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Virtualizing Hands-On Mechanical Engineering Laboratories - A Paradox or Oxymoron

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Abstract

In physical sciences and engineering research, the study of virtual labs (VL) has generally focused on case studies about their implementation into classrooms or engineering design process and elements. However, few (if any) studies have assessed the viability of using conventional course evaluation instruments (originally designed for traditional in-person classroom environments), to evaluate virtual lab classes. This article presents a preliminary set of results from a study that examines and compares engineering undergraduate students' evaluations of a capstone mechanical and aerospace engineering laboratory course taught in two different environments: in-person and remotely (virtual/online environment). The instrument used in both cases was the conventional course evaluation instrument that was quantitative and designed using a Likert scale. The aim of this study is to understand how this instrument captures or does not capture the students' perceptions of their learning of course content in virtual and in-person learning environments. The second aim of this study is to explore students' perceptions of the effectiveness and acceptance of virtual learning tools and environments applied in engineering laboratory classes. A total of 226 undergraduate students participated in this convergent mixed method study within a mechanical and aerospace engineering department at a research-1 institute in the northeastern region of the United States. Our initial analyses of the students' course evaluations indicate that there were no statistically significant differences in the perceived teaching effectiveness of the course. However, statistically significant differences were found between the course final grades between students who participated in the in-person lab juxtapose to those who engaged in the virtual laboratory environment. In addition, qualitative results suggest that students' perceptions of the value of in-person and virtual labs vary depending on prior engineering experiences. These results suggest that there is room for improvement in conventional course evaluation instruments of senior capstone engineering education laboratories that take place either in-person or virtually.

Keywords: virtual and remote laboratories, mechanical engineering laboratories

1. Introduction

The COVID-19 pandemic forced educators to make a paradigm shift in how they teach students in formal and informal settings, where emphasis was placed on the development of educational tools and practices that allow for online, remote, and virtual experiences and interactions. Though the creation of these tools and practices demonstrated an opportunity for a more accessible STEM education via remote and online technologies; it also illuminated the vast disparity of access to technical infrastructure, educational resources, quiet learning environments, and exposure to STEM among underrepresented groups, e.g., people of colour, students of varying physical abilities, students of lower socioeconomic status, and students from rural populations. The era of education within the context of the COVID pandemic has also shed light on the lack of resources available to access the effectiveness of remote and virtual learning environments and, in particular, STEM educational laboratories that were originally designed for in-person interaction and group work in undergraduate (UG) education in higher education.

There has been a great deal of research on inclusion of serious educational games and virtual laboratories (VLs) in e.g., spatial learning *(Martin-Gutierrez, Saorin, Martin-Dorta, & Contero, 2009)*, physics *(Adams, Pilegard, & Mayer, 2016)*, computer science *(Ye, Liu, Polack-Wahl, & Ieee, 2007)*, general engineering *(K. Cook-Chennault, Alarcon, & Jacob, 2022; Kimberly Cook-Chennault et al., 2021; Philpot, Hall, Hubing, & Flori, 2005)*, software and electrical engineering *(Callaghan, McCusker, Losada, Harkin, & Wilson, 2013; Graham & Roberts, 2007; Jimenez-Hernandez et al., 2016; Long, Young, & Asee, 2011; Mitre-Hernandez, Lara-Alvarez, Gonzalez-Salazar, & Martin, 2016; Morsi, Mull, & Ieee, 2015; Murphy-Hill, Zimmermann, & Nagappan, 2014; Musil, Schweda, Winkler, & Biffl, 2010; Ozcelik, Cagiltay, & Ozcelik, 2013; Pantoja, 2017; Smith & Chan, 2017; Sutherland, 2000; Whitehead, Lewis, & Ieee, 2011; Ye et al., 2007)*, mechanical engineering (ME) *(Chang et al., 2016; Choudhury & Rodriguez, 2017; Coller & Ieee, 2010, 2011; Coller & Scott, 2009; Coller & Shernoff, 2009; Joiner et al., 2011; Panagiotopoulos & Manolis, 2016; Pejic, Krasic, Krstic, Dragovic, & Akbiyik, 2017)*, chemical engineering *(Granjo & Rasteiro, 2018; Ramos, Pimentel, Marietto, Botelho, & Ieee, 2016)*, computer aided design *(Kosmadoudi et al., 2013)*, power engineering *(Ozkop, 2016; Yalcin & Vatansever, 2016)* and aerospace engineering *(Okutsu, DeLaurentis, Brophy, & Lambert, 2013)*. In physical sciences and engineering research in higher education, the study of virtual labs (VL) has generally focused on case studies about their implementation into classrooms or the engineering design process and design of virtual lab software and hardware. However, few (if any) studies have assessed the viability of using conventional course evaluation instruments (originally designed for traditional action-oriented, tactile, interactive laboratory classroom environments), to evaluate virtual lab classes to better understand *how in-person and remote labs are perceived by students and connected to student course performance/content mastery*. Since many classes converted to remote and virtual environments due to the COVID pandemic, many laboratories that were traditionally taught in-person were taught remotely, though the mechanisms in which the course labs were evaluated remained the same.

The goal of this study was to understand how a conventional course evaluation instrument captures or does not capture students' perceptions of their learning of course content in virtual and in-person learning environments, in addition to, students' perceptions of the effectiveness of virtual learning tools and environments applied to engineering laboratory classes. To accomplish this goal, a convergent mixed-method research design was used, which included quantitative data from a conventional course evaluation instrument and qualitative data from student interviews. The study was conducted at a research-one institute located in the northeastern region of the United States in a capstone senior mechanical and aerospace engineering laboratory course.

2. What are Virtual Laboratories? How have they been assessed for effectiveness?

Virtual laboratories use media formats to mimic action-oriented laboratories that are traditionally designed for learners who participate in in-person laboratory settings. Virtual and remote laboratories may be divided into two categories: labs where real experiments are computer simulated and accessed online or labs that allow the user to access, remotely control/operate, and/or observe the operation of equipment, computers, and data capture via the internet. The objective of a virtual lab is to be able to perform or observe experiments without being in the physical lab space. VLs have been studied in nearly every discipline in the physical sciences and engineering, i.e. biology *(Scheckler, 2003; Spernjak & Sorgo, 2018),* chemistry *(Achuthan & Murali, 2015; Evans, Yaron, & Leinhardt, 2008)*, physics *(Dong & Zhu, 2001; Tetour, Boehringer, Richter, & Ieee, 2011)*, and mechanical *(Aziz, Esche, & Chassapis, 2009; Chang et al., 2015),* electrical *(Basher, Isa, Henini, & Ieee, 2004; Butz, Duarte, & Miller, 2006),* computer science *(Achuthan & Murali, 2015)*, chemical *(Abdulwahed & Nagy, 2009; Granjo & Rasteiro, 2018)* and biomedical *(Cardoso et al., 2015; Romberg, Dyer, Berbari, & Ieee, 2013)* engineering. The ways in which these virtual and remote learning environments and tools are used varies. For example, VLs have been used to supplement traditional course materials in large-scale lecture classes or distance learning courses, to enhance lecture demonstrations, to prepare students for in-person action-oriented labs prior to engaging in the physical lab, to replace in-person labs, and to assess the performance of a student's ability to operate equipment and apply theoretical knowledge in performing practical tasks, e.g., *(Cherner et al., 2017; Ratamun & Osman, 2018; Romberg et al., 2013; Scheckler, 2003).* Due to the variability in the ways in which these VLs have been used and studied; a myriad of methods has been used to evaluate their effectiveness, e.g., student outcomes (skills required for the Accreditation Board for Engineering and Technology), assessment of educational value as a function students' perceived motivation to learn, and students' *acceptance of new technologies* (ease of use and usefulness, i.e., the Technology Acceptance Model).

Many scholars who have employed virtual laboratories in engineering course students have evaluated VL effectiveness using metrics defined by the Accreditation Board for Engineering and Technology (ABET). For example, *(Jamshidi & Milanovic, 2022)* enhanced a traditional mechanical engineering materials course (that originally comprised a lecture and physical lab) with a learning module that included simulated VLs to enhance students' engineering intuition for predicting material testing results. The VL was also used to expose students to design and simulation software that was deemed to be critical for research and industry settings. The curricular intervention was assessed quantitatively using a questionnaire (Likert-scale) and open-ended comments from the students. In particular, the effectiveness of the VL intervention focused on students' perceptions of the VL's *usefulness towards learning mechanical engineering concepts and simulation skills* and *relation to development of skills for employment (Jamshidi & Milanovic, 2022).* The effectiveness of the VL was also evaluated using the ABET Criterion 3 outcomes 1, 3, and 6 *(ABET Criteria for Accrediting Engineering Programs, 2021-2022)*. They concluded that there were several other advantages of using this type of VL environment within their traditional curriculum. For example, VLs generated interest in the subject matter via visual attractiveness of the simulation results, allowed students to engage in more complex experiments virtually, and helped students to develop critical thinking skills through the connection of multiple learning schema, theoretical, experiment and simulation.

Others have used ABET criterion to evaluate student outcomes using simulation virtual labs such as *(Alkhedher, Mohamad, & Alavi, 2021),* who had students select a process pertaining to dynamic systems analysis and controls, and model it for simulation. ABET criteria were used to assess student outcomes for the engineering project, where it was found that students were able to achieve the learning outcomes specified by ABET. Similarly, *(Morales-Menendez, Ramirez-Mendoza, & Guevara, 2019)* incorporated virtual and remote labs as supplemental materials in an industrial automation course and used a KIPPAS (Knowledge and understanding, Inquiry skills, Practical skills, Perception, Analytical skills and Social and scientific communication) framework, which affirms criterion 3 in ABET. They concluded that the use of VLs had several advantages: VLs are cost effective and can provide multiple students access for participation, thereby facilitating scalability for classes that range from small to large in number of students. They also concluded that VLs give students the ability to model scientific phenomena that are difficult to visualize in a physical environment, are adaptable for diversity of cognitive level, are safe, and encourage student experimentation via multiple attempts, since the is no concern of breaking equipment, and lead to reductions in time to learn. They also concluded that the use of VLs as supplemental tools motivated students to learn more and established a meaningful link between classroom activities and skills needed for future employers. They *(Morales-Menendez et al., 2019)* used a questionnaire to understand students' perceptions of the learning experience and found that all of the students liked the way in which the VL connected the theoretical concepts of the class to practice and over 90% of the students enjoyed the VL technology and thought that the VL tool enhanced their comprehension of course materials. As the aforementioned studies focused on evaluating labs using ABET metrics and student perceptions, others have used pre- and post-content assessments, e.g., *(Ratamun & Osman, 2018; Sharma & Ahluwalia, 2018)*.

A few studies have used VLs as complete replacements for in-person labs and compared the effectiveness of both experiences according to students' pre- and post-content mastery assessments where findings have varied. For example, *(Ratamun & Osman, 2018)* examined the differences between a physical in-person lab and virtual lab using the Science Process Skill mastery pre- and post-tests for a 4th grade chemistry course. They found that students achieved higher scores when they engaged in the in-person labs however, the largest difference between in-person and virtual lab scores was observed for girls in comparison to boys. In particular, boys scored higher on the content mastery than the girls when participating in VLs. On the other hand, researchers such as *(Corter et al., 2007)* conducted a study of student learning outcomes and preferences for several different lab formats, e.g., traditional in-person action oriented labs, remotely operated labs and simulated labs in an undergraduate engineering class. They concluded that in some instances students received higher scores in remote laboratories, while in others, there was no significant difference between performance in different laboratory formats. However, while students recognized the value in remote and simulated labs, such as technology-enabled formats, they still preferred in-person labs. Since, student perceptions of their learning experience have more cognitive impact on them than actual content or psychomotor means associated with the learning activity *(Koballa, Kemp, & Evans, 1997)*, understanding how students perceive benefits and deficits of learning environments is important. Thus, many researchers have used the Technology Acceptance Model to understand how people perceive the value of forms of technology within a learning or working environment.

The Technology Acceptance Model (TAM), developed by Davis *(F. D. Davis, 1989; Fred D. Davis, 1993)*, states that individuals' adoption of information technological systems is linked to and a function of two primary variables: users' *perceived usefulness* and the *perceived ease of use* of the technological system. In other words, people will use or not use an application/tool to the extent that they believe it will help them do their jobs better *(F. D. Davis, 1989)*. According to the TAM, if people deem the level of effort needed to use the tool is too difficult or believe the benefits of use do not outweigh the effort, they will abandon the use of the technology. Several studies have used the TAM to explore students' decisions to use VLs *(Estriegana, Medina-Merodio, & Barchino, 2019; Nguyen, Hite, & Dang, 2019; Raikar, Desai, Vijayalakshmi,* *Narayankar, & Ieee, 2018)*. In these studies, most researchers assert that this model is most effective when other variables are taken into consideration. For example, *(Raikar et al., 2018) have concluded that UGs decide to engage with VLs not only based on ease of use and perceived usefulness, but also based on their* prior knowledge of materials related to the VLs. *(Raikar et al., 2018)* also concluded that UGs with more prior experience achieved better grades in the course and associated higher value to the use of VLs, than those who did not have similar prior knowledge. Similarly, *(Estriegana et al., 2019)* used the TAM to examine students' acceptance of VLs and interactive activities, and found that input variables such as *perceived efficiency/expectation and satisfaction* were important factors to consider when using the TAM. In other words, students' *expectations,* and *satisfaction* with the VL were strongly related to course environment/ expectations, prior experiences with VLs, and ultimately acceptance of this platform.

3. Research Design and Research Question

Due to the contrasting findings and conclusions regarding the effectiveness and student *acceptance* of virtual/remote labs when VLs are used as replacements for in-person labs, more studies are needed to adequately compare and assess in-person and remote laboratories, and the relationship between VL environment and student attributes (student prior experiences, lab environment, and lab content materials), which influence the effectiveness of these educational experiences. The goal of this research project goal is to understand how conventional course evaluation instruments assess (or do not assess) engineering laboratory courses in two different learning environments. Towards achieving this goal, two research questions are posed.

1. *How do students assess their learning of engineering concepts in two different learning environments, e.g., virtual/remote and in-person?*
2. *How do conventional course evaluation instruments access how students perceive their learning experiences in laboratory environments (remote and in-person)?*

The study was conducted at a Research-1 institution in the Northeastern region of the United States in a capstone senior engineering laboratory course. Qualitative and quantitative data was collected via post-questionnaires and interviews. Data was analyzed in terms of laboratory environment, i.e., in-person or virtual/remote and student background/experiences as described in interviews. This work will help researchers and educators understand what aspects of course evaluation instruments are useful in comparing laboratory environments and how these instruments relate or inform the instructor about perceived usefulness of course content and mechanism(s) of course delivery.

4. Methods

A Mixed-Method Convergent Research Design Method *(Creswell & Plano Clark, 2018)* was proposed and approved by the primary Institutional Review Board of the first author. The study took place at a Research-1 *(The Carnegi Classification of Institutions of High Education, 2019),* research-intensive institution in the Northeastern region of the United States. The data described herein represents phases of a multi-year study *(2019-2020)*. In this work, responses from 226 participants are described and discussed. All participants in the study completed course evaluations for the senior capstone laboratory course within the mechanical and aerospace engineering department. Students were not asked to provide demographic information but were prompted (via email) to submit their course evaluations prior to the conclusion of the course. The responses from all students who voluntarily completed course evaluations are described herein. Since course evaluations are submitted by students anonymously, the student demographics of the two cohorts of students in 2019 and 2020 studied are not available. However, the population of the department where the study took place, comprises ~13% women and ~28% racially marginalized students in engineering, i.e., African American/Black, LatinX, Native American, etc.

4.1. Data Collection Protocol

For this study, students who enrolled in a mechanical and aerospace engineering laboratory engaged in five engineering labs. The labs that took place in 2019 were in-person and on campus, while the labs that took place in 2020 took place remotely. The remote labs were designed to mimic the experience of being in the physical lab as closely as possible. For both lab environments, students participated in one course introductory laboratory lecture that discussed course objectives, design, and expectations. Students were divided into multiple sections and were rotated to different labs that occurred simultaneously through the course semester. Prior to participating in a specific lab, students were supposed to download and observe a pre-recorded video lecture describing the theoretical concepts covered in each lab. The in-person and VL both used recorded lectures to cover/review the theoretical content, where recorded lectures were performed by instructors who taught the theory associated in the lab in the technical courses that were pre-requisites to the senior educational engineering lab. Students were also provided equipment manuals and laboratory guides for each lab prior to beginning the lab either in-person or virtually. Prior to engaging in the lab, students are required to take a pre-test to ascertain students' mastery of lab materials prior to engaging in the physical or remote lab. Subsequent to the pre-test, students either participated in the lab in person or remote virtual lab. Students participated in five labs: Labview, Material Testing, Momentum Deficit, Steam Engine, and Vibrations. All the aforementioned laboratories are based on theoretical content covered in courses that the majority of students have taken prior to the senior lab as prerequisites. Students were given two weeks after participating in the lab to submit a laboratory report. Students completed the course evaluation during the three weeks prior to the end of the course.

4.2. Virtual Lab Tools

The in-person laboratories took place in 2019 and the remote virtual labs took place in 2020. The virtual lab was designed to mimic the in-person lab attributes. The course was divided into six sections where attempts were made to balance the number of students enrolled in each section with the room occupancy requirements of the labs. Each lab took place in a room designed and dedicated specifically to the content/subject matter of the laboratory topic. In 2019, students were paired in groups of 4 – 5 to conduct laboratory experiments with the assistance of a teaching assistant (TA). These groups of students also collaborated on a group laboratory report, which is part of the quantitative data for this work. An example of one of the setups for the wind tunnel lab is provided in

Figure *1*. Students engage in similar laboratory setup in other labs. Variability in lab interaction during in-person labs depended on the number of experimental equipment available to students and the complexity of the lab setup. For example, the wind tunnel experiment was primarily conducted by the teaching assistant who had students assist with setting up different air foils and collecting data. On the other hand, individual desktop experiment stations are used for the LabView labs where students work in groups to setup the experiment and capture data.

In 2020, the identical lab setups for all five labs that were conducted in-person lab in 2019 were used. However, instead of students performing the lab tasks with the guidance of the TA; they observed the TA conduct the lab synchronously via multiple video feeds while logged on to a video conference platform. A schematic of the virtual lab set up is provided in Figure 2. In these remote virtual labs, several cameras were used to focus on specific aspects of the equipment where inputs were provided, and data captured. Students observed the operation of the equipment synchronously as the TA directed the lab procedures. In cases where it was possible, TA's asked students to indicate the steps in the procedure and/or express parameters for operation.

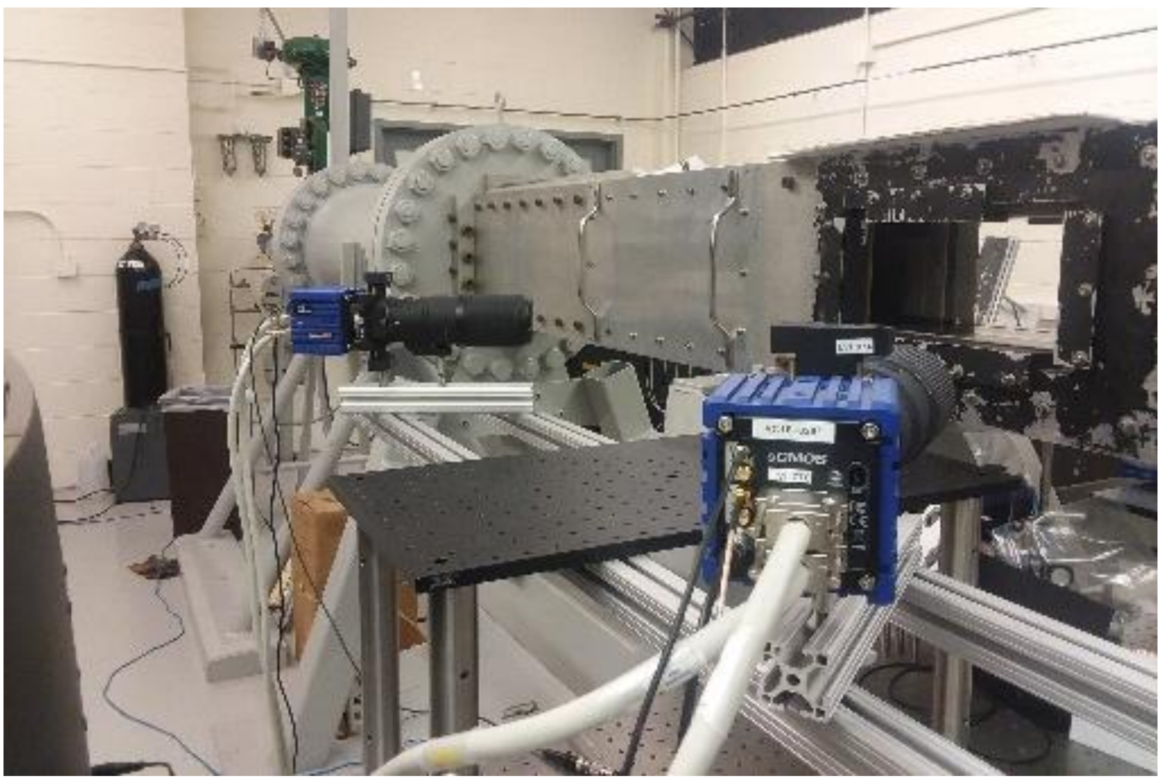

Figure 1: Rutgers wind tunnel laboratory. Photo courtesy of Dr. Edward DeMauro of Rutgers University.

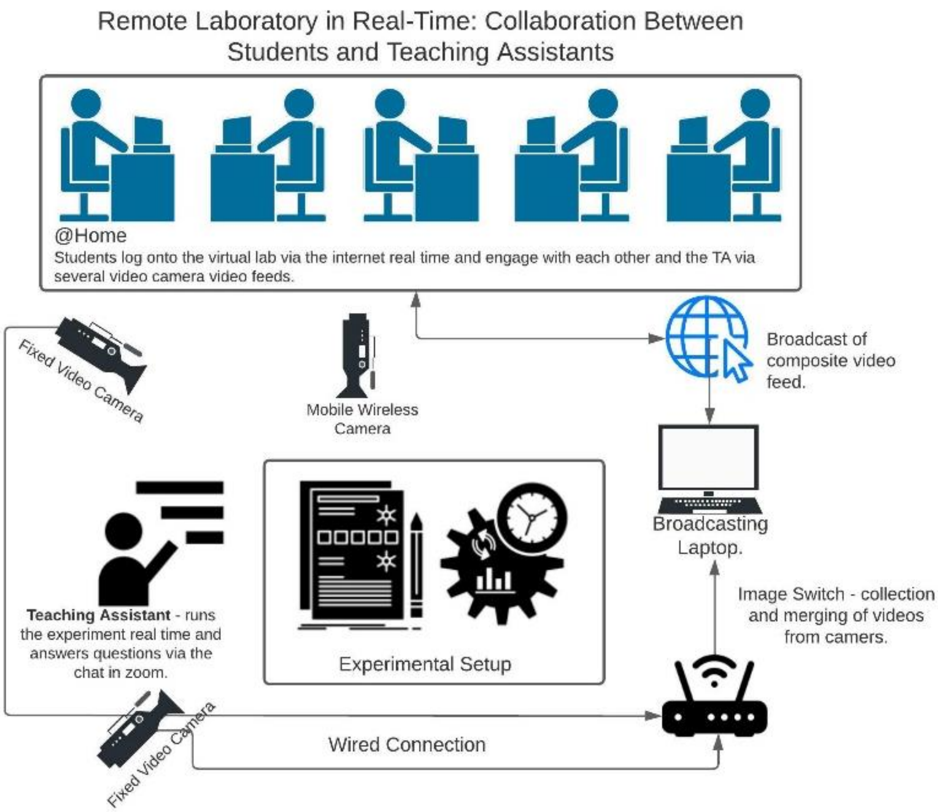

Figure 2: Overview of the virtual laboratory setup.

4.3. Research Method – Statistical Analyses

The course evaluation instrument used for all courses at the institute of the study was used to garner student sentiments regarding the effectiveness of the in-person and virtual labs in 2019 and 2020. The questions selected (from the course evaluation instrument) are provided in **Table 1**. The questions provided in the table were evaluated based on a 5-point Likert scale, ranging from 1 to 5. On this scale, 1 = Strongly Disagree, 2 = Disagree, 3 = Neither Agree or Disagree, 4 = Agree, and 5 = Strongly Agree, except for question 2, which was based on scores of 1 = Poor to 5 = Excellent. For this analysis four questions were chosen from the conventional course assessment instrument: two were instructor focused questions, while the other two questions were student focused.

Two sets of raw data were acquired for the study, the first were the responses of the students for questions in the conventional student assessment survey. These responses were from 2019 Fall semester which was taken in-person and from 2020 Fall semester which was delivered online. The other quantitative data obtained for this study were the final course scores of the students from 2019 and 2020 Fall terms.

Table 1: Questions captured from the course evaluation instrument distributed to students at the end of the course. The questions provided in the table were evaluated based on a 5-point Likert scale, ranging from 1 to 5. On this scale, 1 = Strongly Disagree, 2 = Disagree, 3 = Neither Agree

or Disagree, 4 = Agree, and 5 = Strongly Agree, except for question 2, which was based on scores of 1 = Poor to 5 = Excellent.

Question and/or Statement	Focal point of the question.
Q1. The instructor was prepared for class and presented the material in an organized manner. (*Instructor preparedness)* Q2. I rate the teaching effectiveness of this instructor as: ___ (range from 1 = poor to 5 = excellent) (*Teaching effectiveness)*	Instructor focused question.
Q3. I learned a great in this course. Q4. I had a strong prior interest in the subject matter and wanted to take this course.	Student focused question.

The purpose of conducting a quantitative comparison of years 2019 and 2020 course evaluations using statistical analyses was to understand whether students' perceptions of the teaching effectiveness changed with the change in delivery method, i.e., from in-person to online remote laboratory access. For all statistical analyses, IBM SPSS Statistical Data editor was utilized. To determine if parametric or non-parametric statistics should be used, normality tests (Kolmogorov-Smirnov and Shapiro-Wilk) *(Vexler, Hutson, & Chen, 2016)* were first performed on the collected raw responses for the questions provided in **Table 1** and student final course scores. Normality tests were conducted to determine whether the data had a normal distribution. If data did have a normal distribution, parametric statistics were used for further analyses, e.g., analysis of variance (ANOVA) to ascertain whether there were any statistically significant differences between the means of the responses between the two cohorts. On the other hand, if the data is determined to be non-normal, non-parametric statistics were applied, i.e., the Mann-Whitney U test. In these instances, the Mann-Whitney U test was conducted to understand whether there was a statistically significant difference between a dependent variable for two independent groups. In both non-normal and normal distributions, the two independent groups were the Fall 2019 and 2020 cohorts, where the aim was to determine whether the distribution of the means for variables in the survey and student final course grades were or were not statistically the same.

4.4. Research Method – First Cycle – Structural Elemental Coding

An open categorical first cycle structural elemental coding approach *(Guest, MacQueen, & Namey, 2012; Saldana, 2015)* was employed to identify explicit words, phrases, opinions, and experiences discussed during interview sessions with three students who participated in the virtual remote labs during 2020. The questions posed during the interviews are provided in Table 2. The interview sessions were transcribed and coded. This process facilitated the categorization of the data to identify comparable commonalities, differences, and possible relationships *(Saldana, 2015)*. Students were selected for interviews based on convenience sampling through email solicitation and student availability. Students received a $25 gift card for participation in the interview sessions.

Table 2: Interview questions posed during the focus group discussion.

1. Were there elements of the lab that you would change? Where there any aspects of the lab that were distracting or confusing? Explain.
2. Were you able to interpret your lab data from the course materials or previous knowledge from other classes? If not, what did you do?
3. Was the pace of the lab sufficient, or do you wish it would have gone slower or faster? Explain.
4. Were you able to understand the TA's instructions/explanations during the lab? Explain.
5. Did working on this lab make you feel like an engineer?
6. Did any of aspects of the lab relate to your prior internship/work experiences?

5. Results

5.1. Statistical Analyses

5.1.1. Descriptive statistics results for the Fall 2019 and 2020 data for survey

To test for normality, both sets of response data from the course evaluations for Fall 2019 and Fall 2020 were evaluated for all four questions described in **Table 1**. The results for each question are provided in **Table 3**, **Table 4**, **Table 5**, and **Table 6**, for instructor preparedness, student learning, student interest, and teaching effectiveness, respectively. According to the both Kolmogorov-Smirnov and Shapiro-Wilk tests *(Corder & Foreman, 2014)* all four questions have a significance *p-value* that is less than 0.05, which indicates a non-normal distribution trend for all four questions in the data set. Hence, a non-parametric analysis for all four questions was used for subsequent analyses.

Although a total of 226 students collectively participated in the study over the two-year period, the number of students who responded to the specific questions varied where 158 and 218 students responded to instructor preparedness and student learning questions, respectively, and 226 and 162 students responded to student interest and teaching effectiveness questions, respectively. Since answering all of the questions on the course evaluation survey is not required, some students opted not to submit a response to certain questions. For example, ~70% of the students who responded to the student interest question responded to the instruction focused questions, while 96% of the students responded to the student learning question. Hence, a larger number of responses in student focused questions were recorded in comparison to the teacher focused questions. The descriptive analysis results including mean, median, standard deviation, skewness, and kurtosis for all four questions are collectively summarized in **Table *7***.

Table 3: Test for Normality for the student survey responses (158 students in total) for both Fall 2019 and 2020 regarding instructor preparedness.

Timeline	**Kolmogorov-Smirnov**			**Shapiro-Wilk**		
	Statistic	df	*p-value*	Statistic	df	Sig.
Fall 2019 Instructor Preparedness	0.205	85	<0.001	0.846	85	<0.001
Fall 2020 Instructor Preparedness	0.278	73	<0.001	0.780	73	<0.001

Table 4: Test for Normality for the student survey responses (218 students in total) for both Fall 2019 and 2020 regarding student perceived learning.

Timeline	**Kolmogorov-Smirnov**			**Shapiro-Wilk**		
	Statistic	df	Sig.	Statistic	df	Sig.

Fall 2019 Student Learning	0.197	103	<0.001	0.900	103	<0.001
Fall 2020 Student Learning	0.184	115	<0.001	0.915	115	<0.001

Table 5: Test for Normality for the student survey responses (226 students in total) for both Fall 2019 and 2020 regarding student interest.

Population and Timeline	**Kolmogorov-Smirnov**			**Shapiro-Wilk**		
	Statistic	df	Sig.	Statistic	df	Sig.
Fall 2019 Student Interest	0.172	104	<0.001	0.912	104	<0.001
Fall 2020 Student Interest	0.202	122	<0.001	0.906	122	<0.001

Table 6: Test for Normality for the student survey responses (162 students collectively) for both Fall 2019 and 2020 regarding student perceived teaching effectiveness.

Timeline	**Kolmogorov-Smirnov**			**Shapiro-Wilk**		
	Statistic	df	Sig.	Statistic	df	Sig.
Fall 2019 Teaching Effectiveness	0.185	83	<0.001	0.883	83	<0.001
Fall 2020 Teaching Effectiveness	0.224	79	<0.001	0.884	79	<0.001

Table 7: Descriptive statistics for Fall 2019 and 2020 responses.

Variables	**Mean ($\bar{y}$)**	**Median (M)**	**SD[a]**	**IQR[b]**	**Skewness**	**Kurtosis**
Instructor Preparedness						
2019	3.85	4.00	1.052	2.00	-0.816	0.500
2020	3.78	4.00	0.786	1.00	0.412	-1.259
Student Learning						
2019	3.29	3.00	1.273	2.00	-0.247	-1.029
2020	2.98	3.00	1.155	2.00	-0.035	-0.670
Student Interest						
2019	3.20	3.00	1.169	2.00	-0.218	-0.672
2020	3.21	3.00	1.108	1.00	-0.285	-0.396
Teaching Effectiveness						
2019	3.65	4.00	1.076	2.00	-0.402	-0.384
2020	3.53	3.00	1.060	1.00	-0.217	-0.391

The instructor-based questions were assessed using a Likert scale from 1 to 5, where 1, 2, 3, 4, and 5 represented Strongly Disagree, Disagree, Neither Agree nor Disagree, Agree, and Strongly Agree, respectively. The means for both instructor focused questions pertaining to instructor preparedness and teaching effectiveness were close to 4, i.e., for the Fall 2019 cohort $\bar{y} = 3.85 \pm 1.052$ while for the Fall 2020 cohort the $\bar{y} = 3.78 \pm 0.786$. Since the mean values for both years being close to 4, this indicates that the majority of students agreed that the instructor was well prepared to teach the class, and that the material was presented in an organized manner for both the in-person (2019) and the online (2020) formats.

For student perceived learning, the means were $\bar{y} = 3.29 \pm 1.273$ and $\bar{y} = 2.98 \pm 1.155$ for 2019 and 2020, respectively. Similarly, the median was 3 for both cases. The Likert scale for this set of data ranges from 1 to 5, i.e., from Strongly Disagree to Strongly Agree, respectively. The data suggests that students were unsure whether they learned a lot from the course since the mean values for both years are close to 3. In a similar way, the mean and median scores for student interest were ~3.2 and 3.00 for both years using the same Likert scale as described previously. These results indicate that most students were ambivalent regarding having a prior interest in taking the course. For the student perceived teaching effectiveness, the means were 3.65 $\pm$ 1.076 and 3.53 $\pm$ 1.060 for 2019 and 2020, respectively. In addition, the median values were 4.00 and 3.00, for 2019 and 2020, respectively. The Likert scale for this question ranges from 1 (Very Poor) to 5 (Excellent). The means and medians for this question slightly diminish from a Very Good to Good from 2019 and 2020, however both cohorts seemed to have a positive perception of the teaching for both years whether in-person or online.

Finally, the quantitative results from the course evaluation instrument indicate that there is no significant difference between in-person and remote/online learning environments in terms of student perceptions of instructor preparedness and effectiveness, and student interest. Due to the non-normal distributions of the questions for both years of the study, a non-parametric test, i.e., Mann-Whitney test was performed to learn if the results from the two data sets are significantly different regarding the four questions.

5.1.2. Mann-Whitney test results for survey

Mann-Whitney tests were performed for all four questions and the results are presented in **Table *8***. This test was performed to ascertain whether there was a statistical correlation between the two sets of data for both years. Based on this test, the asymptotic significant value was found to be greater than 0.05 for instructor preparedness, student interest and teaching effectiveness. Thus, there is no statistically significant difference between the two data sets for these three questions, meaning the responses of students for both in-person and online format did not have any significant difference between them. However, the asymptotic significant value for *student learning* was less than 0.05, i.e., 0.020, which indicates a statistically significant difference between the student perceptions of their learning for 2019 and 2020. These results indicate that the students had a more positive perception of their learning from attending in-person laboratories in 2019 ($\bar{y}$ = 3.29 $\pm$ 1.273) in comparison to virtual online laboratories ($\bar{y}$ = 2.98 $\pm$ 1.155).

Table 8*:* The results from the Mann-Whitney U-test for two independent data sets for Fall 2019 and Fall 2020.

Variables	Asymptotic sig.[a]	Result
Instructor preparedness	0.227	Retain null hypothesis
Student learning	0.020	Reject null hypothesis
Student interest	0.965	Retain null hypothesis
Teaching effectiveness	0.714	Retain null hypothesis

5.1.3. Descriptive statistics for Fall 2019 and 2020 student final grades

This mixed-method convergent study includes the triangulation of data from conventional course evaluations, student final grade scores and interviews with students. Here the results from the student final grades from 2019 and 2020 are presented and tested for normality in Table 9. The Kolmogrov-Smirnov and Shapiro-Wilk tests *(Corder & Foreman, 2014)* result in statistical *p-value* that are less than 0.05 for Fall 2019 and Fall 2020 scores, which indicates that data sets have non-normal distributions. Consequently, a Mann-Whitney test was performed to examine if a statistical correlation could be made between student final grades from Fall 2019 and Fall 2020 as shown in **Table 10**. For the Mann-Whitney test, the asymptotic significance was found to be less than 0.05. Therefore, it can be concluded that there is significant difference between the two data sets for Fall 2019 and Fall 2020 final grade score for the students. This signifies that student performance did change between the two different types of laboratory delivery styles and corresponds with the difference in student's perceptions of their learning from the course evaluations.

Descriptive statistics for the two cohorts are provided in **Table 11**, where it was found that the average mean of Fall 2019 final grade scores was more (83.76%) in comparison to Fall 2020 (75.96%). This signifies that the average mean for the students' final grades in 2019 was greater than the 2020 class by ~8 points. Similarly, the median scores were also different, with the Fall 2019 median score being ~7.5 points greater than the Fall 2020 score. This further substantiates the discrepancy student performance between the two modes of laboratory environment and delivery. It is important to note however, that this difference in student performance is validated by students' perceptions of learning shown in **Table *8***.

Table 9: Test for Normality for student final grade scores for both Fall 2019 and 2020.

Population and Timeline	**Kolmogorov-Smirnov**			**Shapiro-Wilk**		
	Statistic	df	*p-value*	Statistic	df	Sig.
Fall 2019 student scores	0.167	228	<0.001	0.781	228	<0.001
Fall 2020 student scores	0.207	235	<0.001	0.660	235	<0.001

Table 10: Mann Whitney test results for the final grades of students from 2019 and 2020 fall terms.

Variables	**Asymptotic sig.**[a]	**Decision**
Test scores for Fall 2019 and 2020	<0.001	Reject the null Hypothesis

Table 11*:* Descriptive statistics for the laboratory report scores for the students from 2019 and 2020.

Variables	**Mean**	**Median**	**SD**[a]	**Skewness**	**Kurtosis**
Student laboratory report scores					
Fall 2019	83.76	88.0	18.16	-3.089	11.309
Fall 2020	75.96	81.50	19.86	-2.152	5.459

5.2. Qualitative Structural Elemental Coding Analysis Results

Three students were interviewed during the virtual engineering lab environments in 2019. A categorical analysis was performed to understand students' perceptions of the learning experiences. Examples of phrases that support the qualitative summaries are provided in **Table** 12.

5.2.1 Were there elements of the lab that you would change?

All students that were interviewed expressed the desire to participate in in-person labs as opposed to virtual labs. However, they varied in level of satisfied/dissatisfaction with the virtual learning environment. Also, things that the students noted for change in the virtual labs differed. The categories for virtual lab modification were to make the lab more interactive, demonstrate each aspect of the lab input and data capture process instead of just showing one out of multiple sets of data acquisition, access to video footage after the lab, and reduce the technical issues such as video lags during synchronous lab lectures. The student that suggested more interaction also indicated that there is value in having students participate in active learning activities such as taking notes, logging their own data (rather than merely depending on the TA to capture data even in remote lab environments). On the other hand, one student expressed frustration at having to take notes while watching the remote lab.

The two students described technical issues with video lagging. Of the two, one stated that she would not change the virtual labs because *there was nothing about virtual labs that she liked or valued*. The other student thought that there would be value in recording video of the virtual labs and post-producing them to optimize timing and camera footage angles and vantage points. This student referenced the value of high quality Youtube videos that removed instances in video footage that provided no meaningful information and also edited video footage to show meaningful camera angles associated with topics of importance in the lab. Students suggested that there would be value to reviewing edited video footage outside of the lab.

5.2.2. Where there any aspects of the lab that were distracting or confusing? Explain.

One student indicated that their home environment was distracting and therefore observing labs in a home environment virtually was difficult. Two students indicated that technical issues with video lagging was also distracting. One student indicated that they did not like the experience of vacillating between taking notes and looking at the screen to see what the TA was doing on the cameras. Another student indicated that having a processed video would have eliminated some of the issues with distraction and confusion thus, making aspects of the virtual lab beneficial.

5.2.3 Were you able to interpret your lab data from the course materials or previous knowledge from other classes? If not, what did you do?

All students indicated that for the instances where they had taken the course connected to the lab, previous knowledge of the course was useful and made it easier to interpret the lab content. They indicated that in previous non-lab courses, the class was based on equations and theory. Hence, the lab helped them make more sense of the theory and equations.

5.2.4 Was the pace of the lab sufficient, or do you wish it would have gone slower or faster? Explain.

The opinions of the three students varied for issues of course pace. Two students said that the appropriateness of the course pace varied based on the course content, i.e., content that she was more experienced with and had taken in-person prior to virtual lectures (other courses) were associated to better paced virtual labs. Another student indicated that they felt that all of the labs moved too quickly and did not spend an adequate amount of time going through each step of the laboratory process. On the other hand, another student indicated that the addition of more time spent in the VL environment may have made the learning process redundant, which could lead to boredom.

5.2.5. Were you able to understand the TA's instructions/explanations during the lab? Explain.

Similarly, the responses of the students somewhat varied pertaining to the instructions given by the TA's. All students indicated that they thought the that the teaching assistants were prepared to give a good lab session. For example, one student stated that the interaction with the TAs was better during the VLs because a microphone was placed close to the TA's mouth, which allowed them to hear the instructions more clearly. Another student indicated that some

TAs were more adept at engaging students in the VL lab by inviting students to ask questions. Another student thought that having the TAs located in a different place other than in-person made it more difficult to couple other physical responses, i.e., facial expressions, hand ques and gestures towards equipment, which would have made learning easier, especially in instances where there may have been concerns regarding interpretation of instructions given by non-native English-speaking TAs.

5.2.6. Did working on this lab make you feel like an engineer?

Two of the students (both men) stated that the VLs supported their connection with being an engineer. On the other hand, the woman student did think that the lab added to her feelings of being an engineer because she linked her being an engineer with conducting the experiment herself, otherwise, observing a virtual lab was according to her, “like watching a Youtube video.” One student (man who had previous internship experience) indicated that an engineer could engage in different aspects of the design and/or production process, so not physically taking measurements did not mean that one was not engaging in aspects of engineering. Therefore, participating in the lab did in fact affirm his engineering identity. Another man student affirmed this believe though he had no previous internship experience prior to participating in this lab.

5.2.7 Did any of aspects of the lab relate to your prior internship/work experiences?

Only one of the three students who participated in the interviews indicated that he had internship experience. He did not think that the majority of the labs in school reflected anything that he had experienced while working in industry.

Table 12: Quotes from interviews of students who participated in virtual labs.

Were there elements of the lab that you would change? - *I would not just show one example and send the remaining data over.* - *It's just so hard to follow the instructor when they're doing it because sometimes the camera image is like lagging a little bit, what they're saying is lagging.* - *I would kind of like to see what would happen if they tried to make a video instead of having it be live-streamed instead.* - *Because like, I would think that with a video, with the time that they can use to like process, render and edit everything, it might make everything smoother.* - *I would actually prefer it to be in person. So, there's not much I would change in a virtual environment, because I would like it to be in person.*
Where there any aspects of the lab that were distracting or confusing? Explain. - *It's just so hard to follow the instructor when they're doing it because sometimes the camera image is like lagging a little bit, what they're saying is lagging. And then sometimes it's just like hard to focus on, like, the screen that's in front of you, when you have, like, your phone, your siblings coming in and out of your room. Like all those distractions are just so hard to do it in a house sort of environment.* - *When they were doing it in front of us, it's just hard to focus on everything that they're doing, especially since they're pointing at so many different screens.*

- *Take some time to actually process the videos that the video doesn't come out all like stuttery or laggy, or unclear. Like, I mean, if you're watching a YouTube video, right, I mean, it's crystal clear pretty much these days. But with a live stream, it's not possible*
Were you able to interpret your lab data from the course materials or previous knowledge from other classes? If not, what did you do? - *Even if they are from other classes, but they're still at this semester with like, virtual environment and everything. So I was like a little bit slower on catching on to exactly what was happening.* - *Because although the labs, in the lab manuals, they provide a lot of equations. Equations can only do so much, right? But when you can apply the knowledge from your class into the lab, it really helps explain what is going on. And that can really improve your understanding. The lab experience plus the knowledge that you learned in class when you add them together, makes a really good package at the end of the day.*
Was the pace of the lab sufficient, or do you wish it would have gone slower or faster? - *…the overall length also was less. So, we got done faster too.* - *Yeah, it was like each lab was different. Some of them I'm like, still processing what they said before, and they've already gone to the next part. And then there were others where, like, "Oh, I'm catching on. This is exactly the pace that I wanted it to be." So it's good. So it all depends on each lab I'm working on.* - *I don't think if they added like an extra 20 minutes, extra half an hour, or whatnot, I don't think it would have improved my understanding anymore.* - *I think they were like, appropriately timed. Because I think one of the worst things that can happen is adding too much time into the lab to the point where we all get bored and we all want to leave.*
Were you able to understand the TA's instructions/explanations during the lab? Explain. - *Yes. I think it was actually better during virtual, for some reason, because they had a mic on the camera, and they were pretty clear most of the time. And the camera setup, it is all in one screen. So, that kind of, being able to understand, was also good.* - *I'll be honest to you. There were one or two TAs that have a bit of a stronger accent. So it was a bit harder to understand them. And especially with like the voice lagging a little bit as they're talking. So I was like wait, I need to like process exactly what they were saying, again. It's a little bit harder to understand exactly what they were saying. So it depended on each TA actually.* - *There were a few TAs who were better than others. And also, there were a few TAs that, like, I think they went above and beyond, you know, in terms of making sure that everybody understands, you know, they would stop periodically, I guess, in order to be like, "Hey, you know, does anybody have any questions?*
Did working on this lab make you feel like an engineer? - *It's just engineers, you're supposed to be there and physically working on those machines. And if you're just watching someone else do it, it's just like watching a YouTube video do the whole thing for you.* - *I guess it kinda depends on the different engineers and what they do out in the field. Some engineers are more conceptually based in nature. They kinda deal with the design, AutoCAD, they do one prototype and, you know, they kinda move on with their life at the end of the day, right? But you know, there are some engineers who are more hands-on, their projects are hands-on from the beginning to the end.*

- *Not the same way as the in-person labs, but something similar to the classes we take, maybe like that. Because we're just instructed to do few things, not like the labs.*
Did any of aspects of the lab relate to your prior internship/work experiences? - *But at the end of the day, I don't think that it would have directly benefited me. Mainly because with the labs, I'm kinda just rehearsing the theories and, you know, getting a deeper understanding on the stuff that I learn in class, but I don't think I would have been able to apply it to my internship in general.*

6. Discussion

A convergent mixed method research approach was used to examine student experiences when participating in two research environments, i.e., in-person active and virtual/online engineering capstone senior laboratories. This approach triangulated quantitative post-course conventional evaluation data with final course student grades and student interviews. The statistical analysis of the post-lab course evaluation results showed no statistical difference between students' perceptions of teacher effectiveness and teaching instructor preparedness, which indicates that the design of both in-person and virtual lab settings were robust and that teaching assistants prepared for both laboratory experiences despite the new virtual environment. However, there was a statistical difference between students' perception of their own learning, and this difference is also supported by students' reduction in course final grades from in-person to remote environments, the average student mean score was found to be 84% during 2019 (in-person) and 76% when the lab was delivered virtual in 2020. However, concrete explanations for the reduced scores cannot be made at this point in the study as other factors such as *zoom fatigue (Williams, 2021)* and COVID related anxiety, depression, etc. *(Wang et al., 2021).*

The triangulation of the students' coded interview transcripts from 2020 with final grade performance outcomes provide greater insight on how students' expectations from laboratory experiences and prior internship experiences may influence the value that they associate with virtual learning environments. The number of students interviewed is small and therefore, the interpretation of them is preliminary. However, motivation theory and expectancy value theory may be used to initiate the analysis of the coded transcriptions, student grades, and overall course evaluations.

According to *(Eccles et al., 1983),* Motivation Theory (Expectancy Value) Theory, claims that students' achievement-related choices, performance, and persistence are predicted and motivated by their expectations for success on those tasks. In addition, these theories posit that the subjective value attached to a task is related to a student's perception of the element's utility (usefulness). According to these theories, students' expectancies and values are determined by other achievement-related beliefs such as achievement goals, self-schemata, and task specific beliefs *(Eccles et al., 1983; Wigfield, 1994)*. Expectancy Value Theory (EVT) identifies four major components of subjective values: (1) attainment value of importance (importance of doing well on a task); (2) intrinsic value (enjoyment from the task); (3) utility value or usefulness of the task (how the task fits within an individual's future plans); and (4) cost. On the other hand, extrinsic motivation refers to the quest for an instrumental goal *(Reiss, 2012; Wigfield, 1994).*

According to these theories, students from both cohorts maintained their extrinsic motivation, i.e., desire to take the engineering laboratories despite the difference in learning environment and mechanism. This may be owing to the course requirement for graduation with an engineering degree in either mechanical or aerospace engineering. However, varying degrees of the students' perceived intrinsic value (enjoyment) and usefulness may have influenced their effort and performance in the course. This is also supported by the TAM model, which suggests that people who do not value a technology are less likely to meaningfully engage with it. For example, both students who saw little to no value in the virtual lab experience scored the lowest (C and C+) on their final grade in the course (interviews were conducted prior to students' receipt of final grades), while the student who attributed value to the virtual labs (despite technical difficulties) achieved a higher final grade (A). This student also indicated that he associated the lab to enhancing his identification as an engineer due to his prior experiences in his internship, which affirmed the value associated with multi-faceted engineering actions, including but not limited to both carrying out an experiment and also interpreting the data on one's own, in addition to, observing someone else capturing the data and interpreting it on one's own.

All of these issues noted by students' personal reflections about the labs in **Table** 12 were not addressed in the conventional course evaluation instrument even though these sentiments elucidate aspects of engineering lab environments that influence the intrinsic and extrinsic values students associate with engineering labs in general whether the labs are in-person or remote. For example, some of the learning barriers students referenced (detailed **Table *13***) are extrinsic in nature, meaning while they are not integrated within the lab environment, the problem occurred due to the nature of the delivery system or home learning environment. The issue of video lagging during video steaming is related to access to reliable and high-quality internet for sustained durations and can occur based on problems associated on both ends of the conference call, i.e., too many apps operating on the user or recipients' end, or problems with WiFi, which can also occur on either end of the conference call. Many of the other challenges described by students are intrinsic in nature and could be addressed to varying degrees by critical examination of the virtual lab environment, mechanisms of content delivery, student-to-student and student-to-instructor interaction. For example, provision of pre-recorded video laboratories could alleviate issues pertaining to video lagging and free students from obligatory course times/dates thereby allowing them to interact with course content during times and locations with less distraction. Also, issues with inability to hear/understand words of teaching assistants could be further addresses via use of closed captioned videos, which is a well-recognized way of providing access to learning for all students regardless of hearing ability *(Cardinal, Boulianne, & Isca-Inst Speech Commun, 2009; Morris et al., 2016)*.

Student engagement with laboratory materials is critical to course mastery and many of the items listed in **Table *13*** are connected to how students engage and are motivated by course environment and the strategies used to incorporate new technology into curriculum. For example, pacing of the course was noted as an issue of concern for all of the students, though each had varying descriptions about how to better pace the course for their needs, depending on their prior experiences with the engineering field, diversity of use of engineering equipment/tools and mastery of prior related course content. For example, we can infer (from our small sampling of students) that prior internship experiences can enhance the knowledge base of students and diminish unrealistic expectations of the engineering profession, (e.g., "*engineers…you're* *supposed to be there and physically working on those machines. And if you're just watching someone else do it, it's just like watching a YouTube video do the whole thing for you.")*, which are sentiments that can reduce motivation towards learning in non-conventional ways.

Table 13: Examples of intrinsic and extrinsic barriers to student's learning during virtual engineering laboratory environments.

Intrinsic	**Extrinsic**
Interaction of TAs with the students through the screen, i.e., facial expressions, gestures, clarity in communication.	Video lagging
Pacing of the lab instruction	Distraction at home environments
Note taking aspect during instruction	
Making lab more interactive	
Demonstrate step by step data capture process rather than showing one of the multiple tests	
Provide after class recording of the sessions	
Difficulty processing multiple images from difference camera views	

Interestingly, none of the items detailed in **Table** 12 or **Table *13*** could be gleaned from the conventional course evaluation instrument. In theory, course evaluation instruments should be used to elevate students' voices about their expectations, educational values, and course curriculum obstacles, which instructors can use to modify and enhance labs so that they leverage and expand students' prior knowledge in addition to providing new course content.

Also, some of the items described by the students pertaining to their intrinsic experiences with the virtual laboratory could be effectively managed via critical examination and modification of laboratory design elements and provision of background materials to students that underscore the relevance of lab materials and general responsibilities of a practicing engineer. In particular, virtual labs should provide incorporate other meaningful and useful materials and procedures to replace what is usually observed experienced in physical action-oriented labs to add value according to the students. For example, during in-person laboratories, students are forced to ask questions when experimental equipment malfunctions or an undesirable outcome arises from problems during the experimental method. In virtual environments where this is not the case, students could be given opportunities to engage with the experiment directly (remote control of equipment) or guide the sequence of the lab as opposed to passively observing the experiment. In addition, period checks (polls/multiple choice prompts) could be intermingled within the remote lab to encourage student interaction and engagement.

Finally, this results from this study are similar to the findings of *(Ratamun & Osman, 2018)*, where students performance in in-person labs was superior to those who participated in virtual labs. Similarly, students' feedback on post-surveys correlate to poorer performance in virtual labs as opposed to in-person labs, though the student perceptions of instructor effectiveness and preparedness remained consistent regardless of learning environment. However, many of the issues listed by students pertaining to obstacles with virtual labs could not be ascertained via the course evaluation instrument used, which suggests the need for the development of better laboratory assessment tools to understand the factors influencing the efficacy of laboratory learning environments and tools.

7. Conclusions and Future Work

A mixed method convergent research method was designed to investigate the ways in which senior engineering capstone educational laboratories are evaluated using a conventional course evaluation instrument. Qualitative and quantitative results were captured e.g., student final grade scores, post-course evaluations, and coded interview transcriptions. These data were triangulated to better understand how effective conventional evaluation instruments for engineering labs (in-person and remote) assessed the effectiveness of the learning environment/design, tools, and pedagogical strategies employed in the classroom/environment. While the conventional course evaluation correctly points to students’ lack of confidence in their content mastery in virtual labs, it does not address why and the degree to which these same issues/concerns may have been present in in-person labs. Understanding how to meet students at their present level of understanding is needed to better improve course engagement and student motivation. In order to better understand these factors, a modified approach for assessment of student learning that can be used in both in-person and remote learning environments is warranted.

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