem instrument to evaluate expert-like thinking for both CURE and traditional lab (~90 % response rate). The demographic composition of the CURE and traditional lab sections were roughly comparable except for the ratio of 1st generation students. The instructors suspect that scheduling mostly drove registration into one or the other. CURE students discussed their morale more than traditional students did.
| 47 | Different | As-school hands-on labs vs. at-home videos AND | At first, experimental videos replaced labs but were then replaced with an at-home, hands-on column chromatography experiment. | Quality of student lab reports for remote vs. previous semesters. | Videos were felt to be ineffective at fostering interaction and learning outcomes. There appeared to be no significant difference between student comprehension of separation and chromatography concepts compared to previous years. |
| 54 | Different | As-school vs. at-home hands-on labs | One of the two planned experiments was converted to an at-home, hands-on kitchen lab. Students made spectrophotometers out of smartphones to collect data on dyed solutions. Students who failed to get data were supplied with sample data. | Lab report grades were similar to historical grades. | Quality of lab reports and student-made videos explaining lab techniques. Student feedback (methods unspecified). |
| 50 | Different | As-school hands-on labs vs. at-home videos, simulations, data, procedure writing | 2D labs were replaced with instructor demonstrations, experimental videos, simulations, readings, more writing-based assignments, and sample data. Students wrote lab reports based on the sample data and determined structures of unknown molecules. They also analyzed journal articles to write a lab procedure and made videos about techniques. | Lab report grades were similar to historical grades. | Students learned new concepts, did simple calculations, and analyzed spectra and TLC results without noted difficulty. They appeared to struggle to build on knowledge, connect topics across questions, and use all relevant data to make conclusions. Students incorrectly assumed incomplete simulated reactions were complete and showed lower comprehension regarding safety, troubleshooting, how to execute practical techniques, and waste disposal. Students gave positive feedback about the digital resources in general but reported that they struggled to make connections between simulations and lab reports. |
| 92 | Different | As-school hands-on labs vs. at-home videos, simulations, data, procedure writing | Students had almost finished collecting experimental data for a multi-stage lab. The remaining computational modules of the curriculum and experimental videos replaced the remaining 2D labs. Students used data from other schools or historical student data to complete their analysis and then present results. | Paired pre/post-Participant Perception Indicator survey (9 students with paired responses). Student feedback on end-of-semester survey (methods unspecified). | Students reported it was hard to write about experiments they didn't do themselves and data that wasn't perfectly aligned with their projects. A survey at one school showed learning gains but not as much as a previous FT precedent; learning gains were higher for computational techniques than biochemical. |
| 74 | Different | As-school hands-on labs vs. at-home videos, procedure writing, data | Experimental videos were made for organic labs, for which students already had prior experience with. Organic students also designed a guided-inquiry lab practical to rank reaction rates, a modified version of a similar guided-inquiry FT lab. Readings, notes, and data were given to analytical students, and the course shifted to focus heavily on data analysis rather than experimentation. Analytical students were anticipated to poorly understand the experiments and so grading and lectures expected mistakes. | Historical grade comparison of organic postlab assignments for remote vs. previous semester. | Students reported positive feedback. |
| 77 | Different | As-school hands-on general chemistry with ~ 150 students at Brown University, USA during Spring 2020 | After 3 FT labs before closure, the remaining labs were replaced with pre-made first-person experimental videos with embedded interactive questions. Lab reports were revised to focus around critical thinking questions. | Student feedback from multiple surveys during the semester. Historical comparison of student perceptions of one lab for remote vs. previous semester. | Students reported the lab videos were well-done and helpful but not as effective as FT labs. By the end of the semester, students reported much lower levels of learning than previous, FT students had. Students commented that they felt that hands-on labs were irreplaceable. |