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Virtual Choose-Your-Own-Adventure Prelabs Improve Student Understanding of Analytical Chemistry Concepts and Instrumentation

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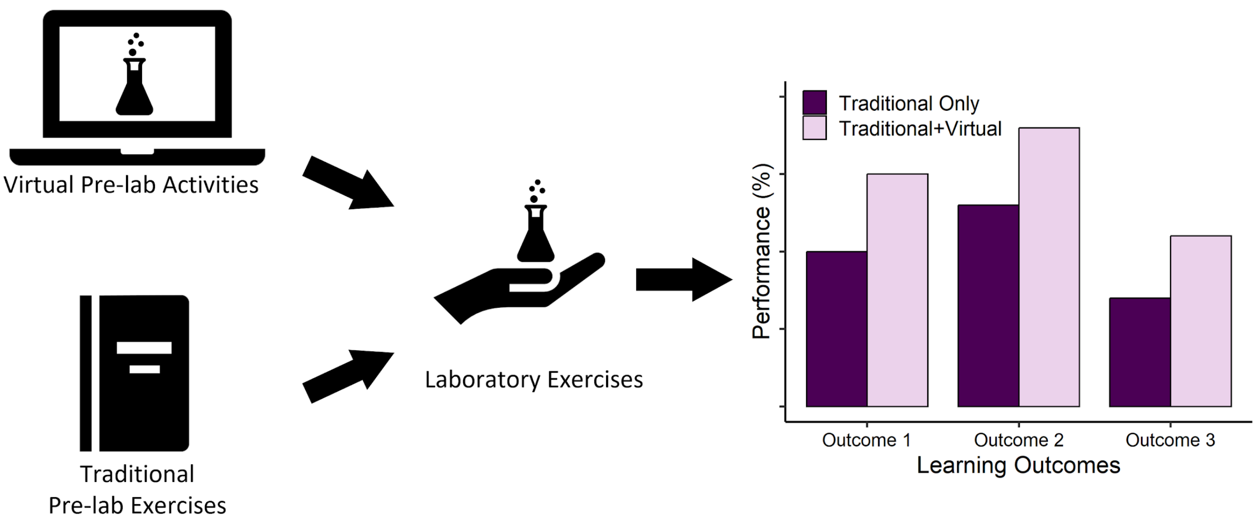
Abstract

The COVID-19 pandemic forced instructors of chemistry lab classes to develop a variety of alternative materials for remote delivery of traditionally hands-on content. One solution to this challenge was virtual choose-your-own-adventure (CYOA) laboratories that allowed students to practice realistic decision-making and collect authentic data. With the return to in-person instruction, these CYOA labs can be modified into prelab exercises to support and supplement in-person experiments. Four virtual CYOA labs were adapted into prelab exercises for an upper-division instrumental analysis course to prepare students for experiments in chromatography method development and electronic circuit design. Students were surveyed to gauge their opinions on the prelabs and their comfort in the laboratory overall. Survey results indicated that students enjoyed the CYOA prelab activities and found them helpful in feeling prepared for experiments and understanding the source and quality of their experimental data. Students who completed the virtual prelabs met more learning objectives in several important categories on lab reports for two electronic circuit design experiments. Virtual CYOA prelabs may be a good way for instructors to expand the depth of their lab curriculum, improve student learning in the lab, and reduce the anxiety their students feel before complex experiments.

Graphical Abstract



Keywords

Upper-Division Undergraduate (Audience), Laboratory Instruction (Domain), Analytical Chemistry (Domain), Virtual Learning (Pedagogy), Prelab Exercises (Topic), Instrumental Methods (Topic)

Introduction

Pre-laboratory exercises are important for preparing students to perform experiments and help avoid cognitive overload caused by focusing on unfamiliar content and new practical skills.[1–6] Many labs assign reading (such as textbook chapters or lab manuals) ahead of time, but students may find these assignments more difficult to engage with than active models that prompt questions.[7] When done effectively, prelab exercises should work to reduce the amount of reading material rather than add to it, reducing rather than contributing to cognitive overload.[8,9] Prelab videos offer a more active option for student preparations and improve student attitudes and feelings of preparation in the course.[10–13] Videos with embedded quizzes show an even higher level of attitude and score performance than traditional narrative videos, a change that is attributed to the more active learning environment.[1,7] Interactive online prelabs have also been used to introduce students to experiments in lower-division chemistry[11,14] and chemical engineering[15] lab courses. Students seem to prefer more active methods of pre-laboratory preparation,[16,17] but many of the strategies reported in the literature have little to no impact on students' overall academic performance.

During the remote instruction part of the COVID-19 pandemic, we developed several virtual laboratory activities for an upper-division combined lecture-laboratory instrumental analysis course using the free, open-source software Twine. Twine is a non-linear storytelling platform that allows users to create interactive games, stories, and learning activities.[18] Other instructors have created virtual learning activities using Twine for laboratory replacements,[19–21] including colleagues in the chemistry department at our institution.[22] These virtual offerings often take the form of a "Choose-Your-Own-Adventure" (CYOA) style activity, allowing students to make choices and determine if the outcome of those choices was correct or if they should try a different procedure instead.[23] For the period of remote learning, seven CYOA labs were generated with Twine, and the resulting HTML files were embedded in pages on our university's Learning Management System. The CYOA format provided a way to keep the emphasis on decision making and analysis of preliminary data in a remote format. Each Twine lab guided the students through a series of instrument optimization steps, giving students realistic data that incorporated their decisions. For example, if a student selected a nonoptimal mobile phase composition for their HPLC experiment, they obtained unsatisfactory peak separation or peak shape. The virtual lab workflow contained frequent prompts for students to evaluate their data and reconsider their previous decisions.

While these Twine labs served as a replacement while physical labs could not be conducted, there have been recent calls to use virtual labs as a supplementary tool for in-person courses even when students can be in the lab.[24,25] Hybrid Laboratory Action-Based Pedagogy (HLAB) focuses on a link between in-lab and non-lab activities in order to complement student learning and maximize student experiences.[26] HLAB suggests that the cognitive overload and anxiety students experience about complex experiments might be lessened by the virtual prelabs because students can review nontechnical skills (conceptual questions about the operation of instruments, ideal parameters, chemistry concepts, etc.) before coming to lab, leaving them free to focus on technical skills (physically conducting and troubleshooting experiments, processing data, and interpreting results) in the laboratory.

Beginning with the return to in-person instruction, we modified the full virtual labs into shorter prelab exercises to familiarize students with equipment, help them perform initial method development steps that they confirmed in the laboratory, and prepare them to collect and analyze data in the laboratory. Our course is structured such that students attend two lectures and a discussion section with the instructor and a seven-hour laboratory period supervised by a teaching assistant (TA) every week. Students taking the course are chemistry majors in their third or fourth year of study who have learned basic analytical chemistry techniques and laboratory report writing skills in prerequisite chemistry courses. Student performance on lab report learning outcomes was compared to offerings of this course where the CYOA prelabs were not used in order to investigate the effect of the new prelabs on student learning. Learning outcomes were chosen to reflect student learning of chemistry content and the principles of instrument operation. We assessed the impact of these prelabs using student survey data that asked them about their attitudes toward the experiments and their opinions of the CYOA prelabs.

Creating and Assessing CYOA Twine Prelab Activities

Four virtual CYOA prelabs were converted into prelab exercises for the return to in-person instruction. These experiments were selected because they contained content and equipment that was new to almost all students and therefore posed a high risk of cognitive overload. Two of them centered on developing chromatography methods, and the other two focused on different types of operational amplifier circuits.

Chromatography Method Development Experiments

The first two experiments for which virtual CYOA prelabs were developed dealt with chromatography method development using HPLC and GCMS. The original in-person versions of these experiments lasted two laboratory periods and required students to develop a method for their separation, then use that method to perform a quantitative analysis. For example, in the HPLC experiment, students worked in groups to identify an ideal mobile phase flow rate and composition for the separation of dihydrocapsaicin and capsaicin, followed by the quantification of these two molecules in several hot sauces. For an in-person chromatography lab, students worked in groups to identify the ideal mobile phase parameters during the first lab meeting, then used those parameters to perform the quantitative analysis during the second meeting. For remote instruction, both parts of the lab were performed virtually in the same lab period because it was much faster to simulate a chromatogram than it was to physically collect one. JavaScript code embedded into Twine was used to simulate chromatograms and generate .csv files for students to download and analyze. The simulations used student choices to generate data and were designed to replicate the results when the experiments were performed on our lab's HPLC system (Thermo Ultimate 3000, Waters Spherisorb ODS2 column, PDA detector) or GCMS system (Thermo TSQ Duo, Agilent VF-5ms column), and were unique to each student.

The method development portions of the full virtual lab were converted into the CYOA prelabs. For both experiments, students went step-by-step through the process of determining the ideal flow rates and either mobile phase composition (HPLC) or column temperature (GCMS). Figure 1 shows the Twine creator view and a partial student view for the part of the HPLC prelab exercise where students find the optimal flow rate for the separation using an optimized mobile phase composition that they found earlier. Students were required to submit van Deemter plots and answers to questions about the method development procedure as part of their online prelab quiz, due before the in-lab portion of the experiment. During the in-lab experiment, their first task was to confirm the method parameters they had identified in the virtual prelab, after which they used their method to perform a quantitative analysis.

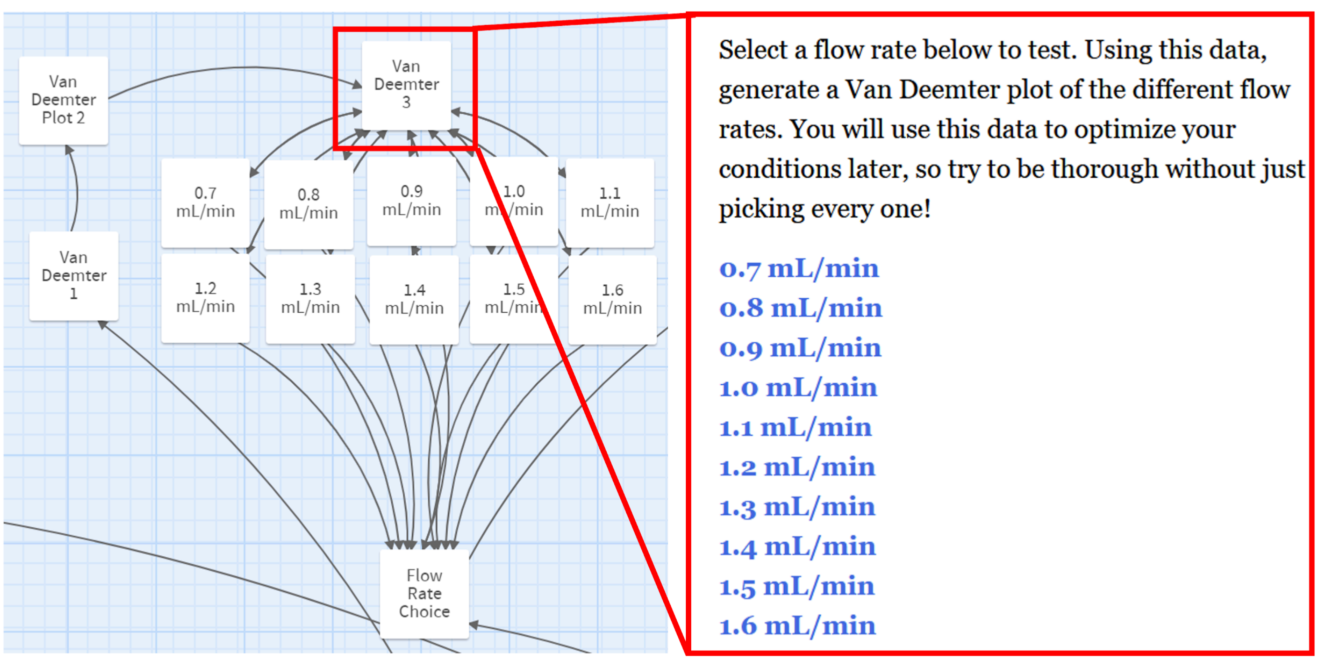


Figure 1. The HPLC Twine prelab activity from the creator/instructor view (left) depicting potential paths students can take in the process of optimizing a flow rate. The expansion outlined in red (right) depicts the interface a student would see as they choose which flow rates to use to simulate chromatograms. The cards called “Van Deemter 1” and “Van Deemter 2” are text-only screens that introduce students to the process of optimizing the flow rate. Students choose their preferred flow rate and enter it on the card called “Flow Rate Choice.”

Electronic Circuit Design Experiments

The other two virtual CYOA labs that were converted into prelab exercises were related to instrument design using operational amplifiers (op amps). Op amps are an important part of the instrumental analysis curriculum because of their ubiquity in chemical instrumentation,[27] but they are not covered in any of our students’ prerequisite courses. This leaves students susceptible to cognitive overload because they are learning an unfamiliar concept (the theory of operation of op amp circuits), while at the same time navigating unfamiliar physical tasks (the process of assembling an op amp circuit on a solderless breadboard).

In the two circuit labs, students built non-inverting and difference amplifiers to amplify the signal from a thermocouple, and a transimpedance amplifier to convert a photocurrent from a photodiode into a voltage. Students build and test these circuits and then use them to construct an adiabatic calorimeter and visible light colorimeter, respectively. The full CYOA virtual labs were designed to give students visual references to the process of building the circuits. YouTube videos were embedded into the Twine virtual labs so that when a student chose to test a given circuit, they first watched the instructor building that circuit. Based on their choices of resistors for a given circuit, they received simulated data from a JavaScript code running in the Twine page. The simulated data was designed to be slightly noisy so that students could do calculations related to data acquisition, and to accurately reproduce the phenomenon of the op amp’s output saturating if the circuit was designed with too large of a gain for the input voltage, a common problem for students performing these experiments. Once students virtually tested their circuits, they were guided to choose a combination of circuit elements to design the full instruments, then given simulated data from an analysis (an adiabatic calorimetry experiment to find the enthalpy of solution of a salt and the construction of a Beer’s law plot to quantify Red 40 dye in a sports drink, respectively).

For the CYOA prelab versions of these experiments, we again used the first half of each virtual experiment. In this case, that meant preserving the parts where students chose circuits to make and watching videos of these circuits being built, after which they received simulated data from testing those circuits. They were also asked to perform calculations to predict the output of a given circuit before getting the simulated data. Their responses to these questions were tracked using Twine variables and exported to a Google Sheet as described above.

Monitoring Student Progress on the Virtual Prelabs

While interacting with both the full virtual labs and CYOA prelabs, students made choices about which instrument settings to use and performed calculations meant to check their understanding of various concepts. Variables in the Twine code were used to track the student responses, count the number of tries to get a correct answer or how many sets of sample data the student generated, and recorded important choices the students made while completing the exercise. When a student completed the prelab, these variables were exported to a Google Sheet to give instructors data on how students were interacting with the virtual prelab.

The original reason for collecting this data was to see whether students were performing calculations correctly and whether they were collecting enough data to draw meaningful conclusions and prepare for the in-person experiment. For example, in the thermocouple electronics experiment, students were asked to calculate a calorimeter constant based on simulated voltage data from measurements using the circuit they chose earlier in the prelab. In Winter 2023, every student calculated their answer to within 5% of the true value as required to move on in the prelab, but the average number of tries it took them to enter that answer was 3.6. This suggests that students in future classes may need more practice on how to do these calculations in the lecture part of the course before they perform the lab. Adding variables to the Twine code is trivial, meaning that the prelabs can be a convenient way to collect data that helps an instructor monitor student understanding of a topic.

Assessment of Student Outcomes and Attitudes

To understand the effect of the CYOA prelabs on student lab report scores, we compared student mastery of learning outcomes on grading rubrics between two offerings of this course (Fall 2022 and Winter 2023) for three different experiments. No Twine prelabs were used in Fall 2021. The Fall 2022 course did not require Twine prelabs for the electronic circuit labs, while the Winter 2023 course did. We compared the circuit labs to an unrelated fluorescence experiment, without a Twine prelab component, performed in both quarters as a control. The GCMS and HPLC labs required Twine prelabs in both the Fall 2022 and Winter 2023 quarters, so we did not perform a specific analysis on laboratory report outcomes for these two experiments. There were 59 lab reports analyzed from Fall 2022 and 54 from Winter 2023. Rubrics for the lab reports and lab manuals for each experiment are available in the Supporting Information.

We qualitatively assessed student knowledge, comfort, and other metrics relating to analytical chemistry techniques, concepts, and laboratory preparedness using the Motivated Strategies for Learning Questionnaire (MSLQ)[28] survey tool along with Likert scale and open-ended questions about the CYOA exercises for the Fall 2021, Fall 2022, and Winter 2023 quarters. The Fall 2021 quarter was included as a "no Twine prelabs" control; during that quarter, students were required to read the lab procedures and complete a short pre-lab quiz before coming to the lab. The Fall 2022 and Winter 2023 quarters required completion of the Twine prelabs in addition to reading the lab procedures and completing the pre-lab quiz before the lab period. For all three quarters, students were surveyed in week one of the quarter as a "pre-quarter" assessment, and again in week ten as a "post-quarter" assessment. They were incentivized to take these surveys via the awarding of intangible tokens to spend on various assignment resubmissions or grade improvements as laid out in the course syllabus. Collection of student survey data was approved by UCI's Institutional Review Board (Exempt Protocol #2231). In total, 115 students took the pre-quarter surveys, and 123 students took the post-quarter surveys. Note that students were not required to complete either survey, and response rate varied during and between quarters due to the grading structure and token economy of the course. The CYOA prelabs applied only to the Fall 2022 and Winter 2023 quarters, with a total of 81 students answering survey questions regarding them. We performed two-sided Mann-Whitney U tests and independent t-tests (95% confidence interval) using R statistical software[29] to compare lab report scores and survey responses between quarters.

Lab Report Outcomes and Survey Responses

Impact of Virtual Prelab Exercises on Assessments

Students generally improved scores on lab report rubric categories related to content knowledge of op amp circuits for both electronics experiments in the Winter 2023 class with Twine prelabs compared to the Fall 2022 class without Twine prelabs (Table 1). Lab reports were graded using specifications grading rubrics, on which each rubric criterion corresponds to one student learning outcome for the assignment and each criterion is graded as either "met" or "not met". Each report was graded by three graders, whose determinations of the numbers of students meeting each learning outcome differed by an average of 8%. Rubrics for the experiments discussed here are available in the Supporting Information. The learning outcomes included in Table 1 were chosen because they relate to chemistry content and the principles of instrument operation, topics that we hoped would be covered by the CYOA virtual prelabs instead of being only introduced during the lab sessions. The number of rubric criteria (that is, learning outcomes) met by students for the calorimetry experiment lab report increases the most for the thermochemistry categories, indicating students had a better understanding of why they were building the circuit and the application of its theoretical principles to calorimetry.

Table 1. Concept-based learning outcomes met by students for three experiments for the Fall 2022 and Winter 2023 quarters. Percentages are averages of results from three graders. Statistically significant ($p < 0.05$) differences are denoted with asterisks.

Experiment	*Rubric Learning Outcome Category*	*Fall '22 % of Students Meeting Outcome (N=59)*	*Winter '23 % of Students Meeting Outcome (N=54)*	*T-test p-values, F22 vs. W23*
Thermocouples and Adiabatic Calorimetry	Operational Amplifier Operation and Calculations	87%	85%	***0.350***
	Seebeck Coefficient Determination and Thermocouple Calibration	62%	71%	***0.134***
	Calibrating and Using the Calorimeter	53%	72%	***0.001****
Transimpedance Amplifiers and Colorimetry	Circuit Building and Calculations	80%	81%	***0.752***
	Nyquist Theorem and Signal Modulation	68%	55%	***0.005****
	Light Measurement and Determining Absorbance	58%	74%	***0.005****
	Circuit Behavior	47%	55%	***0.180***
Fluorescence	Excitation Wavelength Choice	91%	91%	***0.647***
	Analysis of Spectra	86%	82%	***0.507***
	Quantum Yield Determination	68%	70%	***0.601***
	Quinine Quantification	93%	94%	***0.478***

Students struggled with correctly identifying and explaining concepts relating to circuit behavior in the colorimetry experiment in both quarters, though scores improved in the light measurement and determining absorbance (interpreting the colorimetry data to create a Beer's law plot and determining the concentration of dye in a colored sports drink sample) category in the Winter 2023 class. For both circuit experiments, students performed similarly on correctly explaining their operational amplifier circuit setups, but the Winter 2023 section struggled more with explaining the application of the Nyquist theorem and signal modulation to real-world circuit measurements. On a Fluorescence laboratory report that did not have a Twine prelab component in either quarter, students in both quarters performed similarly on rubric items relating to important fluorescence concepts. These results suggest students benefited the most when applying the circuit principles first displayed in the prelabs to the "unknown" part of the calorimetry and colorimetry experiments, where they had to combine previous knowledge of thermochemistry and UV-Visible spectroscopy to their circuit builds. In the Winter 2023 electronic circuit reports, student responses to questions specifically asking about calorimetry and colorimetry were written with a higher level of analysis and connections to relevant lecture material than in the Fall 2022 quarter. Furthermore, TA and instructor discussions during laboratory periods with students showed they made more connections between the circuit labs and the later experiments as related to the fundamental operation of the instruments they were using, which ties into an overall course learning objective. Twine prelab activities for complex or otherwise time-consuming experiments increased the number of students achieving satisfactory learning outcome scores, though their use may not be suitable for all types of chemistry laboratory experiments.

Student Perceptions of CYOA Prelab Exercises

Student opinions on the usefulness of the Twine prelabs differed significantly between the Fall 2022 and Winter 2023 quarters. The Fall 2022 quarter only used Twine for the chromatography labs, while the Winter 2023 course also used it for the two circuit labs at the beginning of the quarter. An overwhelming majority of students in both quarters agreed that the Twine prelabs helped them understand the laboratory procedures, sources and appearance of experimental data, and the concepts involved in the experiments, with a statistically greater portion of students agreeing with the latter two items in Winter 2023 (Figure 2). While both quarters similarly enjoyed the Twine prelabs, the Winter 2023 students particularly said that they would prefer to do the Twine prelabs instead of or in addition to traditional prelab exercises more than their Fall 2022 counterparts. Mann-Whitney U tests determined no statistical differences in student responses about the Twine prelabs better preparing them for the lab, helping them understand the laboratory procedures, or in their enjoyment of the prelabs (Table S1). Five of the seven questions asked about the Twine prelabs had no "disagreement" responses in the Winter 2023 quarter while the Fall 2022 quarter did, suggesting that the students taking the course in the later offering generally found the Twine prelabs more useful. This may be due to student unfamiliarity or confusion with circuits and related concepts, giving them an appreciation for the embedded videos in the prelabs. We often observed students watching these videos during the lab period while building their circuits. The circuit labs occur in weeks two and three of the quarter and are the first in-person experiments students perform, while the two chromatography experiments happen between weeks five and nine on a rotating basis. Student understanding of the purpose behind the Twine prelabs after finding them helpful with circuit building in the first two weeks of the course may have improved their attitudes towards the "additional" prelab requirements for those experiments in the Winter 2023 quarter compared to the Fall 2022 quarter, where they were only introduced starting in week five.

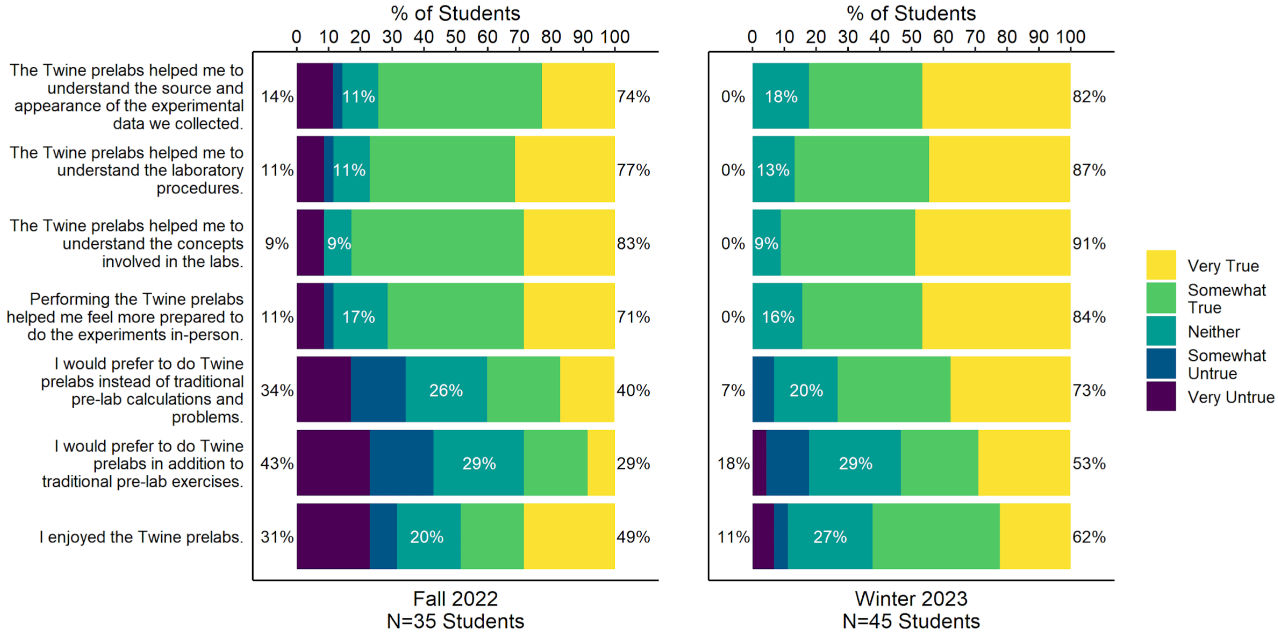


Figure 2. Student post-quarter survey responses about the Twine prelab exercises for the (left) Fall 2022 and (right) Winter 2023 quarters. From left to right, percentages represent the combined negative responses, neutral responses, and combined positive responses.

In an open-ended question asking students to explain their thoughts on whether or not the virtual Twine prelabs helped them understand the experiment better, an overwhelming majority indicated that the CYOA prelabs did better prepare them for the experiment. Many respondents said that these prelabs "helped to set the right instrument parameters" for the chromatography experiments. Another student specifically said that the prelab helped their "understanding [of] the lab…decreas[ing] the actual lab time" they spent doing the experiments, a sentiment echoed in multiple responses to this question. Students also mentioned the visual component of the simulated chromatography data and circuit construction videos multiple times as being helpful for understanding instrument operation and what to expect the data would look like when they collected it during the in-person experiments. We observed many students returning to these videos during the in-person lab as they worked to assemble and troubleshoot their circuits before asking the TA or instructor for assistance. One student wrote that the Twine prelabs "provided the necessary information and setup needed to do the lab in an interesting way", suggesting that this type of interactive prelab activity may improve students' understanding and confidence about difficult experiments. For example, when asked in the lab to explain why they chose a specific flow rate and eluent mixture for the HPLC experiment, students who completed the Twine prelab correctly were able to relate the concepts of peak separation and peak broadening to these parameters. Negative responses indicated that the CYOA prelabs were too time consuming, or that they did not like how they could sometimes continue through the prelab without knowing whether or not they chose the optimal parameters. Overall, student opinions were mostly positive for the Twine prelabs because they provide a different way for students to learn about relevant analytical chemistry concepts and techniques than traditional teaching methods offer.

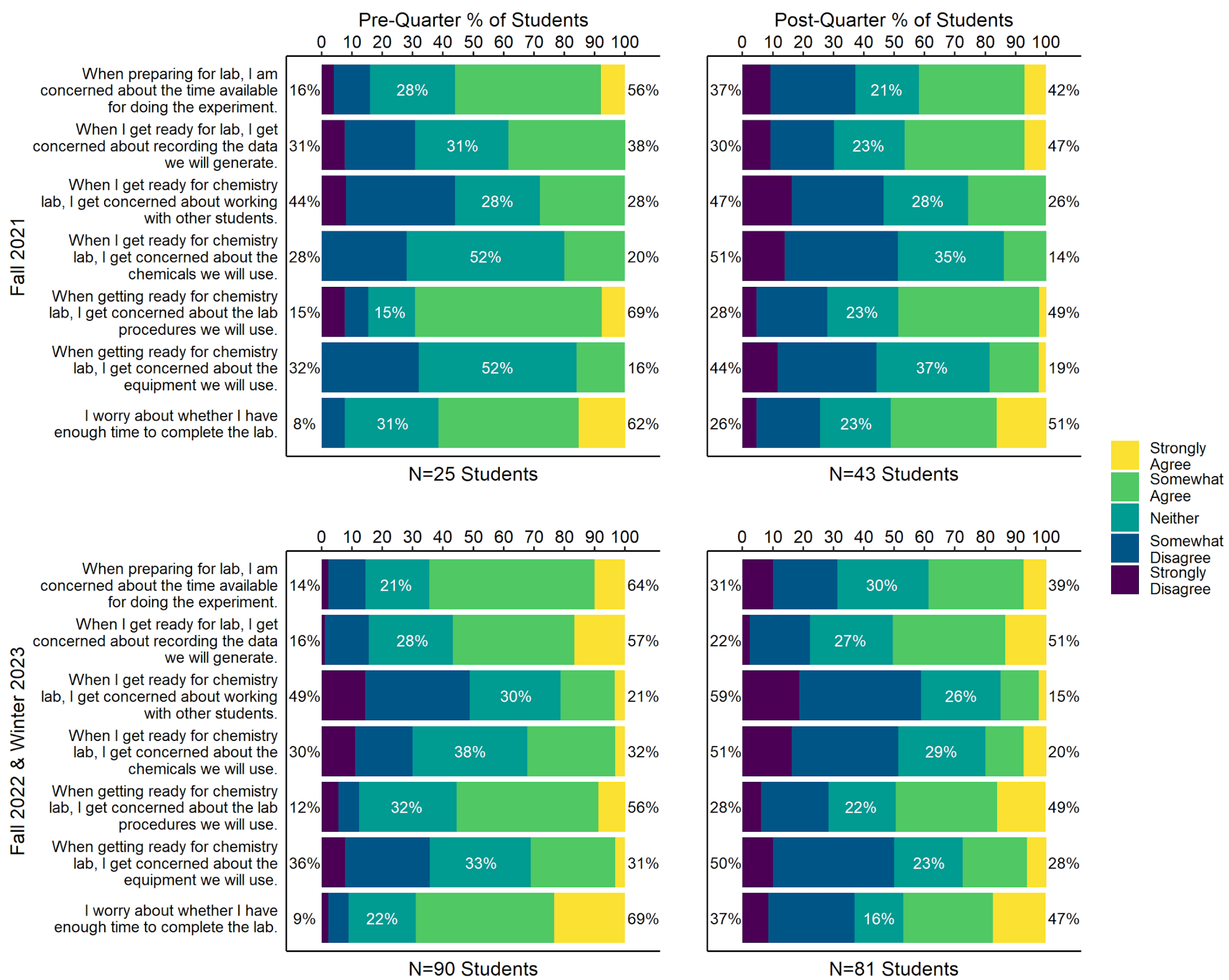


Figure 3. Student responses to (left) pre-quarter and (right) post-quarter MSLQ survey questions pertaining to feelings about preparation before laboratory experiments for the Fall 2021 (top), and combined Fall 2022 and Winter 2023 quarters (bottom). From left to right, percentages represent the combined negative responses, neutral responses, and combined positive responses. Note that N values change due to varying course enrollments and student participation in the surveys.

Student responses to MSLQ survey questions asking about comfort in the laboratory before and after the quarter changed significantly in their distribution with the addition of Twine prelab activities in the Fall 2022 and Winter 2023 quarters compared to the Fall 2021 quarter (Figure 3). Student anxieties around having enough time to complete the lab, the time available for the experiment, and working with chemicals showed statistical differences in the pre- and post-quarter response populations for the Twine-inclusive quarters only. In the pre-quarter surveys, 69%, 64%, and 32% of students agreed with these statements, which declined to 47%, 39%, and 20%, respectively, in the post-quarter surveys (Table S2). The "control" Fall 2021 pre- and post-quarter response populations are very similar for all questions, with similar divisions in agreement type among respondents. This suggests that the addition of the Twine prelabs may lessen student anxieties around preparing for laboratory activities for this course, particularly as it relates to concern about time management while in the lab with unfamiliar concepts like circuit building and instrument operation. Comparison of the Fall 2021 to Fall 2022 and Winter 2023 pre-quarter surveys indicate comparable levels of anxiety about the lab before the course began. The post-quarter surveys had similar response distributions between the quarters as well, indicating that some proportion of students will always be anxious around the lab, regardless of interventions meant to reduce such anxieties or worries about performing experiments with unfamiliar concepts and instrumentation.

Conclusions

Virtual choose-your-own-adventure labs had several benefits for students in an upper-division instrumental analysis course. There was an increase in the number of students meeting learning objectives in several important categories on lab reports for two electronic circuit design experiments when Twine prelab exercises were implemented. The largest benefit observed was an improvement in student attitudes towards the laboratory, including a reduction in anxiety about several aspects of the lab course. A majority of students surveyed reported feeling more prepared after the CYOA prelabs, in particular for the Winter 2023 quarter with the addition of the electronic circuit Twine prelabs. When asked about whether or not the Twine prelabs were useful, many students reported that it better prepared them for what to expect from the experiment and decreased the amount of time they spent in the lab, which agreed with instructors' informal observations. The CYOA prelabs also reduced the anxiety associated with working with chemicals and equipment, preparing for the lab, and recording data that many students reported feeling before the quarter. We suggest this is likely due to the prelabs introducing students to the procedures and equipment used in the experiments before they enter the laboratory. Application of this type of prelab activity to similarly complex advanced chemistry laboratory courses can potentially better prepare students for in-person experiments and reduce their stress surrounding complex techniques and instrumentation.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX.

Rubrics for the two electronic circuits and fluorescence lab reports, Twine-related post-class survey questions, Twine prelab exercise links, and lab manuals for the electronic circuit, fluorescence, GCMS, and HPLC experiments. (PDF, DOCX)

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