Journal of Computing in Higher Education
https://doi.org/10.1007/s12528-024-09403-7

Connecting affordances of physical and virtual laboratory modes to engineering epistemic practices

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Accepted: 16 May 2024

Abstract

Laboratory activities are central to undergraduate student learning in science and engineering. With advancements in computer technology, many laboratory activities have shifted from providing students experiments in a physical mode to providing them in a virtual mode. Further, physical and virtual modes can be combined to address a single topic, as the modes have complementary affordances. In this paper, we report on the design and implementation of a physical and virtual laboratory on the topic of jar testing, a common process for drinking water treatment. The assignment for each laboratory mode was designed to leverage the mode's affordances. Correspondingly, we hypothesized each would elicit a different subset of engineering epistemic practices. In a naturalistic, qualitative study design based on laboratory mode (physical or virtual) and laboratory order (virtual first or physical first), we collected process, product, and reflection data of students' laboratory activity. Taking an orientation that learning is participation in valued disciplinary practice, data were coded and used to characterize how students engaged with each laboratory mode. Results showed that the virtual laboratory elicited more conceptual epistemic practices and the physical laboratory more material epistemic practices, aligning with the affordances of each mode. When students completed the laboratory in the virtual mode first, students demonstrated greater engagement in epistemic practices and more positive perceptions of their learning experience in the virtual mode than when they completed the physical mode first. In contrast, engagement in the physical mode was mostly unaffected by the laboratory order.

Keywords Affordances · Engineering epistemic practices · Environmental engineering · Instructional design · Physical laboratory · Virtual laboratory

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Published online: 13 June 2024

Introduction

The engineering instructional laboratory has long been recognized as critical for the professional formation of engineers. Laboratories provide an opportunity for engineering students to obtain practical experiences interacting with the material world (Balamuralithara & Woods, 2009; Feisel & Rosa, 2005). These experiences can extend and complement classroom learning by engaging students in hands-on engineering practice (Brinson, 2015; Hofstein & Lunetta, 2004; Ma & Nickerson, 2006). Meanwhile, advancements in computing power and access to the internet have enabled new modes for instructional laboratories, often referred to generally as online laboratories. The term online laboratory can refer to different technology types: remote laboratories where students access real laboratory equipment remotely, augmented reality laboratories where technology is leveraged to enhance a physical experience, and virtual laboratories where results are generated from a mathematical model based on student and instructor input and delivered to students either locally or through the internet (Feisel & Rosa, 2005; Ma & Nickerson, 2006; May et al., 2023a). The user interfaces in such laboratories vary from simple graphical representations, recorded videos of real phenomena, or fully situated in virtual reality (May et al., 2023a). In this paper, we focus on virtual laboratories with any level of visual immersion.

Virtual laboratories are becoming popular as an alternative for certain physical laboratory activities (Agustian et al., 2022; Koretsky & Magana, 2019; Potkonjak et al., 2016). Being able to be delivered remotely allows virtual laboratories to serve a rapidly growing population of remote learners (Hachey et al., 2022). However, the instructional design strategies for creating a virtual laboratory activity are rarely explicitly addressed apart from the design of the corresponding physical laboratory. Often, virtual laboratories in science and engineering simply mirror the analogous physical laboratory, borrowing that design and asking students to perform identical tasks (Abdulwahed & Nagy, 2009; Akpan & Strayer, 2010; Bhute et al., 2021; Fung et al., 2019; Klahr et al., 2007; Pyatt & Sims, 2012; Wiesner & Lan, 2004; Zacharia & Constantinou, 2008). Such activity design allows direct comparison of learning outcomes but does not leverage unique learning opportunities possible in the virtual mode. The virtual mode can also be used in combination with the physical mode, and research has shown the benefit of using both modes together (Alkhaldi et al., 2016; de Jong et al., 2013; Kapici et al., 2019; Rau, 2020; Wörner et al., 2022). Finally, some virtual laboratories have been designed to address tasks not possible in a physical laboratory in school (Koretsky et al., 2023; Ouyang et al., 2018; Sánchez Zurano et al., 2022; Zhu et al., 2018). In that case, there is no comparator to evaluate laboratory instructional design, particularly the ways that student learning is related to laboratory mode.

Regardless of mode, a laboratory's instructional design and the resultant outcomes will depend upon the philosophical orientation taken towards what students will learn in that laboratory – we term that the designer's learning orientation. Primarily, past research on comparing learning in virtual and physical laboratory modes has been oriented towards the acquisition of conceptual understanding (Altmeyer et al., 2020; Farrokhnia & Esmailpour, 2010; Flegr et al., 2023; Gumilar et al., 2019; Kapici et al., 2019; Muilwijk & Lazonder, 2023; Olympiou & Zacharia, 2012, 2014; Zacharia & Michael, 2016). These studies measure the conceptual understanding gains of students through test instruments delivered *after* the laboratory activity itself. With a focus on conceptual understanding, designers might make small changes to the virtual laboratory activity, such as providing molecular representations not available in the physical mode (Bennie et al., 2019); however, the overall laboratory instructional design often remains similar to the physical mode.

Following the "practice turn" in the learning sciences (Forman, 2018), we take a different learning orientation, framing learning in terms of participation in the disciplinary practices of engineering work (e.g., designing experiments, analyzing data, effectively working with teammates). From that lens, the virtual and physical laboratories can provide opportunities to cultivate different, complementary engineering practices. Thus, in this study, we sought to create laboratory designs of the same engineering process but that differ in ways that take advantage of the particular opportunities, or affordances, provided by the corresponding laboratory mode. We then characterized the influence of these design choices by identifying the different ways that students engaged in engineering practice *during* the laboratory. We argue such a participation lens can capture students engaging in valued practices that would be opaque with an acquisition lens. Orienting towards engineering practices greatly expands the design space for the virtual laboratory, and, consequently, provides a perspective to contribute to the conversation of how virtual laboratories might effectively be integrated into engineering curricula.

Conceptual framework

As part of the "practice turn" in the learning sciences (Ford & Forman, 2006; Forman, 2018; Passmore et al., 2014), Sfard, (1998) proposed two metaphors of learning: acquisition and participation. The acquisition metaphor has historically been more common in analysis of learning in the laboratory where researchers focus on the acquisition of conceptual understanding (Brinson, 2015; de Jong et al., 2013; Muilwijk & Lazonder, 2023; Wörner et al., 2022). In this work, we instead take a sociocultural perspective that defines learning as more central participation in valued epistemic practices in a community (Furtak & Penuel, 2019; Lave & Wenger, 1991). Instead of the view of knowledge as an abstract entity to be acquired and stored for later use, the participation framing asserts that activities should engage students in ways that resemble the disciplinary practices of engineers since learning cannot be considered separately from the context within which it takes place (Forman, 2018). We argue that the learning as acquisition metaphor and its focus on conceptual understanding naturally leads to creating activities in the virtual mode that tend to mirror the physical mode. On the other hand, the learning as participation metaphor positions each laboratory mode in ways where the affordances of that mode can be tailored to actively engage students with engineering practice in different ways, as described next.

Learning outcomes and affordances

When designing a laboratory activity for instruction, clear learning outcomes should be identified (Wiggins & McTighe, 2005). The learning outcomes guide instructional design and allow meaningful assessment (Feisel & Rosa, 2005; Hofstein & Lunetta, 2004). In 2002, ABET, the primary accreditation body for engineering in the US, convened a colloquy to develop a list of fundamental objectives of engineering instructional laboratories (Balamuralithara & Woods, 2009; Feisel et al., 2002; Feisel & Rosa, 2005). Multiple objectives were identified around topics including instrumentation, models, experiment, data analysis, design, learn from failure, creativity, psychomotor, safety, communication, teamwork, ethics in the laboratory, and sensory awareness. However, the colloquy did not address whether these objectives are things students should acquire or practices they should develop. There has been debate about whether these objectives are all essential (Feisel & Rosa, 2005); furthermore, it is difficult to include all these objectives in a single activity. For instance, it may be difficult to include learning from failure in a traditional laboratory in which iteration is not feasible due to time constraints.

In this study, we posit that laboratory instructional design should also relate the *affordances* of a given laboratory mode to what learning outcomes to target. Affordances, as defined by Gibson (1986), refer to the perceived and actual properties of a thing, particularly as related to functional properties that define how such things could potentially be used. All things have inherent affordances and, as humans, we often perceive and react to these affordances even when we are not conscious of it. You choose a cup instead of a plate to hold a drink because it affords the drink staying in the cup. Affordances are not isolated to a single thing but encompass interactions between things as well. A learning activity, therefore, also has affordances. For instance, imagine a soccer player practicing. In one scenario, they set up cones on the field and dribble through them while, in another, they dribble down a crowded sidewalk. Both drills provide opportunities to improve the player's dribbling ability but have different constraints and affordances. In the first scenario, a constraint is that the cones are in a static pattern. In the second, a constraint is that the playing surface is concrete not grass. In this case, the cone drill better affords developing muscle memory while the street drill better affords learning to adapt to a dynamic environment. Both activities can contribute to the ability of the soccer player to dribble in a real game, part of their soccer practice.

Constraints and affordances of the laboratory depend on many aspects, including, among other things: modality, equipment, expectations, time, participants, location, and the interactions between these factors (Gibson, 1986; Koretsky & Magana, 2019). It may not be possible to predict all affordances; some are dependent on the context, such as the knowledge, attitude, and experiences brought by the participants. However, the affordances of more explicit parts of the laboratory such as the modality can be discovered and more broadly transferred across laboratory designs in that mode. The inherent features of physical and virtual laboratories often lead to the argument that the two modes have different but complementary affordances and that by drawing on the different affordances of each mode the activity as a whole can be improved (Alkhaldi et al., 2016; Coleman & Hosein, 2023; de Jong et al., 2013;

Kapici et al., 2019; Wörner et al., 2022). However, the instructional design must leverage affordances in a way that aligns with the objectives of the laboratory. This dynamic means that each laboratory will leverage affordances differently depending on the context of the activity and the learning orientation taken in its creation.

Engineering epistemic practices

Taking a sociocultural perspective, we relate laboratory instructional design to learning by identifying the *engineering epistemic practices* which are demonstrated by participants as they engage in the laboratory activity. Engineering epistemic practices are the socially organized and interactionally accomplished ways engineers develop, justify, and communicate ideas when completing engineering work (Cunningham & Kelly, 2017; Kelly, 2008). Therefore, instructional design choices that are tailored to encourage targeted epistemic practices can better achieve the learning outcomes of the laboratory activity. Furthermore, it is important to align design choices with the affordances of each mode to effectively promote targeted practices. This analytical framework aligns with our perspective of learning as participation, allowing us to observe how and when students engage in engineering practice.

Engineering epistemic practices can be divided into three categories: material, conceptual, and social (Chindanon & Koretsky, 2023; Koretsky et al., 2023; Pickering, 1996). Material practices refer to interactions with the material world through observation, measurement, collection of data, and production of design artifacts (Bogen & Woodward, 1988; Furtak & Penuel, 2019). Conceptual practices refer to interactions with theory and to developing models to better understand and solve engineering problems (Giere, 1999; Pickering, 1996; Windschitl et al., 2008). Social practices refer to social interactions between engineers to perform engineering work and the social contexts of the outputs of that work (Bucciarelli, 1988; Cross & Clayburn Cross, 1995; Trevelyan, 2014). However, practices often don't fit cleanly into one category and, due to the nature of group interactions, all practices studied here are expressed using verbal or nonverbal communication and, therefore, are social to a degree. Furthermore, engineering epistemic practices do not exist in isolation but instead link together as engineers do work; we refer to this as interlocking epistemic practices (Koretsky et al., 2023).

In this paper, we seek to relate the affordances of physical and virtual laboratory modes to the engineering epistemic practices in which students engage to better understand how each mode's affordances can be leveraged in instructional design. We hypothesize that the physical mode elicits material epistemic practices, affording the development of technical and procedural skills through engagement with physical laboratory equipment (Ma & Nickerson, 2006). The virtual mode affords rapid iterations which can elicit conceptual epistemic practices such as data analysis, experimental design, and metacognitive thinking (Hirshfield & Koretsky, 2020; Koretsky et al., 2011b, 2023). First, we describe the instructional design choices and initial implementation for the physical and virtual mode of the same laboratory activity, the *Jar Test for Drinking Water Treatment*. Rather than having the virtual laboratory mirror the physical laboratory, the design choices of each laboratory mode were influenced by the affordances and constraints of that mode. Within those affordances and constraints, we sought to place students, as much as possible, in the role of engineers doing meaningful work while, at the same time, ensuring productive outcomes. We report on the epistemic practices in which students engage while completing different laboratory instructional designs in the virtual and physical mode. We also account for the impact of the order in which the laboratories were completed. Finally, we discuss how these results are influenced by each mode's affordances and their broader implications.

The research questions for this study are:

- Which types of engineering epistemic practices do groups of engineering students engage in during each instructional mode (physical and virtual) when the laboratory activity (the jar test for drinking water treatment) is designed to align with the affordances of the mode?
- When the same group engages in both modes, in what ways does laboratory order influence the practices students engage in and their perceptions of the laboratory experience?

Instructional design considerations

Commonly, virtual laboratories are designed to replicate the corresponding physical laboratories (Bhute et al., 2021; Fung et al., 2019; Klahr et al., 2007; Wiesner & Lan, 2004; Zacharia & Constantinou, 2008). However, that approach imposes the constraints of the physical laboratory on the virtual laboratory's instructional design, potentially limiting student learning. Here, we took an alternative approach. For the same engineering process, we designed both virtual and physical laboratory activities based on each mode's affordances while seeking to provide experiences that mirror engineering practice as much as possible. In this section, we describe the affordances and constraints associated with each laboratory mode. We then describe how the problem statements for each laboratory activity are *industrially-situated* to reflect real engineering work.

Affordances and constraints

Physical laboratory

Although not universal, there are many affordances and constraints typical of physical laboratories (de Jong et al., 2013; Wörner et al., 2022). Physical laboratories provide students with the opportunity to operate laboratory equipment. While the equipment used can vary, students utilize procedural and haptic skills to collect data. In addition, students are responsible for their safety and the safety of those around them. Skills handling materials and equipment are reflective of real-world engineering practice and difficult to replicate outside a physical laboratory. A large part of this experience is the student's ability to see, hear, touch, and smell things in the laboratory. The tactile information available in physical laboratories has shown to increase conceptual understanding of certain topics (Zacharia et al., 2012).

Physical laboratories can only encompass phenomena that are observable in an educational setting with concomitant size, cost, and personnel constraints. It is typically not practical to replicate industrial-sized engineering equipment in the instructional laboratory. Additionally, certain measurements or techniques are too costly or time consuming to be included in a physical laboratory procedure. As technology advances, equipment becomes more expensive to purchase and more complicated to operate (Feisel & Rosa, 2005). Laboratory costs can limit the scope of physical laboratory procedures to what equipment is available in the instructional laboratory.

Performing a physical laboratory not only requires an equipped laboratory space but also an instructor(s) capable of managing the space and ensuring all students are safe and effective with the tools and procedures. Engineering laboratories can contain many potential hazards, from equipment that could easily be broken to chemicals that are harmful if not handled properly. To safely provide students an opportunity to participate in physical engineering laboratory practices, it is necessary to have instructors available who can train and facilitate students in proper laboratory etiquette and monitor their laboratory activity.

Finally, an unavoidable constraint of physical laboratories is the time needed to perform an experiment. University instructional laboratories typically have set laboratory periods (lasting a few hours) and oftentimes collecting data from an experiment will take most of the period. This constraint often precludes instructional designs where students can iterate or learn from failure, unless additional laboratory time is used. Furthermore, if students fail to obtain quality results from that one opportunity to collect data, learning can be compromised. Thus, many physical laboratories include very descriptive "cookbook" procedures. However, such approaches limit students' agency and ability to engage in experimental design, which is an important part of real engineering practice.

In summary, typical constraints of physical laboratories include the need for adequate budget, equipment, safety, instructors, and time to perform experiments. On the other hand, physical laboratories afford opportunities for students to manipulate real equipment safely and effectively, while observing and otherwise experiencing phenomena and processes in-person and in real time.

Virtual laboratory

Likewise, the affordances and constraints typical of simulation-based virtual laboratories can influence their instructional design. A useful affordance of virtual laboratories comes from the reduced time to complete simulation-based experiments. In many cases the simulation will only take a couple of seconds, orders of magnitude faster than running a physical experiment. This affordance allows iteration to be incorporated into the instructional design. The ability to iterate gives students the opportunity to redesign experiments based on the analysis of their data from previous experiments. Thus, their analysis becomes *consequential*, and they can learn from failure between trials, a feature that is reflective of engineering practice (Cunningham & Kelly, 2017; Vincenti, 1990). However, being able to obtain results so quickly can short circuit learning if students employ a guess and check approach. As described below, intentional design features such as imposing virtual time or virtual cost constraints can discourage students from taking this approach.

Virtual laboratories can create learning environments by modelling and visualizing systems in ways not achievable in physical laboratories. First, virtual laboratories can represent industrial-scale equipment that are too large or complex to be implemented in an instructional laboratory, and thereby engage students in realistic engineering practices (Koretsky et al., 2008, 2022, 2023; Ouyang et al., 2018; Sánchez Zurano et al., 2022; Zhu et al., 2018). Second, virtual laboratories can provide students with information not available in a physical laboratory, such as visualizing the flow of electrons through wires (Sengupta & Wilensky, 2009) or molecular interactions in a gas (Bowen et al., 2014; Koretsky, 2020). This feature allows designs where students can better connect the measurements to the foundational principles they are learning.

A defining constraint of simulation-based virtual laboratories is the inability to observe actual physical phenomena (Potkonjak et al., 2016). Instead, the relevant data are simulated based on theory, added noise, and input from the learners. Some phenomena can be simple to simulate, such as the flight of smooth ball thrown at a specific velocity and neglecting air resistance. However, complicated phenomena are more challenging to simulate accurately. Additionally, virtual laboratory simulations can include random error to provide realistic data similar to physical experiments.

The ways students can interact with the activity in a virtual laboratory are constrained by the activity being enacted on a computer. Furthermore, the nature of this interaction is dictated by the comprehensiveness of the technology design. This constraint poses a challenge of making virtual laboratories feel real and engaging, often referred to as feeling *presence* in a virtual laboratory (Felton & Jackson, 2022; Witmer & Singer, 1998). Virtual laboratories have been critiqued for an inability to elicit students' presence (Nunez & Blake, 2003; Zeltzer, 1992; Zywno & Kennedy, 2000). In a physical laboratory, everything is inherently situated in the physical world. However, in a virtual mode, everything meant to reflect the physical world must be intentionally programmed. At the minimum, the laboratory should provide output data comparable to the physical world so that data analysis in the virtual mode is representative of real engineering practice. Other engineering skills can be more difficult to scaffold in the virtual mode. For example, gaining experience using engineering instrumentation could require creating a graphical representation for students to interact with in virtual space. This virtual representation is possible to create, but expensive and time consuming and could require equipment beyond a computer, such as virtual reality (VR) goggles (Jensen & Konradsen, 2018; Ke et al., 2020; Kumar et al., 2021; Zhu & Howell, 2023). Development time, cost, and technology requirements can constrain virtual laboratories.

In summary, if adequate theoretical models exist and there are adequate time and resources for software development then virtual laboratories allow the simulation of complex, expensive and industrial-scale equipment not typically accessible in physical laboratories. Once developed, virtual laboratories afford the opportunity for students to examine phenomena quickly and provide the opportunity for students to iterate. Additionally, once developed, they can be inexpensively transferred to other institutions. However, in the virtual mode, students lose the ability to directly observe phenomena and manipulate real processes and equipment.

Industrially situated instructional laboratories

To engage students in engineering epistemic practices, the work they are tasked with should reflect real engineering practice as much as possible within an instructional setting. In both laboratory activities described here, we utilize industrially-situated problem statements, creating a task which encourages real engineering thinking where students must collaborate with peers and actively engage with the problem to reach a solution (Collins & Kapur, 2014; Du et al., 2023; Sánchez-Peña et al., 2022; Van den Beemt et al., 2022). Such framing seeks to elicit epistemic practices reflective of practicing engineers (Koretsky et al., 2011a, 2023). However, these designs must fit within the constraints of the laboratory modality and instructional setting. In the physical laboratory studied here, the problem statement is framed so that students are positioned as engineers fulfilling a work task, but the constraints of the mode necessitated a more prescribed experimental approach to ensure students obtained viable data. On the other hand, the virtual laboratory's affordances allowed for the problem to be open-ended, not providing any instructions on what parameters to run and giving students agency to design experiments.

Figure 1 provides a simplified representation of laboratory practice to ground the instructional designs of the physical and virtual laboratory activities reported here. Figure 1a outlines the experimental path a practicing engineer might take to make a process recommendation. Each step is central to participation in engineering practice. Importantly, the arrow on top indicates the process is iterative, and the results from initial experiments can add to an engineer's knowledge about the system (Vincenti,

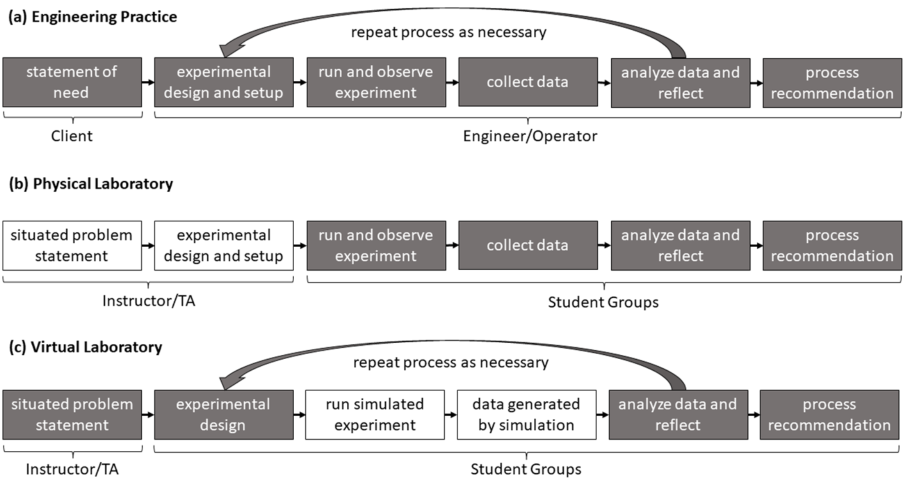

Fig. 1 Comparison of (**a**) engineering practice with (**b**) physical and (**c**) virtual laboratory designs in this work. Shaded boxes indicate elements that physical and/or virtual laboratories share with engineering practice. Unshaded boxes are elements that deviate from engineering practice due to constraints of the laboratory modality or setting

1990). That knowledge can be used to improve experiments to iteratively develop the process recommendation. In a recent survey study, 160 engineering educators ranked the ability for students to design, understand the operation, and analyze the results of experiments to be the most important laboratory objectives (Nikolic et al., 2023).

Due to the affordances and constraints of the respective modes, certain aspects of engineering practice align with the physical laboratory and others with the virtual laboratory. Figure 1b and c compare steps for the physical and virtual instructional laboratories designed here with the conceptualization of engineering practice shown in Fig. 1a. Laboratory elements shaded grey more closely emulate real engineering practice. Even though the problem statements in both laboratories had industrially situated framing, only the virtual laboratory's is shaded grey as it provided the student group with agency to design their experiments, an important aspect of authentic engineering problems. The physical laboratory provides haptic elements and the material practices of observation and measurement, allowing students to experience how laboratory equipment and procedures operate. However, constraints on time and resources limit the ability to incorporate realistic experimental design and iteration. On the other hand, the virtual laboratory affords opportunities for iterative cycles of experimental design, data collection, and analysis/reflection while sacrificing the haptic elements and real-time observation. In the instructional designs reported here, we used both modes in series with the intent that students' cumulative experiences would more completely reflect engineering practice.

Laboratory instructional design

In this section we describe the instructional designs developed for each laboratory mode (physical and virtual). Information about the process (jar testing) which is the basis for these laboratories is provided in the supplemental information.

Physical laboratory instructional design

The physical laboratory instructional design incorporated five main instructional elements: an industrially-situated problem statement, pre-laboratory certification, performing experiments and collecting data, data analysis and reflection, and the development of a process recommendation. These steps reflect elements of real engineering practice as highlighted in Fig. 1b. The problem statement was delivered as a memorandum, requesting engineering services from the student group that intended to place them in the role of practicing engineers (see supplementary information, Figure S.1). Removal guidelines were approximated from USEPA guidelines, because of constraints measuring the total organic carbon. Before entering the laboratory, students watched a video of a jar test, answered a question set, and completed a pre-laboratory assignment. The pre-laboratory assignment had students calculate the volumes of chemical they would need to achieve the doses prescribed in the procedure. These calculations were checked by the instructor before groups were given access to the experiment.

The procedure was delivered as a standard operating procedure from a hypothetical company (see supplementary information, Figure S.2). The procedure first asked students to characterize the source water provided by measuring pH, turbidity, and the absorbance of UV light at 254 nm (UV_{254}). Source water was prepared by the graduate teaching assistant beforehand using a specific recipe. Next, students separated the source water into six beakers and prepared doses of destabilizing and pH controlling chemicals. These chemicals were aluminum sulfate (alum) and calcium hydroxide (lime), respectively. Each of the six beakers received a prescribed dose, and the effects were later analyzed.

The procedure included all three major steps of a jar test: coagulation, flocculation, and sedimentation. For all three steps, the rate of the mixing and duration of mixing were specified in the procedure. Students were instructed to monitor the jars and record any observations during this time. Figure 2 shows a picture of the jars once sedimentation was complete; different chemical doses clearly resulted in different levels of removal as can be seen from the contrasting clarity of the solutions. The final step was to measure the pH, turbidity, and UV_{254} absorbance from samples collected from each jar. Students were expected to use these data to develop a process recommendation of optimal doses of alum and lime. Data analysis and developing a process recommendation were primarily completed outside of the laboratory due to time limitations.

Virtual laboratory instructional design

The virtual laboratory instructional design also incorporated five main instructional elements: an industrially-situated problem statement, pre-laboratory certification, virtual jar test simulation, data analysis and reflection, and a final process recommendation. These steps encompass the aspects of real engineering practice highlighted in Fig. 1c. The simulation revolved around a mathematical model, coded in Python, and

Fig. 2 A photograph showing the results of a typical jar test completed in the physical laboratory mode. The leftmost jar is the control, with chemical dosage increasing to the right. Clearer water is desired

housed in an html user interface. The mathematical model is based on the work of Weber-Shirk and co-workers (Du et al., 2019; Pennock et al., 2016, 2018; Swetland et al., 2013, 2014) with added functionality to simulate changes in aqueous inorganic chemistry and to account for the removal of natural organic matter (Edwards, 1997). In addition, random noise was added to the output. The laboratory was implemented through an online software called Concept Warehouse (Koretsky et al., 2014). The user interface includes an industrially-situated problem statement (see supplementary information, Figure S.3), a pre-laboratory certification, a screen for students to input experimental parameters (Fig. 3), a results screen (Fig. 4), a screen to input final recommendations, and a final screen to confirm the activity is complete.

Like in the physical laboratory, the problem statement was delivered as a memorandum requesting engineering services. Also like in the physical laboratory, the pre-laboratory assignment included sample calculations for determining the volume of chemical needed to achieve a certain dose. Students were tasked with developing a recommended dosage of alum and lime by the end of a hypothetical workday. The initial turbidity, organic carbon concentration, UV_{254}, pH, and alkalinity of the water are set by the instructor in the Concept Warehouse and provided in the memorandum. In this way, each group worked with water of different quality. The objectives for turbidity, pH, and carbon removal were based on USEPA guidelines.

In the virtual laboratory, students authored their own experimental design. No doses or volumes of chemical were provided, prompting students to use their foundational understanding and past results to generate each experimental design. After the group obtained results from an experiment, they could choose to either run more experiments or submit final recommendations, allowing students to iterate until they achieved satisfactory results or ran out of time. A time constraint was imposed on the virtual laboratory, allowing a maximum of four iterations. This constraint both situ-

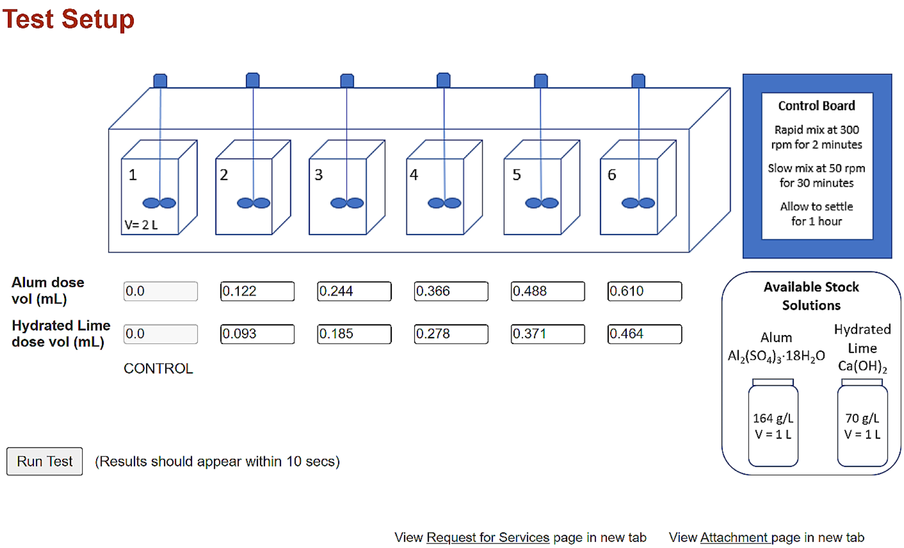

Fig. 3 Screenshot of the virtual laboratory user interface for students to input the chemical doses they choose to run. Mixing settings and available stock solutions are displayed on the right

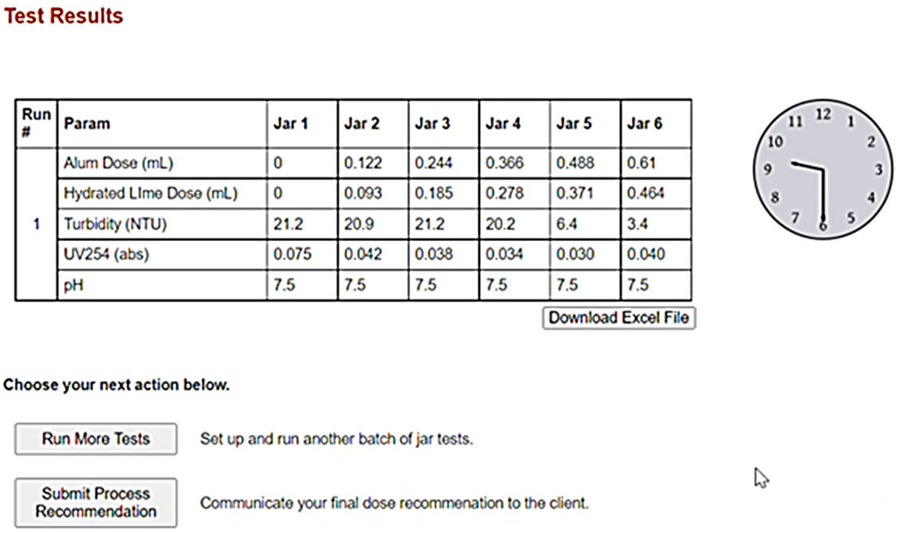

Fig. 4 Screenshot showing the virtual laboratory results screen. This provided the simulation results from previously run experiments, and options for running more experiments or submitting final process recommendations. The simulation time is displayed on the right, informing students how much time (how many iterations) they have remaining

ated the activity in a hypothetical workday and made each experiment consequential. Students needed to recommend an optimal dosage within three iterations, but they could use a fourth run that required charging the client overtime. The optimal dosage had to meet removal requirements for turbidity and organic carbon concentration.

Summary

To summarize, design features and related affordances and constraints for each mode are tabulated in Table 1.

Methods

Research design

This naturalistic, qualitative study design used a small sample (4 groups of 3 students) but collected rich data from each. Data collected included process (video), product (written reports), and reflection (semi-structured interviews) measures. We used these complementary measures to account for context and provide a thick description of the phenomenon we observed (Geertz, 1973). We employed a quasi-experimental 2×2 factorial design based on laboratory mode (physical or virtual) and laboratory order (virtual first or physical first).

Table 1 Summary of design features and their relationships with the affordances and constraints of the jar test physical and virtual laboratories

	Design Feature	Affordance leveraged	Constraint addressed
Physical	Prescribed chemical doses	-	Can only run a single test
	PPE and instructor supervision	Using laboratory equipment and chemicals	-
	Measure UV absorbance as a surrogate for organic carbon	-	Equipment to directly measure organic carbon is not available
	Relaxed removal guidelines	-	Experimental variability
Virtual	Agency to set experimental parameters and iterate	Receive data quickly from the simulation	-
	Imposed virtual time constraint	-	Can guess and check
	Delivered through the internet	Not bound to location	-
	USEPA removal guidelines	Precise data	-
	Variability added to data	-	Data from simulation

Positionality

The authors of this work are US-born, cisgender, white, able-bodied, straight men, all with engineering degrees. The first author is a graduate student in chemical engineering, whose thesis work focuses on education research. He was an undergraduate student during the COVID-19 pandemic and brings the experiences of being a student enrolled in remote learning. Both the second and third author have extensive experience teaching chemical and environmental engineering, respectively. The second author directs a research program studying learning and engagement in the formal, post-secondary classroom targeted at the development of disciplinary practices. His group has experience studying epistemic practices and virtual laboratories in engineering (Bowen et al., 2014; Koretsky, 2020; Koretsky et al., 2011a, b, 2023). The third author brings industrial and research experience in water treatment and has taught several laboratory courses which incorporate jar testing. As authors, we acknowledge our privilege as white, male engineers, and recognize that positionality influenced our choices in this research study.

Participants and setting

The laboratories were delivered to junior and senior chemical engineering students in an upper-level laboratory course. The students performed the experiments in groups of three, completing a laboratory in each mode over two consecutive weeks. To accommodate physical equipment constraints, half the groups completed the Jar Test Physical Laboratory first followed by the Jar Test Virtual Laboratory and the other groups performed the laboratories in the reverse order.

Data were collected for four groups of three students as they completed each laboratory task. All students provided informed consent. Student groups were video recorded any time they were in the laboratory. Three data sources were used. First, video data were collected. Audio was captured using speakerphones placed throughout the laboratory. During these laboratory recordings, field notes were taken by the researcher present (the first author). In addition to recording their work in the laboratory, groups were invited to be recorded as they worked outside of the laboratory session on their final reports. Two groups consented but the recordings only captured a part of the time that they worked outside of the laboratory. Second, all student work products, including their final written reports, were collected. Third, eight of the twelve participants were interviewed about their experience. The interview protocol is provided in the supplementary information.

Data analysis

Video data and interviews were transcribed verbatim. The video recordings of laboratory activity were divided into episodes bounded by a change in strategy or change in topic. Then, discourse analysis (Fairclough, 2003; Handford & Gee, 2012) was used to identify the types of epistemic practices the groups engaged in and the ways those practices moved the work forward. Preliminary codes were generated by the first author using the software Atlas.TI 9 (Hicks, 1996; Ryu & Lombardi, 2015) and lending from past work (Chindanon & Koretsky, 2023). As the analysis progressed, coding was refined, with existing codes being changed and emergent codes being added as new phenomena were identified. The codes that are reported and analyzed in this work were grouped into larger categories of conceptual, material, and social epistemic practices. These epistemic practice codes are tabulated and described in the supplementary information (Table S.1). A subset of codes is presented in Table 2 to exemplify the types of practice in each category. All three authors met regularly to discuss codes, coding strategies, and iterate on interpretations. Following the coding of the laboratory observations an ANOVA was performed which compared the effects

Table 2 Example codes from each of the three epistemic practice categories (conceptual, material, and social)

Category	Code	Definition	Example
Conceptual	Analyze experimental data	Group members make sense of experimental data they have collected.	Spotting a trend in the data.
Conceptual	Principles reasoning	Using fundamental engineering, math or science principles to reason/make an argument.	Using stoichiometry to determine how much lime needs to be added to keep pH constant.
Material	Discussing equipment use	When the group is discussing how they'll use lab equipment to achieve a task or about how a piece of equipment works	"Do I need to calibrate this pH probe before I use it?"
Material	Elaborate experimental strategy	Clarifying and justifying experimental strategy to other group members.	Tell the group what alum and lime concentration they will add to a certain jar.
Social	Co-constructing understanding	Group members collectively making sense of the laboratory through discussion.	Group members all providing differing reasoning for accepting or rejecting an experimental plan.
Social	Sharing information	Sharing information from sources (internet, book, laboratory notes, analytical equipment, virtual laboratory) among group members.	Relaying experimental results to group members.

of laboratory mode (physical or virtual) and order (first or second) on the occurrence of engineering epistemic practices (conceptual, material, and social).

Following analysis of the laboratory observations, the interview and laboratory report data were coded for confirmation or disconfirmation of the findings and to understand students' perceptions of their experience in each of the laboratory settings. Due to the different content in the interviews and laboratory reports, different coding schemes were used for each. For the interviews, the focus was on how students engaged with the instructional design and conceptualized their learning. For the reports, we looked at the types of evidence and justification students presented to support their conclusions. These codebooks can also be found in the supplementary information (Tables S.2 and S.3).

Trustworthiness

To establish trustworthiness in this study we have followed guidelines from the literature, seeking to establish the credibility, dependability, confirmability, and transferability of our study (Forero et al., 2018; Stahl & King, 2020). The second and third authors brought expertise in engineering education research and environmental engineering, respectively. This expertise related to both the content of the laboratories and the research methods employed. The first author spent approximately seven hours with each student either observing group work or interviewing them individually. The interview protocol that was used was successfully employed in previous studies (Gilbuena et al., 2015). Interviews and collected artifacts were used to cross-validate the analysis of the laboratory observation videos when developing the codebook and interpreting the data. The authors met weekly throughout the coding process to discuss findings and make changes to the codebook. Furthermore, education researchers from outside the group were consulted about preliminary findings. The coding was done iteratively with the first author frequently reviewing and recoding the transcripts based on the developments in the codebook and the feedback received. These iterations allowed us to reach a theoretical saturation of data as eventually the coding became stable from iteration to iteration.

Results

This section presents the results of our analysis of the process, product, and reflection of learning by students in the Jar Test Physical and Virtual laboratories. First, we describe the epistemic practices that the students demonstrated in the physical and virtual modes, answering our first research question. We then present findings related to how the laboratory order influenced student engagement and learning, answering our second research question.

Student epistemic practices

Table 3 shows the occurrences of engineering epistemic practices based on the coding of the video recordings. Individual codes were quantified by the number of epi-

Table 3 Observed occurrences of engineering epistemic practices, time spent, and number of iterations for each laboratory

Laboratory	Virtual Laboratories (V)					Physical Laboratories (P)				
Order	First		Second			Second		First		
Group	A	B	C	D	Mean (M_V)	A	B	C	D	Mean (M_P)
Epistemic practice					**Number of occurrences**					
Conceptual	112	80	43	42	69.3	6	7	10	4	6.8
Material	54	49	23	19	36.3	48	69	86	99	75.5
Social	215	175	129	123	160.5	91	136	161	167	138.8
Total Count	380	305	195	184	266	145	212	257	270	221
Time Spent (min)	121	94	52	57		168	144	160	160	
Time Off-topic (min)	12	1	0	14		62	44	33	51	
# of Iterations	4	3	2	2		1	1	1	1	

sodes in which they appeared and then grouped into broader categories of conceptual, material, and social practices. The effect of laboratory mode (physical or virtual) and laboratory order (first or second) on these coding categories was then compared with ANOVA, the results of which are provided in the supplementary information. In terms of frequency, groups demonstrated greater engagement in conceptual epistemic practices during the virtual laboratory ($M_V = 69.3$, $M_P = 6.8$, $p = .002$) where M_V and M_P refer to the mean code counts of each category in the virtual and physical modes, respectively. On the other hand, groups showed greater engagement in material practices during the physical laboratory ($M_V = 36.3$, $M_P = 75.5$, $p = .003$). The engagement in social practices wasn't significantly different between the two laboratory modes ($M_V = 160.5$, $M_P = 138.8$, $p = .226$).

Information about how each group spent their time in the laboratory and the number of iterations they completed are also shown in Table 3. Not only did the virtual laboratory elicit greater engagement in conceptual practices than the physical laboratory, but the engagement was achieved in less time. Groups spent longer working in the physical laboratory (144–168 min) than the virtual laboratory (52–121 min). The Jar Test Physical Laboratory includes about an hour of waiting while the flocculation and sedimentation processes occur. Although groups used some of this time to make observations of the jars, they often were off topic, ranging from 33 to 62 min in the physical laboratory compared to 0 to 14 min in the virtual laboratory.

Students' reflection interviews align with the epistemic practices in which they engaged. When asked about the physical laboratory, students recalled material practices like learning to use the measurement tools and watching the flocculation and settling occur. Students discussed how these practices aided them in reaching their goal of physically completing the process and collecting data from it. For example, a student in group C described the physical laboratory as follows:

> We went into it with a plan. So, we had some extra work that we put in beforehand. Then we did the experiment, we put the alum in the lime, and then monitored the jars for an hour. It was like half an hour, and then half an hour. So, we monitored the jars. Then did our calculations. It felt pretty straightforward.

When asked about the virtual laboratory, students recalled conceptual practices like analyzing experimental data, then using this analysis to develop new ideas and further their understanding of the system. Students discussed how these practices led to them reaching their goal of providing an optimized recommended dose of chemical within the time constraint. A student from group A described how each run had a specific purpose, to expand their understanding or improve their confidence in their answer.

> The way we went about approaching that was because we had two different variables that we could change was the alum dose, and then the pH. I guess we looked at it as a ratio of the lime stock to alum. And so we did one factor at a time. So we got a basis with the first run. And so we did a skew, so a bunch of different doses of alum. And then for the second run, we did essentially the same thing, but for lime stock concentration. And then for the final one, which

we went into overtime for it, but we were just curious on if we could improve our results at all.

Students did not use the terminology of material and conceptual epistemic practices, but they did acknowledge using different skills and thought processes to complete the two different laboratory modes.

Laboratory reports are commonly used to assess if students have achieved the intended learning outcomes. However, while the video showed clear differences in types of engagement, the laboratory reports, themselves, showed little difference between laboratory modes. All groups were able to come to reasonable conclusions on optimal parameters for water treatment in each laboratory mode. These were reported similarly for all groups. Optimal dosages were justified by meeting the removal requirements with the least amount of chemicals. Additionally, some groups used statistics to defend their dosage recommendations further, arguing that they would be reproducible in an industrial setting. There were only subtle differences between the modes. The physical laboratory reports provided the procedure and observations made during the experiment in greater detail. Groups reported more data in the reports of the virtual laboratory because they ran multiple iterations of the experiment in that mode. Furthermore, the industrial situation presented in each laboratory's problem statement was slightly different and the reports reflected that. The physical laboratory asked students to look at the feasibility of a new water source while the virtual asked students to respond to a storm that had impacted water quality.

Laboratory order

The order that groups completed the laboratories had a significant impact on the frequency of epistemic practices observed; groups engaged in more epistemic practices in the first laboratory they completed (see Table 3). This effect was significant for all three categories of epistemic practices: conceptual (p=.030), material (p=.007), and social (p=.031). The interaction between laboratory mode and order also had a significant effect on conceptual epistemic practices (p=.031). Groups completing the virtual laboratory first engaged in an increased amount of conceptual epistemic practices (M_1=96) when compared to the groups that completed that mode second (M_2=42.5). The interaction of laboratory mode and order was not significant for either material (p=.795) or social (p=.576) practices. The laboratory reports corroborated the finding that groups that completed the virtual laboratory first engaged differently in conceptual epistemic practices than those completing the virtual laboratory second. Groups that completed the virtual laboratory first ran more experiments, providing a larger corpus of data to include in their reports. Additionally, these groups' reports had a more in-depth discussion of what trends emerged from their data.

Interview responses relevant to this analysis are summarized in Table 4. Students tended to place higher value on the types of epistemic practices they engaged in the first laboratory they completed, painting two very different pictures of their laboratory experiences. In all but one case, students expressed preference for the first laboratory mode they completed (five of five for the physical mode and two

Table 4 Summary of responses to interview questions from participating students

	Order	Virtual Laboratory First			Physical Laboratory First				
	Group	A	B		C		D		
Question	Student	1	1	2	1	2	1	2	3
Laboratory preference		V	P	V	P	P	P	P	P
Best laboratory for a class		P	P	V	P	P	P	P	P
Order preference		V -> P	N/A	V -> P	N/A	P -> V	P -> V	N/A	P -> V
Most constrained laboratory		P	V	P	V	V	V	V	V
Most industrially-situated laboratory		V	V	V	N/A	P	N/A	V	P
Suggestion for physical laboratory		Ability to do multiple runs	Better stirring for the water	Ability to do multiple runs	Get procedure with pre-lab	Better glassware	Better measuring tools	More space to work	Have students label the materials
Suggestion for virtual laboratory		Ability to do DOE, have more runs	Prompts to explain thinking more	Feedback on final dose	Visuals and procedural steps when running tests	Visuals when running tests	Go through procedural steps when running tests	N/A	Visuals when running tests

of three for the virtual mode). Other than the one case, the laboratory mode that students preferred aligned with the mode they thought would be best to use in class; one of the students who preferred the virtual mode said the physical mode would be preferred if they could only use one mode because "nobody likes virtual apps," and "the hands-on experience is unique." The order the laboratories were completed tended to correspond with students' order preference, opinion of how constrained each laboratory mode was (inversely), and industry relevance of the modes. There were two exceptions - one student who completed the virtual laboratory first thought it was more constrained and one student who completed the physical laboratory first thought the virtual laboratory was more industrially relevant. Furthermore, the students' suggestions for the laboratory they completed second typically related to making it more like the one they completed first. Four of the five students who completed the physical laboratory first made suggestions for the virtual mode to involve visuals or procedural steps when performing experiments. These students saw value in the material interactions they had in the physical laboratory, receiving visual and haptic feedback for their actions, and wanted similar experiences in the virtual laboratory. On the other hand, two of the three students who completed the virtual laboratory first wanted to be able to do more experiments in the physical laboratory and have agency to choose the input parameters. Here, students saw value in designing experiments and building an understanding of how chemical doses affected the outcomes of the laboratory this way. A detailed account of the type of reflection seen with each laboratory order is provided in the supplementary information.

Instructional design alternatives

Like the experimental design in the virtual laboratory presented here, instructional design is iterative. We have shown that our design leveraged the affordances and constraints of each mode to elicit specific epistemic practices. In the case of the laboratories presented here, we identified three features salient to the effectiveness of using the Jar Test Physical and Virtual Laboratory in succession: *order*, *degree of replication*, and *prescription*. Below we elaborate on these three features and illustrate how we could use this understanding to improve the instructional design. The potential improvements will be specific to the context of the Jar Test laboratory design but serve as an example of how to design laboratory activities with affordances in mind.

Order refers to the order in which the laboratories are completed. The additional information students had when they completed the physical laboratory first resulted in a short-circuiting of experimental design and iteration in the virtual mode. Degree of replication refers to the extent to which the laboratory objectives, initial conditions, and experimental parameters replicate one another in the physical and virtual modes. Aligning the conditions of each mode can lead to more information being able to be transferred from the first to the second laboratory. Alternatively, if the conditions in each laboratory are not the same (in our case, using a different source water, or a different coagulant), an opportunity for cognitive dissonance is created where students need to reconcile how those conditions change the outcomes of their experiments. Finally, prescription refers to the extent to which process parameters are prescribed for students. Prescribed parameters can help ensure that students get quality results in limited laboratory time, while leaving the parameter selection to students gives them the opportunity to engage in authentic, iterative experimental design.

We illustrate the three features discussed above with two improved designs of the physical and virtual modes used together in the Jar Test laboratory. In this work, we implemented the laboratories with aligned initial conditions, prescribed doses in the physical mode, and in two possible orders (physical first or virtual first). Based on our observations, one possible improved design would involve completing the physical laboratory first with prescribed doses but *not* having the initial conditions align with the virtual laboratory. That is, change the initial water quality in the virtual mode so that the parameters provided in the previous physical mode do not effectively treat that water source. This positions the virtual laboratory as a place for students to grapple with the dissonance of the optimal doses not being the same, leading them to explore the differences through the experimental iteration afforded by the mode. Presumably, this design would encourage students to develop understanding of the trends that occur in a jar test and how the initial water quality affects those trends, engaging in valuable conceptual epistemic practice – an aspect that was mostly unexplored by Groups C and D. The second design would have the virtual laboratory completed first; the physical laboratory would then have aligned initial conditions but no prescribed doses. In this implementation, the virtual laboratory could serve as a pre-laboratory activity where students would choose the parameters they wanted to run in the physical mode based on their virtual results. In this design, the physical laboratory gives students the material context for their work in the virtual laboratory, getting to observe the processes and take the measurements firsthand, while also giving them agency to design their experiment and use what they had learned the previous week. In both modified designs, we sought to adjust our original instructional design to leverage the affordances of each mode to a greater extent, thus engaging students in a deeper and more extensive set of engineering epistemic practices.

Discussion

Research question 1: epistemic practices

For research question 1, we found that even though both the physical and virtual laboratory modes had the same deliverable - recommending process parameters to provide clean drinking water - they engage students in different types of epistemic practices. In the physical laboratory, students more frequently engaged in material epistemic practices, while in the virtual laboratory they more frequently engaged in conceptual epistemic practices. This observation aligns with the instructional design and affordances of each mode. This finding suggests that virtual laboratory developers should not constrain themselves to replicate an analogous physical laboratory, but rather orient the design around engagement in epistemic practices afforded by the technology. The work presented here contributes to the recent conversation about the pedagogical and social aspects of online laboratories (see for example, May et al., 2023b, c) by providing insight into how students engaged in a virtual laboratory by characterizing the different engineering practices the groups employed while completing the task.

Looking through the lens of participation in valued epistemic practices instead of acquisition of conceptual understanding, we were able to see how activity differed between the modes. Many studies which compare laboratory modes compare students' scores on tests taken before and after completing the laboratory, not focusing on activity in the laboratory itself (Brinson, 2015; Nikolic et al., 2021). In contrast, we used a participation orientation to shift focus to characterizing how students participated in their laboratory work rather than knowledge, skills, and dispositions that were acquired and measured afterwards. The physical laboratory afforded students the chance to interact with laboratory equipment and observe the physical processes of the jar test (coagulation, flocculation, and sedimentation) while following a technical procedure, facilitating material epistemic practice. However, the instructional design directed students to follow a prescriptive procedure since they were constrained to one data collection opportunity within the time allocated for the laboratory period. Without such direction, many students likely would not have the chance for the type of rich analysis of their experimental data that leads to learning (Renken & Nunez, 2013). Consequentially, students engaged in material practices, using equipment and making observations, but did not have the agency to design their own experiments. Physical laboratories often limit student agency in experimental design because of time and money constraints (de Jong et al., 2013; Wörner et al., 2022). Past studies have found physical laboratories to be more effective when haptic feedback is an important part of the learning experience (Lazonder & Ehrenhard, 2014; Zacharia et al., 2012). Engagement in material practice can be a mechanism for students to receive this feedback, an affordance of the physical mode that should be considered in instructional design.

Furthermore, the enactment of disciplinary practices was mostly sequential in the physical laboratory. Students first engaged in material practices as they collected data and then engaged in conceptual practices when they analyzed the data later outside the laboratory. This design did not challenge them *during* the laboratory to conceptually grapple with why doses did not work or evaluate if they could better optimize the dose. They were not prompted to reflect on results until writing the report later. That is not to say that conceptual practice was entirely absent during the physical laboratory. For example, students repeated measurements that they were unsure about and one student reported during the post-laboratory interview that the physical laboratory made them think about why they were using equipment. However, this latter case was described as an internal process and wasn't observed in their interaction with the group. Primarily, students in the physical mode spent the time in the laboratory focusing on the material practices needed to complete the procedure with less attention to conceptual practices needed to understand the phenomena they were observing.

In contrast, the virtual mode afforded students the opportunity to engage in conceptual practices as part of their experimentation - needing to analyze data, learn from failure, and create new experimental plans multiple times in a single laboratory period. We attribute the increased frequency of conceptual practice to the cycles of iteration and the lack of a specified experimental procedure in the virtual mode. With each iteration, student groups grappled with new data that they needed to understand to either design their next experiment or justify a final process recommendation. To progress in the laboratory, students had to make sense of the system *using* their data, encouraging conceptual practice to inform experimental design. This cycle facilitates students' conceptual epistemic practice as they proceed towards the laboratory deliverable and is enabled by affordances of the virtual mode. Particularly, the affordance of quick data generation allowed multiple trials to be run in much shorter time (de Jong et al., 2013; Muilwijk & Lazonder, 2023; Wang et al., 2014; Wörner et al., 2022). Since the virtual laboratories were completed in less time than the physical laboratories, results reported in terms of epistemic practices per time instead of per laboratory would reflect even more favorably on the virtual laboratory. Here, we reported results in the more conservative way.

Our results are consistent with that of Puntambekar et al. (2021) despite differences in level (middle school vs. university) and disciplinary orientation (science vs. engineering), suggesting the transferability of a participation learning orientation focused on epistemic practices. They compared middle-school students' science talk in completing either a physical or virtual laboratory about pullies. By looking at students' talk during the activity, they inevitably oriented towards their disciplinary practices while participating in the laboratory. In the physical laboratory, students mostly discussed setting up the apparatus, measuring, and calculating outputs. This talk type aligns with the material epistemic practices we observed in the Jar Test Physical Laboratory. On the other hand, talk during the virtual laboratory was mostly focused on making predictions and understanding patterns, more akin to the conceptual epistemic practice we observed in the Jar Test Virtual Laboratory.

We observed students engaged in different epistemic practices in physical and virtual modes; this finding is consistent with reports that claim physical and virtual laboratories have complementary affordances, and that, correspondingly, student learning increases with instructional designs that use both modes together (de Jong et al., 2013; Flegr et al., 2023; Kapici et al., 2019; Wörner et al., 2022). Most of the reports looking at physical and virtual laboratories together orient primarily around the acquisition of conceptual understanding and find that combining laboratory modes leads to better student performance on conceptual tests given after the laboratory activity. However, our orientation on learning as participation in disciplinary practice leads to a conceptualization of affordances as providing the opportunity to engage in different engineering epistemic practices. In both a participation orientation or an acquisition orientation, the differences of affordances with mode enrich student learning.

Recently, researchers have approached instructional design and learning in physical and virtual laboratories taking an inquiry lens (Brinson, 2015; Muilwijk & Lazonder, 2023; Rau, 2020; Wörner et al., 2022). While inquiry can be framed in terms of participation in epistemic practices, often educators remain tethered to an acquisition orientation of learning. For example, in their reviews, Wörner et al. (2022) and Muilwijk and Lazonder (2023) analyzed 42 and 35 studies, respectively, that examined only gains in conceptual understanding measured after the activity. Similarly, Rau (2020) takes a theoretical approach comparing five learning theories but contrasts the theories only in ways that they explain the acquisition of conceptual knowledge. We do not question that gains in conceptual understanding are an important outcome of science and engineering education; rather, we seek to call broader attention to all the material, conceptual, and social practices needed to make progress in this disciplinary work.

There is recent interest in how students learning in the laboratory extends beyond conceptual understanding (Reynders et al., 2019); yet, few reports explicitly address the influence of laboratory mode. Brinson (2015) scopes his comparison of laboratory mode to also include "inquiry skills, practical skills, perception, analytical skills, and social and scientific communication" (p. 218). He concludes that relatively few studies have addressed these broader skills with most studies focusing on conceptual understanding. Importantly, relative to what is reported in our work, the studies identified in that review orient learning towards the acquisition of these skills as determined through a measure *after* activity rather than viewing learning as participation in valued practices *during* activity. Bumbacher et al. (2018) do examine practices during activity, comparing experimentation strategies students used in different laboratory modes. A cluster analysis identified two groups of strategies (productive and unproductive) based on differences in scores on a pre and post laboratory conceptual test. Their learning orientation is conceptually focused as they seek to engage students in practice that will cause them to perform better on tests of conceptual physics knowledge. Our orientation, in contrast, is industrially situated, seeking to engage students in practice representative of engineering disciplinary practice. Bumbacher and colleagues found that experimentation strategies mediated the effect of mode on conceptual understanding and that this effect was dependent on the affordances of the mode (which they call a manipulative environment). In our work, affordances mediated the effect of the instructional design of each mode and we found that led to engagement in different engineering epistemic practices.

Despite differences in learning orientation, a connecting thread across these findings is that virtual laboratories are predisposed to engaging students in different practices than physical laboratories. We add to the conversation on how students engage in practice differently between laboratory modes by describing it through the lens of participation in engineering epistemic practice with a corresponding focus on activity during the laboratory.

Research question 2: laboratory order

For research question 2, we found that laboratory order influenced the epistemic practices the students demonstrated, especially regarding the conceptual practices in the virtual laboratory. This effect is demonstrated by the significant interaction effect between laboratory mode and order on conceptual epistemic practices. This finding was evidenced in two ways. For groups completing the virtual laboratory first, (i) the video evidence showed a deeper level and more extensive use of conceptual epistemic practices; and (ii) during interviews, the reflections of these students indicated they valued the virtual laboratory more than the groups that completed the physical laboratory first. However, when reviewing the virtual laboratory final reports, differences were limited to groups A and B having more data to discuss since the virtual laboratory allowed multiple trials. Reports are a typical form of laboratory assessment and, looking at them alone, all four groups were able to synthesize similar information and appeared to achieve similar learning outcomes. It was only through our other forms of analysis that significant differences between mode and order emerged.

The effect of order was more prominent in the virtual mode than the physical mode, with students reporting very different experiences depending on the order that the labs were completed. The virtual laboratory instructional design was based on the premise that students would begin with incomplete knowledge of the system, needing to use information from successive runs to build understanding. Consequently, the groups who completed the virtual laboratory first used theory to determine their initial experimental strategy, which they then modified multiple times during the laboratory activity. However, when students completed the physical laboratory first, they were (unintentionally) provided a set of initial doses that had been prescribed in the physical laboratory they completed the week before. These conditions came close to meeting process objectives in the virtual laboratory, short-circuiting the need to grapple with choosing the initial conditions and build understanding. This finding is reflected in student interviews. One student who completed the physical laboratory first described their experience in the virtual laboratory, “I mean, we were just looking at a white screen, with some numbers, and a table. It was very boring and tiring.” In contrast, a student who completed the virtual laboratory first compared the virtual laboratory to their summer internship stating it felt like an authentic industry task. On the other hand, the physical laboratory appeared to be experienced similarly by students regardless of laboratory order. Students leveraged the affordances of the physical mode to engage in material practice by following the procedure. The effects of laboratory order on student experiences shows the importance of instructional design, particularly in the implementation of the virtual mode in this context. Students engaged in more conceptual epistemic practices and had a more positive perception of the virtual laboratory when completing it before the physical laboratory.

Previous researchers have sought to determine sequencing strategies for using physical and virtual modes together in instruction, but results have been inconclusive about laboratory order. Many studies have found the sequence of laboratories have no effect on the outcomes of using physical and virtual laboratories together (Kapici et al., 2019; Olympiou & Zacharia, 2012; Wörner et al., 2022; Zacharia & de Jong, 2014). Others have found it more effective to place the virtual laboratory first (Achuthan et al., 2017; Akpan & Andre, 2000; Toth et al., 2014), including a review (Wörner et al., 2022) that identified 13 cases which only used a combination of laboratories with the virtual mode first, arguing it would provide abstract knowledge or procedural skills necessary in the physical mode. However, other studies found the opposite, claiming a better outcome was achieved with the physical mode positioned first (Gire et al., 2010; Smith & Puntambekar, 2010).

We argue that optimal laboratory order is not an intrinsic property of laboratory mode. Rather, the optimal laboratory order depends on the instructional design, learning orientation, and context. How the affordances of a laboratory mode are leveraged in its design will influence the effect of sequencing. For example, during the design of the laboratory reported in this study, we could have set the initial water quality in the virtual mode to be very different from the physical mode. In that way, the initial doses in the physical mode would not have provided a viable starting point and the groups completing the virtual laboratory second would need to grapple with why the doses in the physical mode did not adequately work. In terms of learning orientation, we compare our results with Kapici et al. (2019) who found no difference in the effectiveness of sequences of physical and virtual laboratories when comparing how students performed on tests of conceptual understanding and inquiry skills. Their approach used an acquisition orientation of learning that evaluated conceptual understanding and inquiry skills through testing after completion of the laboratory activity. In our work, all groups produced similar laboratory reports despite the fact that other measures found epistemic practices were dependent on the mode and sequence of the laboratories. Had our work taken an acquisition orientation rather than a participation orientation, we may have arrived at different conclusions.

Limitations

This work has several limitations. First, the laboratories only address a single engineering topic delivered in a single upper-level chemical engineering course and, therefore, the epistemic practices are only explored in this context. Additionally, this study only investigated one virtual laboratory design along with a physical laboratory; it would be useful to have parallel studies using other virtual laboratory technologies. Both the laboratory affordances and epistemic practices are contextual and will depend on the environment in which the laboratory is implemented. For example, it would be interesting to investigate the epistemic practices elicited by other variations of an online Jar Test laboratory, such as laboratories that are remotely accessed or have virtual reality based user interfaces. The virtual Jar Test Laboratory reported here was developed as a minimum viable product and partially served to aid in the development of a more sophisticated user interface where students will control an avatar in a 3D simulated laboratory space. However, even with this preliminary interface design, the results are promising. Future work will focus on the extent to which visual immersion influences activity in the virtual laboratory mode.

As a naturalistic study, the laboratories were delivered within the structure and rules of an existing course. For example, while this topic draws on curricular knowledge of both chemical and environmental engineering, the backgrounds of students studied here were in chemical engineering; we are currently investigating how environmental engineering students engage in this laboratory topic, and suspect that their different disciplinary background will influence the conceptual practices that are elicited. Finally, the class was structured for one student to be group leader each week, receiving twice the number of points for that laboratory as the other group members. Such disproportionate responsibilities could influence the social practices of the group. Again, here we are currently exploring delivering these laboratories in a context of more equal participation responsibility. Furthermore, data analysis taking a participation orientation is cumbersome, resulting in smaller sample sizes than studies using an acquisition orientation. Despite these limitations, this study revealed the different ways that students used epistemic practices of engineering to complete physical and virtual laboratory tasks.

Conclusions

We describe instructional designs of a Jar Test for Drinking Water Treatment laboratory for both physical and virtual modes. Each laboratory was designed differently, matching the affordances of the respective modes. The design objective was to engage students in a broad range of engineering disciplinary practices. Framing learning as participation in disciplinary practice rather than as acquisition of conceptual understanding, we evaluated which practices students engaged in during the laboratory activities. The idea was not to compare the merit of one mode relative to the other but instead to investigate how the disciplinary practices students engaged with differed between modes and how this understanding could inform laboratory instructional design. To do so, we collected a rich set of qualitative data to look at three aspects of students' experience: process, product, and reflection.

Through this study, we found that each mode elicited different engineering epistemic practices. Material epistemic practices were more frequently observed in the physical mode, while conceptual practices were more efficiently scaffolded in the virtual mode. Moreover, instructional design choices (such as laboratory order) affected how laboratory affordances were leveraged by students, therefore changing how they engaged in practice within each laboratory. In the study presented here, positioning the virtual laboratory before the physical laboratory led students to engage in conceptual practices to a greater degree in the virtual mode while engagement in the physical laboratory was mostly unaffected by laboratory order. When combined, both modes were positioned in a way that leveraged the affordances of each, and students engaged in a wider and deeper set of practices than with either mode individually. This result suggests promise for instructional uses of virtual laboratories both as complementary pieces to physical laboratories and as stand-alone activities.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12528-024-09403-7.

Acknowledgements The work reported here was supported in part by a grant from the National Science Foundation (EEC 2204885 and EEC 2204933) and the Oregon State University Center for Research in Engineering Education Online (CREEdO). We appreciate the cooperation of Prof. Skip Rochefort for supporting the delivery of these laboratories. The views represented here are those of the authors.

Land acknowledgments The research that is presented in this manuscript was conducted at Oregon State University in Corvallis, OR. We acknowledge that the lands we now live and work on were the traditional homelands of the Marys River or Ampinefu Band of Kalapuya who were forcibly removed following the Willamette Valley Treaty of 1855. The living descendants of whom are part of the Confederated Tribes of Grand Ronde Community of Oregon and the Confederated Tribes of the Siletz Indians.

Declarations

Conflicts of interest There are no known conflicts of interest related to this work, either from funding sources, or the personnel involved.

Research involving human participants and/or animals Observation and interview protocols utilized in this work were approved by the Oregon State University and Tufts University Institutional Review Boards. All participants provided informed consent.

Informed consent All participants in this research signed informed consent documents approved by the Oregon State University and Tufts University Institutional Review Boards.

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