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Chapter 11

Options and Experiences for Online Chemistry Laboratory Instruction

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While online course offerings have been on the rise for many years, there was a rapid transition to online courses due to campus closures and social distancing protocols associated with the COVID-19 pandemic. This has caused significant disruption in traditional chemistry laboratory activities. In this chapter, features of various distance laboratory approaches options are presented, including wet chemistry and dry laboratory options. Because the existing research comparing effectiveness of these strategies is scarce, no attempt is made to argue the effectiveness of one modality over the other, but rather advantages and disadvantages of each method are presented and discussed. The best fit for a specific institution will depend on many factors that must be considered.

Introduction

The laboratory experience is crucial to a student's chemistry education. Laboratory exercises serve several instructional functions, including reinforcement of concepts learned in lecture, the opportunity to apply knowledge, and development of laboratory and safety skills. Skills learned in the laboratory, such as solution preparation and data collection take chemistry beyond a purely academic exercise to a practical level of application.

In the last decade an increasing number of science courses have migrated to nontraditional formats, either fully online or using hybrid approaches, where the lecture portion takes place online and the laboratory experience occurs in person in a traditional laboratory. Fully online laboratory courses cover concepts and skills often applied in traditional in-person laboratory courses, though the nature of the experiment must be adjusted in order to perform experiments at the student's home, and potentially without supervision. Even traditional chemistry laboratory courses have adopted some non-traditional experiences such as remote equipment operation to varying degrees. Current global health concerns have precipitated the migration to these non-traditional laboratory learning environments. The COVID-19 pandemic and social distancing mandates have made instruction in the traditional laboratory setting difficult, if not impossible to accomplish. It is expected in a post-pandemic setting that online chemistry laboratory instruction will continue and the ideas discussed here will remain relevant.

Within higher education, some faculty and administrators suggest that laboratory courses cannot be offered remotely (*1*). Claims that chemistry cannot be taught online are often rooted in the claim of an inability to effectively teach the lab component outside of a traditional laboratory environment. However, the current literature supports the efficacy of the online laboratory instruction methods (*2*, *3*). In the following sections, we will explore online and distance laboratory instruction options and review the literature on equivalence between traditional and nontraditional instruction techniques. Strengths and weaknesses of various laboratory modalities will be discussed, including issues like safety and student learning.

Laboratory Instruction Options

The literature does not present standard terminology for different teaching options for laboratory experiences. This chapter will define a traditional laboratory as one where students perform experiments in person in a physical laboratory. Wet chemistry activities include distance options where students make use of laboratory equipment, mixing chemicals and observing the results of those reactions. Dry lab options include simulations, virtual experiments, and remote laboratories, where the students do not handle chemicals themselves. Results for both these appraches can be reported online and the experiments can be performed synchronously or asynchronously.

There is no single answer for which laboratory approach works most effectively for every specific course or institution. The best instructional method depends upon specific factors, such as the primary purpose of the experiment, budget constraints, targeted rate of program growth and infrastructure capacity, and acceptable safety and access parameters. Faculty and administrators who are faced with making a chemistry laboratory modality decision may find a Lab Format Decision Matrix to be a helpful tool (*4*).

Similarly, the best-fit distance laboratory approach for students will depend upon student-specific external and internal factors. Sensory feedback may be more important to some students than others based on learning styles and preferences. Students' anxiety related to learning chemistry and handling chemicals is well known. It is unclear at this time how modality may influence student anxiety, as it is likely confounded by factors like math anxiety and computer anxiety. Currently, there is a gap in the literature to address this question, though it is likely that students will select online laboratory modalities through considering factors relevant to non-laboratory course modality decisions, including cost, with online courses typically being less expensive, time, and asynchronous flexibility for managing educational responsibilities with personal and professional commitments. Adequate workspace and technology requirements such as computer and internet availability may also be factors that influence student attitudes regarding laboratory instruction.

Distance Wet Chemistry Options

There are both positive and negative aspects to consider for distance curriculum that has students physically mixing chemicals when performing laboratory experiments. These features are summarized in Table 1 (*5*).

Table 1. A comparison of features of distance wet chemistry approaches

	Commercial Home Kits	Kitchen Chemistry
Tangible results with sensory feedback	✓	✓
Practical skill development	✓	✓
Low operating & maintenance costs for institution	✓	✓
Scalable (class size and sections)	✓	✓
Asynchronous 24/7 availability	✓	✓
Multiple access opportunities	✓	✓
Extended access time	✓	✓
Disability access	✓	✓
Student-instructor contact	(variable)	(variable)
Materials & Equipment Convenience	✓	
Additional student costs		✓
Replication of experiments		✓
Safety		

Both mail-order kits and kitchen chemistry provide lower operating and maintenance costs for the institution as there is no physical laboratory space to furnish and maintain. These methods also require no chemical inventory or institutional waste disposal. Both distance options are scalable for larger class sizes and more sections, where a traditional laboratory has limited time and physical space limitations. Students can benefit from the opportunity to engage with the material asynchronously, on their schedule rather than a fixed laboratory time. Multiple Access Opportunities refers to the ability of students to perform the exercises more than a single time, as there is often enough material to allow two or three experiment attempts. Students can also spend extended time working on an experiment or break the work into multiple sessions. This accessibility also extends to disability access to those with psychological or physical disabilities that limit or alter their ability to engage in a traditional laboratory.

A common argument in support of traditional laboratory experiences is the development of practical skills through hands-on work; distance laboratory options provide sensory feedback and allow for practical skill development in a way that online options cannot achieve. Because students are performing hands-on wet chemistry at home, they will need adequate space, ventilation, and safety equipment. Care and diligence must always be practiced by the student to use personal protective equipment like approved lab goggles and to prevent personal injury or damage to property. If the course is taught asynchronously, students will be working alone, without a lab partner, and without a lab instructor or teaching assistant to act as a safety observer. As with traditional laboratory courses, instructors teaching distance chemistry laboratory courses must attend to their duty of supervision and duty of care.

Instructor responsibilities that fall under duty of supervision include hazard communication, training in categories such as general emergency procedures and PPE use, waste management, and documentation. In a non-traditional laboratory, these duties could be upheld by infusing the course with laboratory safety skills and requiring students to demonstrate actionable safety knowledge in pre-lab assessments. Requiring students to submit a tour of their work area as an initial laboratory activity allows instructors to inspect housekeeping and chemical hygiene. Handling of wastes can be addressed both in pre-lab and post-lab activities. Instructors could even request video documentation of student procedures to provide feedback to refine laboratory skills and to ensure appropriate student behaviors. Including student compliance with health and safety policy as a graded course component could enhance documentation and provide a means of disciplinary action for noncompliance such as a reduction in assignment score or overall grade.

Instructor responsibilities that fall under duty of care include risk assessment and mitigation, generation of SOPs, consideration of PPE and engineering controls, emergency response, and documentation. Commercial companies and retailers may review their products for safety but they are held to different safety standards as they sell to the general public. To satisfy the duty of supervision, it is important that all experiments - whether materials are purchased as kits or not - are thoroughly reviewed for safety, including the generation of hazardous waste. When identifying laboratory experiments for distance students, perform rigorous hazards assessment If an institution has a safety review board, it may be beneficial to have the board review the selected laboratory experiments for use in the distance kits. Each laboratory experiment should have a standard operating procedure (SOP) developed and approved through the institution. According to OSHA's Laboratory Standard, the SOP should be reviewed annually. Many institutions offer template forms for hazard assessments and SOPs. Whether the SOP is administrative or is presented to students is an instructional design decision.

A passive approach by students will not work for distance lab activities. Students need to be engaged with the concepts and procedures and be able to troubleshoot problems that occur during the experiment. For this reason, students can benefit from options for reaching out to their instructor and their peers while performing an experiment at home. In synchronous courses, this can be achieved through various platforms, including Zoom, Skype, and Adobe Connect. In asynchronous courses, this can be achieved through platforms including the discussion forums within the learning management system and external options such as Google Hangout.

Commercial Home Kits

Students can purchase mail-order laboratory kits from a company like eScience Labs or MEL (*6*, *7*). One logistical consideration with commercial kits is that instructors are reliant on companies to maintain appropriate inventories and shipping schedules. As many online and distance courses operate on a condensed semester schedule and shipping delays can quickly become problematic for students. A 2019 merger between home lab kit providers HOL and eScience combined with supply chain disruptions due to the COVID-19 pandemic continued to cause shipping delays (or shipment of incomplete kits) throughout 2020. Shipping to students living overseas can also be subject to delays due to international relations and global health measures. Equipment breakage can present additional complications for this approach. Glassware that arrives broken or breaks during the experiment are potentially hazardous and can be difficult to replace in time to allow students to meet assignment deadlines.

A key benefit of mail-order kits compared to kitchen chemistry is that they come with the chemicals and equipment necessary for students to perform experiments at home. Depending on the number of experiments in the course, the number of kit items can be overwhelming. Safety storage of chemicals and materials is another consideration. Students must take time to inventory the items and identify any pieces that are missing or broken. Having the instructor require this initial inventory and make it a graded exercise will increase the likelihood that the materials will be checked and deficiencies can be addressed quickly (*8*).

For safety and waste consideration, kits typically support microscale experimentation. For this reason, students often only have one opportunity to properly execute an experiment. If their work fails for any reason, they may be unable to generate the necessary data. This limitation is fairly unique to this lab option as traditional labs, kitchen chemistry, simulation, and virtual reality options offer easy avenues for replication of an experiment.

Many of the companies allow instructors to develop custom kits to align experiments with their curriculum. Instructors must choose from a limited menu of available experiments. Without a significant investment of time to develop in-house laboratory instructions, this can result in a piecemeal laboratory manual for students to follow. For example, a custom kit from e-Science may include experiments from two standard kits.

The laboratory manuals contain the full breadth of the experiments in the standard kits so either students have too much material to sift through or a trimmed version has inconsistent page numbers and experiment identification numbers. If instructors wish to have a more cohesive and polished presentation, they also must develop the laboratory manuals themselves. Creation of custom lab manuals requires a significant up-front investment of time, plus continued maintenance if the vendor changes lab equipment or procedures.

A post-lab discussion exercise could allow students to share experiences and collected data. This could enable students missing chemicals and equipment to still perform required calculations and draw conclusions from the exercise.

Kitchen Chemistry Experiments

The idea of at-home chemistry experimentation has been around for decades. If kitchen chemistry is used as a formalized approach within a nontraditional chemistry laboratory, a list of materials and lab procedures are provided to the student. The burden of collecting appropriate lab materials falls on the student, with purchases typically available through grocery and hardware stores. Online ordering may ease this burden, but availability will vary based on the geographic location of students. Unlike mail-order kits, purchases of chemical supplies are often in greater quantity than what is needed for experimentation. This provides some room for replication of experiments, though it generates an added risk for storage and disposal.

The internet abounds with ideas for kitchen chemistry experiments, from pen chromatography to the chemistry of rusting nails. Published literature on this approach is only starting to appear (*9*). Some websites offering other kitchen chemistry ideas include:

- The Royal Society of Chemistry's Kitchen Chemistry (*10*)
- Fizzics Education's Kitchen Chemistry Experiments (*11*)
- Science Center's Kitchen Chemistry Summer Camp Framework (*12*)
- American Chemical Society's Adventures in Chemistry (*13*)

When identifying potential kitchen chemistry experiments, instructors must consider appropriate rigor, affordable and accessible chemicals and materials, and safe chemical storage, use, and disposal. Just because a chemical is readily available does not mean that it is appropriate for at-home experimentation. For example, dissolving a nail with copper sulfate (available from the hardware store as a root killer for septic tanks) is not ideal as copper sulfate should be collected as hazardous waste due to its environmental toxicity (depending upon the concentration, volume, and institutional decisions regarding waste disposal).

Online Dry Lab Options

As with wet chemistry laboratory options, there are factors to consider when determining if a dry lab approach is workable for laboratory curriculum. Dry lab options, such as simulations, remote labs, and virtual reality, do not require students to manage physical inventory which greatly simplifies their laboratory experience. Many of these approaches require access to updated computer resources and the understanding of how to use them. There is also a learning curve for mastering the computers and the simulation software, and these hardware and software requirements can be barriers to learning (*14*). Another point to consider that dry lab experiments are not as immersive as their wet chemistry counterparts, but improvements and cost reductions in computer hardware and software should improve this aspect. As compared to learning via a distance wet chemistry approach, dry lab options provide the highest level of safety. These considerations are summarized in Table 2.

Table 2. A comparison of features of online laboratory modalities

	Laboratory Simulations	Remote Laboratory Experiences	Virtual Reality Experiments
Tangible results with sensory feedback			
Practical skill development		✓	(unknown)
Low operating & maintenance costs for institution	✓		✓
Scalable (class size and sections)	✓		✓
24/7 availability	✓	(variable)	✓
Multiple access opportunities	✓	✓	✓
Extended access time	✓	(variable)	✓
Disability access	✓	(variable)	✓

Table 2. (Continued). A comparison of features of online laboratory modalities

	Laboratory Simulations	Remote Laboratory Experiences	Virtual Reality Experiments
Student-instructor contact	(variable)	(variable)	(variable)
Materials & Equipment Convenience	✓		✓
Student costs	✓	✓	✓
Replication of experiments	✓	(variable)	✓
Safety	✓	✓	✓

Laboratory Simulations

Simulated chemistry experiments can be used for both traditional and nontraditional laboratory experiences (*15*). Simulations mimic the laboratory environment and have students manipulate digital versions of laboratory equipment and materials. Distinct from laboratory simulations, there are many interactive elements available that aim to teach specific chemistry concepts at the macro and micro level, including PhET interactive simulations, MERLOT Chemistry Simulations, and ChemReaX (*16–18*). Some sources, like ChemCollective, offer virtual lab experiments, simulations, and molecular level visualizations (*19*). Commercial options for laboratory experiment simulations include Labster and LateNiteLabs (*20*, *21*).

While virtual labs offer safety, they often ignore safety skills. For example, within LateNiteLabs, students cannot accidentally spill chemicals and when they are done with an experiment, they discard chemical labware and chemicals into a trash bin, which in no way simulates an actual laboratory environment. Students who progressed to a hands-on second-semester laboratory course would be under equipped to deal with chemical and physical hazards present when working with chemicals. Simulations also lack realism in other ways. They often do not provide variability of results and present occasional random outcomes. One benefit of simulations, though, is also safety. Simulations are ideal for allowing students to experience laboratory activities that are simply too dangerous for the average undergraduate student to execute in a wet chemistry experiment, and this is true for both in a traditional or nontraditional lab settings.

Remote Laboratory Experiences

Data acquisition through remote equipment operation is an option that has been used for decades in traditional laboratories, though often for advanced laboratory operations like atomic absorption spectrometry (*22*). Furthermore, there is complexity in scheduling student remote access and shipping samples to the instrumentation for data acquisition. The dominating factor for remote laboratories, however, is cost. The Colorado Community College System received external funding to set up and run a remote laboratory for students studying chemistry, physics, and biology. Remote experiments were effective for student learning, but the arrangement was not financially sustainable. The remote laboratory closed when the external funding ran out (*23*).

Virtual Reality Experiments

Virtual reality (VR) laboratory experimentation is an emerging modality option. Common applications of VR include exploration of chemistry concepts on the microscopic/submicroscopic scale (molecular shape, bonding, etc.), but there is an increasing attention to the use of this technology for macroscopic exploration through experiments and experiences. Students can move around a three-dimensional virtual laboratory space through digitized video and animations of experiments, creating an interactive and immersive experience. VR experiences have varying levels of reality, ranging from idealized or abstracted experiences to fully interactive visualizations (*24*). The use of fixed narrative structures or fixed viewing perspectives limits interactivity and active learning (*25*). The advancements in affordable high-quality 360° video recording technology has made fully interactive visualizations easier to achieve.

VR laboratories can be deployed with 1) readily-available portable headset hardware like Google cardboard device and app or 2) high-performance PC-tethered technology. The portable option would have low cost to students to purchase the cardboard kit but would require access to a high-quality smartphone. The high-performance option would require hardware not likely to be possessed by students in a distributed (off-campus) model and would require coordination with an institution's information technology team to establish for on-campus use (*26*).

Because VR experiences are so novel in higher education, it may be challenging to seamlessly integrate into the curriculum with appropriate scaffolding for students. Disability access must also be considered, including alternative options for manipulating the interactive environment. Students will have a range of spatial skill proficiency; alternative options can ensure equitable learning opportunities. Ergonomics is another potential limitation of VR hardware such as use for students who wear glasses.

Comparison of Laboratory Choices

Currently, the research comparing chemistry laboratory modalities is very limited. With the rapid transition to online in the wake of COVID-19, it is likely that there will be more research in this area moving forward. Emerging data suggests that chemistry laboratory courses are amenable to online learning in higher education and can promote achievement of student learning outcomes at least equivalent to traditional laboratory environments.

Comparisons for single-experiments offered as an online simulation versus in-person showed that simulations were equivalent to or better than in-person experiences for student performance and content knowledge mastery (*27*). No difference in practical motor skill development has been reported and one study reported higher student performance in a simulated lab compared to a teacher-centered, expository lab (*28*).

Comparison for an entire course offered using laboratory kits versus in-person showed no difference in pass rate or withdrawal rate but did report a positive skew in grade distribution for students using the lab kits compared to in-person experimentation (*29*). At the secondary level, a lab course using simulations has been shown to be as effective as a traditional in-person laboratory experience (*30*). When comparing single experiments offered as VR versus in-person, no difference in long term content knowledge retention was shown, but students did self-report stronger learning with VR relative to 2D text and images (*31*).

There are many aspects in comparing laboratory modalities that are as-yet unexplored. While VR, lab kits, and in-person laboratories require motor skills and application of practical laboratory skills, it is unclear at this time if skill development is equivalent across modalities. It is unclear if student actionable safety knowledge is equivalent across laboratory modalities. It is also unclear how modality may influence chemistry and laboratory anxiety.

Conclusions

At this time, there is not enough evidence to definitively evaluate equivalence between these different laboratory options in areas including mastery of disciplinary knowledge, laboratory skills, actionable safety knowledge. Student opinions and attitudes towards learning chemistry by different online methods also remains under-explored. However, there are certain features of these strategies that make one approach more viable than another for a given institution. Understanding the benefits and disadvantages can help administrators, curriculum developers, and educators evaluate which online modality may work best in their setting and for their students.

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