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Evaluating and Comparing Delivery Strategies for Hardware-Based Online Labs

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Abstract
Online education is widely used, and has numerous benefits that promote access to learning resources for students otherwise isolated due to location, schedule, or even a global pandemic. However, gaps in course delivery strategies remain, which likely result in less than optimal delivery from a student perspective. For lab-based classes that require physical hardware this is especially so; recreating the experience of roaming a lab session and looking over students' shoulders is difficult for many online instructors. This paper centers on studying student experiences and learning outcomes across different levels of synchronous delivery of an online lab class (relative to an in-person class in the same student body) to help answer questions about how to administer hardware-based lab learning online and how much synchronous engagement is enough in these cases. The presented work compares data from three different implementations of an upperclassmen-level lab-based measurement and instrumentation class at a large public university, which uses a "lab kit-in-a-box" model. We collected data from versions of the course that varied instruction synchronicity, spanning the following scenarios: asynchronous online, synchronous online, and in-person. The resulting data from approximately 200 consenting undergraduate mechanical engineering students in each of the synchronicity options ($N > 600$) showed that grades for certain lab experiences (i.e., early labs with high levels of skill-building) actually benefitted from an asynchronous online format, even above in-person offerings, while a later lab with deeper dives into specific skills produced better learning and ratings from students when offered either in-person or synchronously online. The results of this investigation can benefit engineering educators, as well as those with interest in online physical labs in other disciplines.

Keywords: Online Education, Laboratory Learning, Student Experience

Introduction

Since the rise of online education, researchers in engineering education have been studying the virtual delivery of coursework, especially for job training or re-training topics like programming and mechatronics. Yet gaps in online course delivery and understanding remain, especially for lab classes that require hands-on experiential learning with real hardware. This type of hands-on instruction is critical for student comprehension and skill transference, but to date there is limited consensus on how best to deliver this experiential course content, especially in online education contexts [12]. This general situation led our team to become curious about differences in experiences and learning outcomes across ranging modes of delivery for online hardware-based lab courses.

Approaches to implementing online labs range from students gathering in-person for online module-based group work to students individually working with real hardware in a remote setting [12]. While synchronous online work with classmates can promote more assignment submission and better comprehension [7], as well as higher levels of satisfaction [15] and engagement [10], the flexibility inherent to asynchronous offerings is often touted as a key advantage of this type of coursework [5]. However, almost no research to date has focused on both synchronous interactions and hardware-based labs in online education to provide better estimations of what might be an 'ideal' lab setting for online learners. Thus, our research centered on studying student experiences and learning outcomes across different levels of delivery synchronicity of an online lab class (relative to an in-person class in the same student body) to help answer questions about how to administer hardware-based lab learning online and how much synchronous engagement is enough for these use cases.

The key research goals in the presented exploratory work were to 1) compare student experiences and learning outcomes across two different levels of synchronous teaching when administering an online lab class (i.e., asynchronous vs. synchronous) and 2) evaluate the above experiences and learning outcomes relative to a similar-level in-person class taught to the same general student population. Accordingly, we collected data from seven total iterations of a required, hardware-based engineering course, three virtual and asynchronous, two virtual and synchronous, and two in-person. Taken together, the results of this work can offer important suggestions for the level of integrated synchronous experience to be included in online engineering labs, constrained by a comparison to a traditional in-person lab experience, in addition to insights on how best to design effective teaching of physical lab coursework in online lab-based contexts.

Related Work

Online education in engineering has grown significantly over the last two decades [2,6], particularly for areas like computer programming [9] or mechatronics [21]. Within our home university (i.e., Oregon State University), this trend is likewise visible; for example, the university's Ecampus offers more than 1,500 courses online, and there are multiple efforts within the College of Engineering to move the full curriculum online. Despite this growth, within the engineering education community there is little consensus about the best way to administer lab courses online, particularly for coursework that involves assembling and programming physical hardware systems and has a discrete experiential component [12].

A variety of approaches for administering online lab courses have been proposed, ranging from students gathering in person and completing virtual lab activities to students working independently through labs using real hardware in a remote environment [12]. Initial evidence shows that online students who work synchronously with classmates to complete virtual labs (labs that involve simulated, not real, hardware setups) tend to submit more course assignments, and demonstrate higher levels of understanding [7]. While appropriately structured fully-online experiences can lead to equivalent learning gains in some topic areas, it is imperative to realize that students still do need ready access to the instructional team to support these efforts [16]. This insight is perhaps not surprising, as one of the main complaints of online learners is that they often feel isolated or frustrated within asynchronous course content and the types of peer interaction they afford [8,20]. Providing a chance to work synchronously with a team may assuage these concerns somewhat, encouraging students to more consistently engage with both lab material and their peers in meaningful ways. Indeed, research has suggested that providing the opportunity to interact synchronously with classmates and instructors does often lead to higher levels of satisfaction [3,15] and engagement [10,22], and does not necessarily detract from, nor inhibit, engagement with other independent asynchronous course content [19]. Higher perceptions of social interaction also tend to increase the likelihood that students will continue to take additional online coursework [22], suggesting that such interaction is perceived as a desirable component by potential students.

However, an open question is: how much synchronous engagement is enough? In other words, it seems useful to explore the boundaries of this need for synchronous interaction, and more importantly, to rigorously compare the benefits of such effects to a traditional in-class instructional baseline. Further, while students seem to have an expectation for some kind of social interaction in online coursework [18], it is not entirely clear how much synchronous contact is normally anticipated. One might speculate this expectation varies within the online student body, as flexibility (e.g., not having to be in class or interacting at a specific time of the day) is often touted as a major draw of online instruction [5]. At the same time, this assumption of course flexibility as a necessary characteristic of online education has recently been challenged as problematic, and in fact prohibitive of an optimal learning experience [13]. These questions, taken together, led to the presented work, which holds the course design, facilitator, and general student body the same over different modalities (i.e., spanning different virtual deliveries, as well as an in-person comparison point) of a lab-based measurement and instrumentation class.

Methods

This project considered student experiences and learning outcomes in an upperclassmen-level lab-based measurement and instrumentation class at Oregon State University, which uses a “lab kit-in-a-box” model. We collected data from versions of the course that varied instruction synchronicity and setting, as further explained below. These efforts were approved by our university ethics board.

Study Design

The study design included three different types of course experience, spanning the following delivery modes: asynchronous online, synchronous online, and in-person. The instructor for all of these offerings and the design of the course were consistent across the full study.

- *Asynchronous online* offerings (3 class sections) involved no synchronous interactions with the teaching team, aside from almost fully unused interaction with teaching team members during office hours (held via Zoom).
- *Synchronous online* offerings (2 class sections) involved fully synchronous virtual labs (held via the gather.town platform) and office hours (held via Zoom).
- *In-person* offerings (2 class sections) involved synchronous in-person labs and in-person office hours, as is typically standard of in-person university course learning.

As further background, *Zoom* is a videoconferencing tool that allows for remote video- and audio-based conversations. In the class, Zoom was typically used for one-on-one virtual conversation, occasionally with screen-sharing and showing of hardware setups using one’s webcam.

Gather.town is an online platform that allows users to navigate a two-dimensional virtual space and converse with other users using video and audio, typically with the audio volume of the users’ speech adjusted based on proximity to others in this online setting. The teaching team constructed a virtual lab space in gather.town, as shown in Fig. 1, which included a location at the front of the class from which a user’s voice could be broadcasted uniformly across the space (similarly to a speaker's voice projecting from a podium microphone in in-person settings). Regions around tables in the virtual space (as shown by differently-colored checker squares) were private to that particular table and allowed a subset of students and instructors to converse without distracting other groups of users in the space. The tables colored in green in the classroom setup image were typically used by students, with instructors roaming the space to check for questions. The purple tables in the lower left of the room were most typically used for conversations with the instructors, and included an easy path to Zoom (as an a backup option for private conversation). This setup allowed for students and instructors to easily move around the lab space to have peer-to-peer and peer-to-instructor conversations with a low barrier to entry.

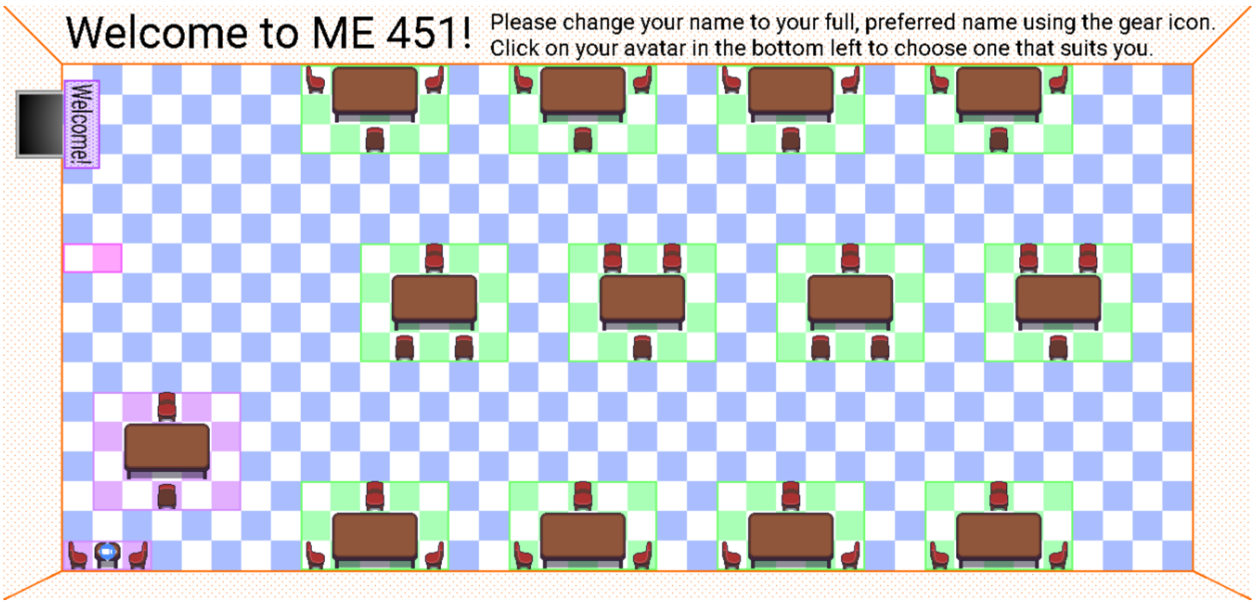

Figure 1: The gather.town lab space, including student and instructor desks and different zones of audibility. Further information on classroom elements appears in the Study Design subsection.

For both synchronous online and in-person classes, attendance of labs was expected (but not directly graded), as the students would perform system demonstrations via sign-offs in the gather.town and physical lab spaces, respectively. Students could work with one another to troubleshoot and progress in the lab activities, as well as interact with instructors for questions and sign-offs, during their time in the virtual and physical lab spaces. In the asynchronous course administration, the sign-offs occurred via file submissions.

The *lab kit* for the course was the commonly available Elegoo UNO Project Super Starter Kit, which can be sourced from both Amazon.com and AliExpress.com. This option provided good overall global reach, even in the case of students who were taking the remote course while living or traveling internationally. This kit includes the Elegoo UNO board (a close analog to the popular Arduino UNO microcontroller), as well as a range of beginning sensor and actuator hardware with great relevance to undergraduate-level mechatronics education.

Procedure

Each term of the course was taught using one of the studied delivery modalities. Specifically, we studied seven total course instances; all instances were distributed across the 2020 and 2021 calendar years, with each modality offered at least once in each calendar year (see Table 1).

Table 1: Information on the timing, modality, and student enrollment for each of the studied instances of the course. During the first term considered, demographics were not collected.

Academic Term	Delivery Mode	Enrollment	Age	% Non-Male
Winter 2020	In Person	80	n.r.	n.r.
Spring 2020	Asynchronous	139	24.3 (15.1)	11.1%
Summer 2020	Asynchronous	36	23.3 (2.6)	33.3%
Fall 2020	Synchronous	115	22.9 (2.5)	14.6%
Winter 2021	Synchronous	182	22.8 (3.2)	14.2%
Fall 2021	In Person	124	23.3 (2.6)	12.4%
Fall 2021	Asynchronous	42	23.8 (4.3)	12.8%

During the course, one of the main facets (approximately one third of the course grade) was lab activities. After each lab, students completed the lab assessment questions further explained below.

For the current analysis, two target labs were considered. The first target lab occurred during Week 2 of a 10-week term, and covered the basics of the design and construction of a simple circuit (e.g., using a breadboard, LEDs, resistors, and simple sensors). The second target lab occurred during Week 7, and required students to integrate a sensor circuit within a more complex system (i.e., a DC motor and its controller). These labs were selected for their related nature, as the work in Week 7 represents a more complex implementation of the simpler information learned in Week 2. For brevity, from this point on, the Week 2 lab will be referred to as the 'simple' lab, and the subsequent Week 7 lab activity will be called the 'complex' lab.

Measures

From the students in the mentioned class, we collected the following for the two target labs. We normalized scores to 1.00 maximum for the first three bulleted items.

- *Pre-lab knowledge assessment* that evaluated how much students knew about the topic before completing the lab.
- *Grades* for each lab, as one measure of learning performance.
- Likert-scale-based self-reports of *overall experience, how much students enjoyed the format of the lab,* and finally the *perceived usefulness of the lab*.
- Numerical self-reports of *time spent on each lab*.

The student experience questions were based on measures used in past work (e.g., [11]).

From a separate course evaluation survey that students completed at the end of the term, we also have approximate demographic data (i.e., age and gender) for each student cohort. The match is not perfect because most, but not all, of the course cohort members completed this survey.

Participants
In total, we collected data from approximately 200 consenting undergraduate mechanical engineering students in each of the synchronicity options ($N > 600$). Basic demographics for each course cohort appear in Table 1. Overall, participants were all upperclassmen-level undergraduates in mechanical engineering at a large public university who were enrolled in the studied lab-based measurement and instrumentation course.

Analysis
We assessed the data from varying levels of course synchronicity using analysis of variance (ANOVA) and analysis of covariance (ANCOVA) tests. ANOVAs helped us to identify the presence of significant differences across conditions, and we used ANCOVAs for a similar purpose when another measurement seemed highly likely to influence a given variable. Tests used an $\alpha = 0.05$ significance level, and we computed effect size using η^2. To compare student experiences and learning outcomes pairwise across the three variations of the studied class, we performed post hoc comparisons using Tukey's test.

Results

Pre-lab Knowledge Assessment
Students were asked to complete a pre-lab knowledge assessment that evaluated how much they knew about each lab topic prior to completing the lab. As reiterated in Table 2, for the simple lab, there was a significant effect of format ($F(2, 693)=10.22$, $p<.001$, $\eta^2=.03$). Post hoc tests revealed that students in the synchronous format knew significantly more about the simple lab content than either the asynchronous or in-person formats. The in-person format was not significantly different from the asynchronous group. For the more complex later lab, there were also pre-existing differences in knowledge ($F(2, 668)=15.64$, $p<.001$, $\eta^2=.04$). Post hoc tests revealed that the in-person format was significantly lower than both the asynchronous and synchronous groups. The asynchronous and synchronous groups were not different from one another. Given these pre-existing knowledge differences for both lab exercises, it is important to control for these differences, and as such pre-existing knowledge was used as a covariate when examining lab learning performance (reported next).

Table 2: Summary of statistical results for the pre-knowledge assessments from the simple and complex labs. Descriptive statistics are listed in the form of mean ± standard deviation.

	ANOVA Results			***Descriptive Statistics***		
Lab	***F***	***p***	***η^2***	***Asynchronous***	***Synchronous***	***In-Person***
Simple	10.22	<.001	.03	.95 ± .06	.97 ± .05	.94 ± .10
Complex	15.64	<.001	.04	.93 ± .08	.95 ± .08	.90 ± .11

Lab Learning Performance
The results for lab learning performance appear in Table 3. For the simple lab exercise, when controlling for pre-existing knowledge using a between-groups ANCOVA, there was a significant difference observed in terms of learning ($F(2, 683)=7.51$, $p<.001$, $\eta^2=.02$). The asynchronous activity significantly outperformed both the in-person and synchronous sections, as evidenced by Tukey post hoc testing. There was no observed difference between the synchronous or in-person formats. For the more complex later lab, however, there was a different pattern of learning results.

While there was a significant difference based on class format (F(2, 663)=11.45, p<.001, η^2=.03) on these more complex labs, this time the synchronous and in-person formats significantly outperformed the asynchronous format (as evidenced by Tukey post hoc testing). There was no difference between the synchronous and in-person sections. Thus, it appears that while in simple cases asynchronous presentations produced the best learning, having synchronous or in-person interaction led to the best lab performance with more complex content.

Table 3: Summary of statistical results for the learning from both studied labs, as gauged using grades on the assignments.

	ANCOVA Results			***Descriptive Statistics***		
Lab	***F***	***p***	***η^2***	***Asynchronous***	***Synchronous***	***In-Person***
Simple	7.51	<.001	.02	.91 ± .11	.88 ± .11	.87 ± .11
Complex	11.45	<.001	.03	.88 ± .13	.92 ± .08	.93 ± .14

Overall Lab Experience Ratings

In terms of students' overall ratings of both the simple and complex labs, in both cases there was found to be no reliable difference, regardless of format. Ratings were equivalent across format for both the simple (F(2, 571)=2.34, p=.10) and complex (F(2, 547)=.56, p=.57) labs. Thus, in an overall sense, students did not have strong opinions about the nature of the labs themselves, regardless of format or lab content. These results are summarized in Table 4.

Table 4: Summary of statistical results for the overall lab experience ratings.

	ANOVA Results			***Descriptive Statistics***		
Lab	***F***	***p***	***η^2***	***Asynchronous***	***Synchronous***	***In-Person***
Simple	2.34	.10	.01	.52 ± .17	.49 ± .13	.51 ± .14
Complex	.56	.57	.00	.48 ± .17	.50 ± .13	.49 ± .15

Enjoyment Level

As shown in Table 5, when asked to rate how much they enjoyed completing the lab, there was found to be no reliable difference across formats for the simple lab (F(2,578)=2.96, p=.05). While this result approached statistical reliability, Tukey post hoc tests revealed no differences across formats, and all formats yielded equivalent levels of enjoyment. However, for the more complex lab, there was a significant main effect of enjoyment (F(2,552)=9.71, p<.001, η^2=.03). Consistent with the learning results above, post hoc tests revealed that the asynchronous format produced significantly *lower* levels of enjoyment than both the synchronous and in-person formats. There was no difference between the synchronous and in-person formats in terms of enjoyment on the complex lab.

Table 5: Summary of statistical results for the reported enjoyment levels.

	ANOVA Results			***Descriptive Statistics***		
Lab	***F***	***p***	***η^2***	***Asynchronous***	***Synchronous***	***In-Person***
Simple	2.96	.05	.01	.70 ± .20	.74 ± .19	.75 ± .19
Complex	9.71	<.001	.03	.67 ± .21	.75 ± .17	.73 ± .19

Perceived Utility of Labs

Table 6 shows that students' ratings of the usefulness of the lab exercises followed a similar pattern to enjoyment ratings. For the simple lab, there was no reliable difference found across formats ($F(2, 577)=2.87$, $p=.06$), suggesting that perceived utility was not different across groups. However, for the more complex lab, there was a significant effect of format ($F(2, 552)=7.57$, $p<.001$, $\eta^2=.03$). Once again, usefulness ratings were significantly lower in the asynchronous group than in both the synchronous and in-person formats, as evidenced by Tukey post hoc tests. There was no difference between the synchronous and in-person groups. These results suggest that while overall usefulness was not variable across formats in the simple lab, with the more complex material, format significantly impacted student perceptions.

Table 6: Summary of statistical results from the perceived utility of labs question.

	ANOVA Results			***Descriptive Statistics***		
Lab	***F***	***p***	***η^2***	***Asynchronous***	***Synchronous***	***In-Person***
Simple	2.87	.06	.01	.82 ± .16	.84 ± .15	.86 ± .14
Complex	7.57	<.001	.03	.73 ± .19	.80 ± .16	.78 ± .18

Perceived Time Spent on Lab Activities

Finally, students estimated how many hours they spent working on each lab exercise, as evidenced in Table 7. For the simple lab, there was a significant effect of class format on these estimations of effort ($F(2,575)=3.66$, $p=.03$, $\eta^2=.01$). Post hoc tests indicated that the asynchronous group estimated they took significantly longer to complete the lab than the in-person group, and was marginally longer ($p=.12$) than the synchronous group, although this second result was not statistically reliable. There were no other differences on the simple lab. For the complex lab, there was no effect of class format ($F(2,545)=1.10$, $p=.33$). This result suggests that there were no perceived differences in time input on the more complex lab.

Table 7: Summary of statistical results for the perceived time spent on the studied lab activities.

	ANOVA Results			***Descriptive Statistics***		
Lab	***F***	***p***	***η^2***	***Asynchronous***	***Synchronous***	***In-Person***
Simple	3.66	.03	.01	9.58 ± 4.74	9.12 ± 4.79	8.15 ± 2.84
Complex	1.10	.33	.00	4.82 ± 2.74	5.00 ± 3.40	4.50 ± 1.62

Summary of Key Results

Key results included the insight that certain lab experiences (e.g., early labs with high levels of skill-building for the class) yielded the best student grades in the asynchronous online iterations, while later labs with deeper dives into specific skills yielded higher grades for the synchronous online and in-person delivery conditions. In terms of satisfaction and usefulness ratings, when there was a significant difference, the consistent trend was for synchronous and in-person ratings to be better than asynchronous ratings. Further, the simple lab took marginally less time for the synchronous condition and significantly less time for the in-person condition, compared to the asynchronous condition. Overall, when there was a significant difference, it highlighted some advantage of the synchronous and/or in-person learning experience.

Discussion

Results indicated that asynchronous interaction positively influenced learning on simple labs, and that for more complex labs either synchronous or in-person interaction led to best learning. This second finding is likely a result of students being confused or struggling with the material in the asynchronous format, as any interaction or assistance was temporally detached from their lab activities and efforts. The lack of such interaction has been shown previously to detract from learning in online contexts [14]. This insight is also consistent with observed differences in not only enjoyment, but also perceived utility in the more complex lab, although there was no difference in perceived time expended on the lab. In other words, it appears that students were working more effectively, as any troubles or issues could be addressed in close temporal proximity to their actual occurrence, rather than having to wait on a response in asynchronous case. Even though the asynchronous classes did not think they were spending more time on the complex lab, they were learning significantly less, and also enjoying the material less. This result suggests that not only were they less efficient learners because of this lack of interaction, which has been suggested previously [1], but also raises the possible concern that such lack of efficiency might have downstream effects of retention or engagement, as students are expressing significantly lower interest in the topic, which usually correlates with persistence within the field [4,17]. This concern is further exacerbated when we consider the simple lab timing results, which showed asynchronous-term students to spend more time on that assignment than any other group.

There are strengths to the current investigation. The current study included both objective and subjective measures of performance, which seem to provide a fairly consistent portrayal of differences in format, especially within the more complex lab. Further, while classroom research is challenging for many logistical reasons, the current study was able to maintain the same instructor for all seven sections, minimizing differences in instruction across offerings. Finally, the fact that this effort was conducted over multiple terms, with multiple sections of each instance, is encouraging, as the large overall sample size in each condition, coupled with the multiple measurements, lessens the possibility that unique differences from a single class section might be driving the observed pattern of effects.

This said, there are of course some limitations to the current study. While conducted over a two-year period, this study occurred immediately after the COVID-19 pandemic began, and this worldwide phenomenon might have impacted student performance in these courses in ways that have not been clearly anticipated or identified. Future researchers studying this topic might also consider the potential of set lab hours influencing student timing and expectations, as well as different ways asynchronous vs. synchronous instructor feedback might affect students' knowledge self-reports. The current study, while occurring over multiple sections and a multi-year period, was also conducted at a single university; additional investigation with other and perhaps more diverse student populations might identify further interactions of interest that could expand the application of the current findings.

Conclusions

The current investigation was aimed at better understanding whether synchronous interaction significantly affected performance on lab-based activities in online mechanical engineering coursework. Both a simple and more complex lab were examined, and students completed these labs either completely asynchronously, with synchronous online interaction, or in-person in a more traditional classroom. Importantly, in more complex learning settings, synchronous online delivery was often indistinguishable in end result from in-person delivery, which is encouraging news. This outcome suggests an important result, namely that online learning, especially for complex lab material, can best be supported through the inclusion of synchronous activity. For simple labwork, traditional asynchronous methods of online instruction produced the best learning; however, asynchronous instruction produced the worst learning for more complex material, and also produced lower levels of enjoyment and perceived utility related to this complex material. Thus, adding synchronous interactions to online instructional efforts can bolster learning and student perceptions when students are faced with more challenging material, consistent with what is normally observed in in-person offerings. In closing, this work helps to answer important open questions about how to deliver hands-on experiential training to engineering students in online learning settings. Outcomes of the work can contribute to the groundwork for broader and more theoretical investigation into pedagogical questions on hardware-based online lab work, as well as the importance of synchronicity in online learning, while also addressing the pressing need for access to high-quality engineering training for all learners.

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