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Efficacy of Virtual Reality-Based Simulations in Training Aviation Maintenance Technicians on Maintenance Procedures

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EFFICACY OF VIRTUAL REALITY-BASED SIMULATIONS IN TRAINING AVIATION MAINTENANCE TECHNICIANS ON MAINTENANCE PROCEDURES

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Industrial Engineering

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by
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ABSTRACT

The COVID-19 pandemic forced institutions of higher education (IHEs) to halt in-person classes and transition to online platforms. Given the intricate process of adapting hands-on experiments to the online environment, this transition seemed particularly challenging for Science, Technology, Engineering, Mathematics, and Medicine (STEMM) labs. The abrupt nature of this transition added to the difficulties, given that the IHEs were inadequately prepared for seamless continuity during the pandemic. In the first phase of this project, a literature review was conducted to understand the impact of COVID-19 pandemic on education. Specifically, the review explored the challenges that institutions of higher education faced, including technology and internet issues, workload constraints, maintaining academic integrity, and ensuring a comprehensive lab experience. The review also indicated that student learning outcomes were consistent between in-person and online labs. Instructors and students provided the most favorable responses for online labs incorporating video recordings and simulations within a synchronous platform. This approach was favored because it fostered more substantial and engaging interactions. These meaningful interactions incorporated frequent live engagement with instructors during synchronous sessions. Video recordings were praised for providing a clearer perception of scientific concepts, while simulations enabled students to conduct experiments virtually.

In the second phase, a standardized process was formulated based on the human-centered design framework to develop online labs, aiming to mitigate the challenges of creating a comprehensive online laboratory experience and facilitating a smoother transition to online platforms. This approach aids instructors in tailoring online courses to their specific needs and demands, moving beyond solely relying on existing simulation platforms or open resources. It results in a more customized approach that aligns with distinct courses and specific educational requirements.

In the third phase of this thesis, we adapted the *fluid lines and fitting* laboratory used for aviation maintenance technician training for online instruction using the process developed in the second phase. It included short video lectures, assessments, video demonstrations, and Virtual Reality (VR) simulations. This study aims to address the research gap in understanding which instructional strategy, video demonstrations, or virtual reality simulations are more effective for teaching procedural labs, especially in highly technical fields such as fluid lines and fitting fabrication for aviation maintenance. The study employed a between-subjects research design, wherein participants were assigned randomly to different instructional modes, video demonstrations, or VR simulations. Video lectures were common to both groups. The participants had to fabricate the fluid line based on the training received. The dependent variables were learning gains, task performance, perceived workload, and perceived usability.

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Lastly, I want to express my heartfelt thanks to my family—my husband, daughter, son, and parents—and my friends for standing by me, motivating me, and being my strength throughout this journey.

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CHAPTER ONE

INTRODUCTION

As we strive to make the Science, Technology, Engineering, Mathematics, and Medicine (STEMM) courses available to a broader geographically distributed student population, it becomes imperative to find efficient ways to integrate traditional lab experiences into online platforms. STEMM courses include many hands-on laboratory activities as part of the coursework. STEMM labs play an essential role in allowing students to engage in hands-on learning, including conceptualizing and experimentation, followed by subsequent analysis and interpretation of data (Bhute et al., 2021). According to the Constructivist theory of learning, students learn when they can actively construct knowledge by integrating new information with their existing understanding (Hein, 1991). Hein further proposed that this learning happens through hands-on learning through experimentation and manipulating the objects of the world. Some studies showed that hands-on learning fostered critical thinking skills (Hmelo-Silver, 2004), and students were more engaged in hands-on learning, allowing for better student test scores (Stern et al., 2008).

However, with the occurrence of COVID-19 pandemic, educational institutions had to put a halt to in-person classes. Teachers and students weren't sure how long this situation would continue and how it would affect teaching and learning. Also, not all institutions of higher education (IHEs) were ready with plans to keep education going smoothly during this time. Providing hands-on laboratory experiences became a significant challenge as traditional laboratory setups were no longer feasible due to the sudden shift to emergency online teaching. Online labs emerged as an ideal solution to address this issue. Despite their existence for over a decade, their usage notably increased during the pandemic as educators sought alternative ways to provide practical learning experiences in an online environment (Baker & Cavinato, 2020; Colclasure et al., 2021). This unexpected transition to the online platform also led to several challenges across STEMM education. The literature review identified significant barriers such as technological challenges, workload and expertise constraints, academic integrity issues, and the need for complete lab experience.

However, the rapid progress of digital technology and the Internet has created exciting possibilities for conducting online labs. These include using simulations, automated data acquisition, and remote control of instruments, all conveniently accessible through online platforms (Chen et al., 2010). Computer simulations offered flexibility, encouraging students to actively solve problems and think more critically while enhancing their practice (Hargrave & Kenton, 2000). Both educational institutions and providers of distance learning aim to broaden the array of online courses, including online laboratories available in the fields of STEMM.

Offering labs in educational settings is challenging due to the limited availability of machinery and tools, many students, and restricted class and lab schedules. Teaching such tasks became particularly challenging during the pandemic when the traditional in-person lab classes had to be transformed into online platforms. Leveraging technologies such as computer-based desktop Virtual Reality (VR) enabled simulations presents a solution to address time and cost challenges. There are two types of VR experiences: immersive and desktop. Immersive VR uses head-mounted displays to give participants a feeling of being in a realistic environment, achieving a high degree of immersion (Freina & Ott, 2015). In contrast, desktop VR gives users a three-dimensional multimedia environment on a computer screen, which they can navigate using familiar tools like a keyboard, mouse, or trackpad (Ausburn & Ausburn, 2004). Immersive VR, when combined with sensors, is better suited for tasks that require students to control their surroundings and maintain situational awareness. Oculus Rift, an affordable and high-quality VR headset, and ongoing research into other cost-effective alternatives (Basu & Johnsen, 2014) have made immersive VR more feasible in education and training settings. However, desktop VR applications can be easily hosted online and accessed by anyone with a computer and an internet connection without needing any additional equipment, thus making this medium more accessible for use in educational and training settings (Upadhyay et al., 2023).

Desktop VR simulations present a feasible solution for training technicians and students in procedural tasks, leveraging its practicality and advantages. Generally, training in an industrial setting is essential, though it can be costly and time-consuming. The costs can arise from equipment unavailability, staff being diverted from their regular duties, and extensive material usage (Ganier et al., 2014). These simulations can be useful in scenarios requiring specialized training, particularly in aviation maintenance training.

Despite their advantages, VR simulations introduce new challenges to learners. These challenges involve inadequate instructional design and the intricate interactions within simulations, directly influencing how learners perceive the training experience (Upadhyay et al., 2023). While past research has explored the effectiveness of desktop VR simulations in teaching procedural tasks, there's limited research in the aviation domain (Gutierrez et al., 2010; Pratticò & Lamberti, 2021). Moreover, various STEMM domains, like chemistry and engineering, have employed desktop VR simulations in educational settings, focusing mainly on transferring content knowledge rather than procedural knowledge (Brinson, 2015; R. Gao et al., 2020; Liang et al., 2020). Educational institutions resorted to desktop simulations for hands-on lab teaching, particularly during the COVID-19 pandemic. However, they utilized available simulations that didn't encompass all learning outcomes.

Research Objectives

The primary objectives of this thesis are:

- To identify the challenges faced, strategies used, and the effectiveness of transferring from traditional in-person to online labs for STEMM education by IHEs during the COVID-19 pandemic.
- To develop a standardized process for creating online lab courses.
- To demonstrate the effectiveness of desktop VR simulations through a case study.

Thesis Organization

This thesis is organized as follows: Chapter 2 presents a comprehensive review of the existing literature regarding the transition of lab courses to online platforms in STEMM education, specifically focusing on the adaptations made by IHEs during the COVID-19 pandemic. Chapter 3 introduces the standardized process developed and offers an illustrative example of the course designed based on the proposed process. Chapter 4 explores the effectiveness of simulation-based and video-based strategies in delivering the fluid lines and fittings tasks.

CHAPTER TWO

ADAPTING INSTRUCTIONAL LABS FOR REMOTE DELIVERY DURING THE COVID-19 PANDEMIC: A REVIEW OF STRATEGIES, OUTCOMES, AND PERCEPTIONS

Introduction

As a result of the COVID-19 pandemic, educational institutions had to modify their pedagogical strategies. The most immediate effect on students was the suspension of face-to-face instruction. This placed them in an entirely new situation and caused uncertainty regarding several aspects: the duration of the changes, the impact on their daily lives, and the continuity of their education. Instructors also encountered significant disruptions, especially when it came to teaching virtually. The effect of this turbulence was more pronounced in institutions of higher education (IHEs), where Science, Technology, Engineering, Mathematics, and Medicine (STEMM) courses are prevalent, and laboratory work is an essential component of the curriculum. Research has shown that hands-on practice is vital in STEMM education (Hofstein & Lunetta, 2004; Hofstein & Mamlok-Naaman, 2007; Lunetta et al., 2007; Ma & Nickerson, 2006; Satterthwait, 2010; Tobin, 1990). With the specific aim of integrating theory with practice, lab courses had to be adequately developed and designed to make this integration as effective for learning as possible. Since classes and labs could no longer meet in person, educators had to create or adopt new innovative tools, approaches, and teaching methodologies as they moved to online platforms (Cuaton, 2020; Ferdig et al., 2020; Kaup et al., 2020; Neuwirth et al., 2021; Pace et al., 2020; Toquero, 2020). Not all IHEs had strategies to ensure the continuity of teaching activities; this was especially true for the lab courses, as they require extensive hands-on participation, which is difficult to achieve in an online environment.

Internet and computing technologies have transformed traditional instructional laboratories, facilitating virtual and remote experiments using interactive learning tools, facilitating collaboration through digital platforms, and allowing for personalized learning experiences, thus making learning more flexible, accessible, and engaging beyond traditional lab boundaries (Feisel & Rosa, 2005). Previous research has demonstrated the effectiveness of such online labs in achieving student learning outcomes equal to or better than traditional in-person labs (Brinson, 2015; Faulconer & Gruss, 2018; Reeves & Crippen, 2021). However, none of these studies explored the effectiveness of transitioning these labs to online platforms to support remote instruction and ensure academic continuity during the COVID-19 pandemic. This systematic literature review identifies the challenges faced by the IHEs in transitioning to the online platform and how they adapt to the changes during the COVID-19 pandemic.

Online labs can be defined as instructional labs in which students and equipment are not located in the same physical space (May, Alves, et al., 2023). Online labs have long been considered an alternative to implementing laboratory experiences in STEMM fields. However, to ensure that students receive an effective learning experience, it is important to carefully evaluate online labs' pedagogical and curricular value compared to traditional, in-person labs (May, Morkos, et al., 2023). There are several approaches to conducting online labs: Remote, Virtual, and Video-based. A remote lab is conducted remotely through the Internet, where the actual components or instruments used in the experiment are located separately from the control or execution site (Gamage et al., 2020). Virtual labs utilize virtual reality and computer-based simulation tools (Gamage et al., 2020). Video-based labs provide students with a detailed overview of a real lab so that the student can visualize the whole experimental process and its environment (Gamage et al., 2020). Alternatively, labs can also be conducted by providing students with lab supply kits or utilizing equipment available at their homes, known as home labs (Liang et al., 2020). Unlike remote labs, which involve real equipment and experiments located at different facilities, home labs utilize equipment with students in the same location, typically at their homes. Home labs can be facilitated using everyday kitchen utensils, instructor-assembled kits, or commercial lab kits (Jeschofnig & Jeschofnig, 2011). For clarity and ease of understanding in this review, we have consistently used the term "online labs" throughout the manuscript to describe all the labs conducted entirely or in part on an online platform. However, we have clearly outlined the strategy or type of technology utilized in these online labs.

Our specific objectives were to identify the strategies used by IHEs to transition to online labs, understand the effectiveness of these online lab courses, identify the perception of students and instructors regarding these online labs, and explore the challenges faced by instructors and students during the transition. Based on our objectives, the following research questions (RQ) were proposed:

RQ 1: What strategies and technologies were used by IHEs to deliver online labs?

RQ 2: How effective was the transition from in-person to online platforms?

RQ 3: What challenges did IHEs face in addressing the barriers caused by the pandemic in delivering online labs?

In this review, Section 2 outlines the methodology for selecting articles based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Section 3 examines the strategies and technologies utilized during the transition, the effectiveness of the transition to online platforms, and the challenges encountered by IHEs in this process. In Section 4, researchers present a User-centered Design framework that facilitates the shift of lab courses to remote delivery that can apply to various domains. This framework emphasizes the importance of incorporating design and human factors considerations to develop and implement successful online lab courses.

Materials and Methods

PRISMA systematic literature review framework (Moher et al., 2011) was used to search for research articles involving digital technologies and online labs implemented across IHEs during the transition from in-person to online platforms during the COVID–19 pandemic.

Information sources

For this literature review, a broad search was conducted for articles in the Education Resources Information Center (ERIC) and ProQuest, as these provided extensive, multi-disciplinary results within STEMM fields.

Eligibility Criteria

Each article had to fulfill specific criteria to be included in this review. Specifically, the studies had to be conducted in the STEMM fields, written in English, and published in a peer-reviewed journal between March 2020 and October 2021. They had to focus on the adaptations and strategies used by educational institutions during the transition from in-person to online instruction. This review excluded articles not written in English, conference proceedings, letters, and review articles that did not explore STEMM education and online learning.

Search Strategy and Outcomes

The research team considered search terms appropriate for the research questions. The keywords listed in Table 2.1 below were combined using Boolean operators (and/or):

Table 2.1: Search keywords

Topic and Cluster	Search terms
Pandemic	“COVID-19”
AND	
Higher education	“Higher education” OR university* OR college* OR undergrad* OR graduate* OR Engineering* NOT (“K-12” OR Kindergarten*)
AND	
Tools	“Digital learning tools” OR “Teaching methods”
AND	
Mode of delivery	“Distance learning” OR “Online laboratories” OR “Online learning” OR “Remote learning” OR “Virtual learning”

111 articles were divided among all three researchers for title and abstract screening based on the inclusion and exclusion criteria. The title and abstract screening resulted in 79 articles. The three researchers then independently reviewed all 79 full-text articles and

excluded 50 for failing to meet the inclusion criteria. The decision to exclude articles was made through discussions among the three researchers and was based on mutual consensus. This final screening resulted in retaining 29 articles. An additional ten articles were selected from the references of these 29 articles, which were finally selected. These articles were then screened, with seven satisfying the inclusion criteria. After removing two duplicate articles, 34 were chosen for this literature review, as shown in Figure 2.1.

Data Abstraction and Synthesis

The research team extracted data from the selected articles, conducting a detailed examination and validation process. Once the team carefully collected the data, the results were organized thematically to provide more detailed information. The data is presented in Appendix A (Author/Journal, Place/Domain, Study Design, and Measures).

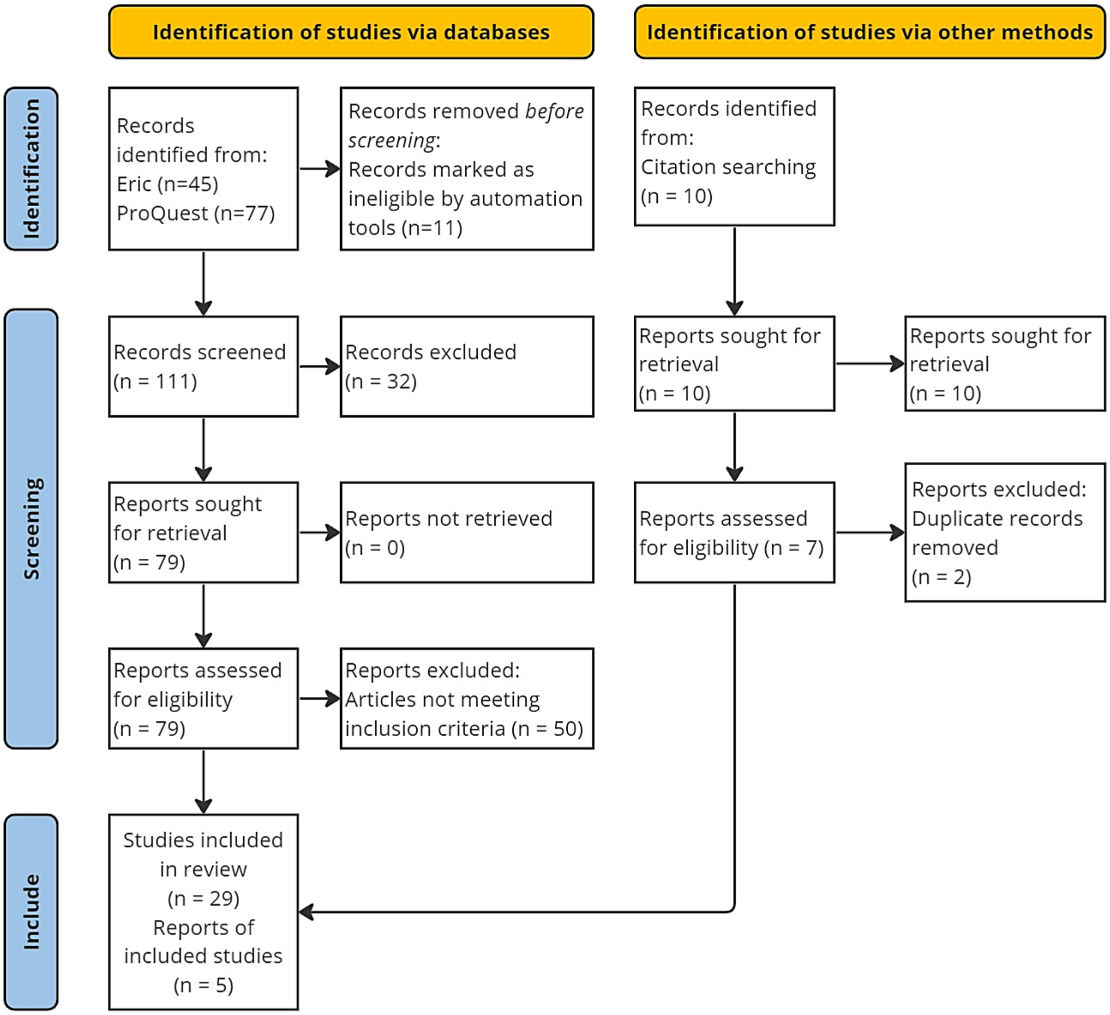


Figure 2.1: Article selection process

Results

Of the 34 articles selected for this review, 19 studies were conducted in the United States, three in Canada, two in China, and one each in Finland, France, Ireland, Palestine, Poland, Saudi Arabia, Spain, and the West Indies, and two studies involved a team of educators from different countries (Chang et al., 2021; Choate et al., 2021) as shown in Figure 2. 2

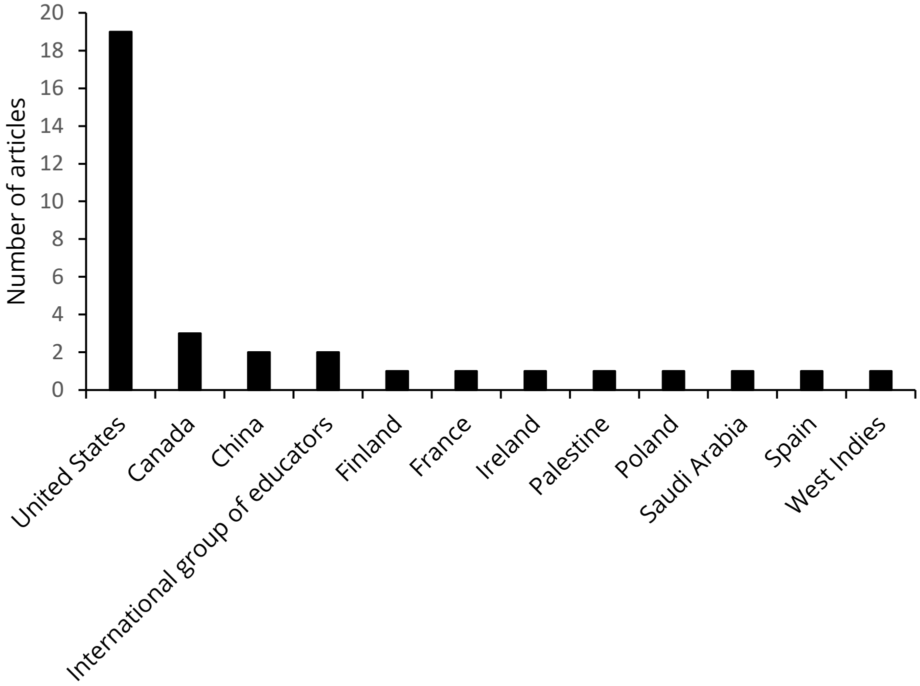


Figure 2.2: Regions of sourced studies

The articles reviewed in this study were sourced across four domains from the STEMM fields. Of the 34 studies reviewed, 67.64% were from science, 20.58% from engineering, 8.82% from medicine, and 2.94% from technology, as shown in Figure 2.3. Of the 23 studies conducted in the science domain, 16 were from chemistry, six from biology, and one from physics.

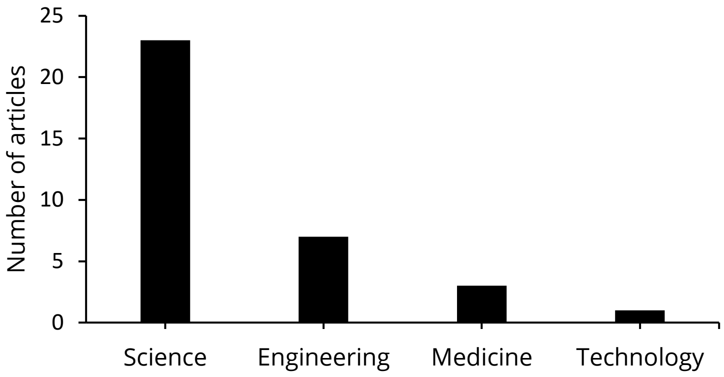


Figure 2.3: Domains of study

Since most of the articles reviewed in this research were from the chemistry domain, 16 publications were identified from the *Journal of Chemical Education,* as shown in Figure 2.4.

The primary areas explored in this literature review are the strategies and technologies used in transitioning in-person lab participation to lab participation via remote learning during the COVID-19 pandemic, the effectiveness of these techniques, and the challenges faced during this transition.

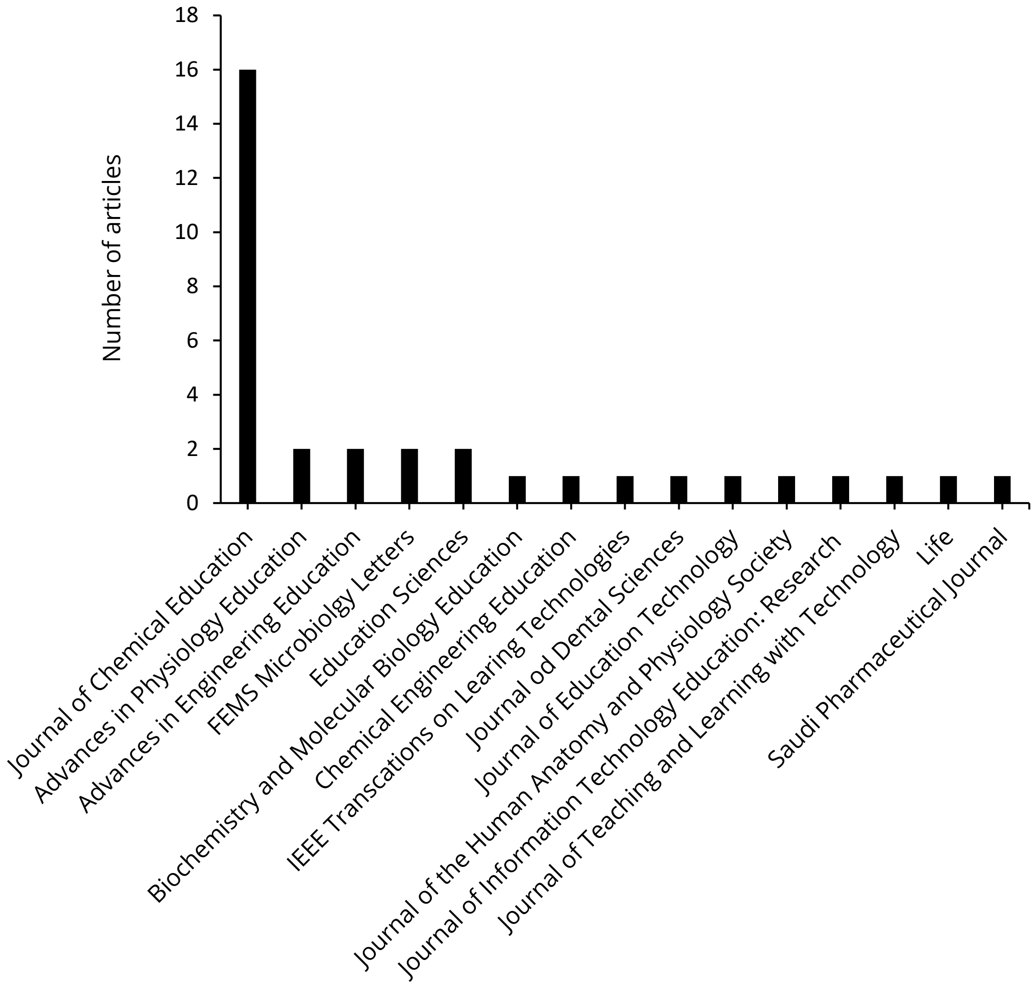


Figure 2.4: Journals in which articles are published

Strategies Used in the Transition of Labs

The quick transition of labs to the virtual environment due to the pandemic was a complex process, requiring careful planning, development, and coordination. This systematic review delved into the different methods employed by IHEs to deliver lab courses remotely to determine their effectiveness in knowledge acquisition and experimental skills developed. During the review, it was found that video recordings, desktop simulations, and home labs were the most widely used across the various domains of STEMM fields. Pre-recorded videos were the most frequently used (45%), followed by desktop simulations (25%), home labs (6%), and live-streamed videos (6%). Other pedagogical techniques included remote programming labs (4%), an online panel format (students divided into tutorial and learning teams) (2%), analysis of previous data (2%), a remote titration unit (2%), an online learning platform with data acquisition equipment (2%), and a visual tutor (online learning tool introduced in the digital electronics course) (2%). Two studies specifically suggest strategies that were implemented during the later phase of the pandemic (4%) (Hamed & Aljanazrah, 2020; Koort & Åvall-Jääskeläinen, 2021). Both synchronous and asynchronous modes, either alone or in conjunction with each other, were used across all strategies explored. The consolidated list of strategies used in the identified articles is provided in Table 2.2.

Table 2.2: Strategies used across the articles.

Strategies used	Number of articles
Video recordings	9
Video recordings and live-streamed videos	1
Video recordings and desktop simulations	9
Live-streamed videos	2
Desktop simulations	1
Video recordings, desktop simulations, and home labs	1
Desktop simulations and home labs	1
Home labs	1
Remote titration labs	1
Hybrid onsite and online labs with video recordings	1
Hybrid onsite and online labs with video recordings and desktop simulations	1

Remote programming lab	1
Online panel format	1
Analysis of previous data	1
Remote machine learning module	1
Online learning platform integrated with data acquisition equipment	1
Visual tutor with video recordings	1
Total number of Articles	**34**

Instructors created videos by recording their lab demonstrations, which are referred to as pre-recorded videos. Of the 23 studies that focused on video recordings, 11 examined pre-recorded videos (Almetwazi et al., 2020; Buchberger et al., 2020; Chierichetti & Backer, 2021; Choate et al., 2021; Davy & Quane, 2021; Franklin et al., 2021; Leung et al., 2020; Ożadowicz, 2020; Petillion & McNeil, 2021; Tran et al., 2020; Wasmer, 2021). However, some institutions rely on commercially available (Anstey et al., 2020; Hamed & Aljanazrah, 2020; Huang, 2020; Lacey & Wall, 2021; Liang et al., 2020; Wang & Ren, 2020; Zhou, 2020) open online sources such as massive open online courses and YouTube platforms (Anzovino et al., 2020; Choate et al., 2021; Dukes, 2020; George, 2020; Jones et al., 2021) when they were unable to record the lab activities before their schools were locked down. These commercial and YouTube videos were also used as supplementary instructional materials along with pre-recorded videos. For example, students who wanted to learn more about lab safety and cleaning while conducting chemical experiments were provided with YouTube links demonstrating these activities in detail. Learning using recorded videos has immense promise in laboratory-based fields, where brief video clips can effectively illustrate complicated or complex processes (Dash et al., 2016). These video recordings helped teach students about the operation of the instruments and observing the experiments. However, the videos lacked interactivity as students became passive observers unable to engage in hands-on activities. Unlike video recordings, live-streamed videos included an instructor conducting real-time experiments in a physical laboratory. This strategy was primarily used in labs teaching chemistry, involving handling glassware and equipment, waiting for reactions, and recording observational data. Students could verbally interact with the instructor and, thus, participate in the experiment (Davy & Quane, 2021; Petillion & McNeil, 2021; Woelk & Whitefield, 2020). As the live-streamed sessions were intended to improve the lab experience, the instructors had to ensure they used high-resolution cameras to capture the salient features of the experiment (Davy & Quane, 2021). The instructor also interacted with students by eliciting discussions about the experiment. Students were also encouraged to observe and record the data their instructor reported during the sessions (Woelk & Whitefield, 2020). In addition, live-streamed videos allowed the students to observe issues or unexpected results and to participate in developing solutions to address these errors (Petillion & McNeil, 2021). As a result, students were actively involved in the process in real time through verbal interactions and observations. For example, students could determine the drop rate of the burette and whether to stir the sample when titrating through live interactions (Davy & Quane, 2021).

Instructors used simulations as an alternative pedagogy for implementing online labs where students could interact with these simulations using a computer or a smartphone. Through these virtual lab simulations, students participated in lab experiments or modeled physical phenomena (Fox et al., 2020). They completed all these steps by interacting with the models of the experiment on their computers or smartphones (Jones et al., 2021). For instance, in a simulated chemistry Buffers lab, students created a buffer (an acid-base pair), prepared the solutions, and collected and independently analyzed the data obtained by measuring the pH values of all solutions (Jones et al., 2021). These students could "get the feel" of working on the experiment by adjusting the apparatus, pouring solutions, and measuring the variables by systematically controlling the simulation platform from their computers. However, students could not gain genuine hands-on experience through these simulations, which is important in STEMM fields. Few studies made the simulation labs more engaging by adding supplement videos that were either pre-recorded or from commercial platforms (Aguirre & Selampinar, 2020; Hamed & Aljanazrah, 2020; Jones et al., 2021; Liang et al., 2020; Wasmer, 2021).

Unlike video recordings and simulations, instructors assigned home labs to provide students with hands-on activities (Ediger & Rockwell, 2020; R. Gao et al., 2020; Liang et al., 2020). These labs used readily available smartphones/laptops and software, kitchen utensils, common materials/ingredients found at home, and inexpensive lab kits mailed to the students. For example, a mechanical measurements engineering course used heating devices like electric and gas stoves at students' homes to investigate the characteristics of thermocouples (Liang et al., 2020). While home labs could replace some lab experiences, not every lab could be replicated at home. Some labs required expert supervision, whereas others utilized expensive, specialized equipment students could not access at home.

Two studies have investigated substituting practical lab work with alternative approaches, such as online panel formats (J. Gao et al., 2021) or replacing laboratory work solely with previous data analysis (Dietrich et al., 2020). The online panel format divided students into tutorial and learning teams (J. Gao et al., 2021). Tutorial teams consisted of students who had already finished the in-person lab activities, while learning groups consisted of students who still needed to perform them. This format implemented a team-based approach where tutorial teams created mini-lessons that provided specific and in-depth information about the experiments for the learning teams. This strategy leveraged skills taught before distance learning to enhance learning during the pandemic.

Two studies explored the use of remote programming labs, primarily in engineering. For example, an engineering dynamics system lab used a machine learning module focused on basic statistics, data analysis techniques, and machine learning concepts using MATLAB live script. MATLAB live script is an interactive document created by MathWorks® to combine codes and output/graphics with texts and equations (Nevaranta et al., 2019). The instructors provided interactive materials that allowed students to conduct experiments with available resources like smartphones to gather motion data to classify human activities and make subsequent analyses using machine learning algorithms (Leung et al., 2020). On the other hand, a software engineering lab used a remote lab infrastructure that included an open-source computer monitoring system (Veyon), a virtual private network, remote lab scripts for restarting and installing the remote labs gathering information about all lab attendants, and a Web conferencing platform (Garcia et al., 2021). The monitoring system allowed instructors to monitor students' computers and even lock them when needed while conducting exams. The web conferencing system facilitated the synchronous delivery of remote labs. Instructors could explain the lab tasks, engage with students through audio and chat, have one-on-one conversations, and share lab resources. Additionally, the system allowed instructors to receive student uploads and utilize screen sharing and whiteboard features. After the instructor explained the programming problem using a Web conferencing platform, the students worked on the lab activity while being monitored (Garcia et al., 2021).

Other strategies used by instructors to replace in-person lab experiences were a remote titration unit, an online learning platform with data acquisition equipment, a visual tutor, and hybrid in-person and online labs. A remote titration unit utilizing a Raspberry Pi architecture equipped with a webcam and a servo motor allowed students in a chemistry lab to control the experimental unit remotely (Soong et al., 2021). This procedure included selecting the titrant volume to be added to the solution and monitoring the titration progress via the webcam. This approach allowed students to participate remotely in a true laboratory setting. Additionally, this remote lab configuration had the potential to solve accessibility issues by enabling students to engage in a laboratory activity in an environment suitable for their learning requirements.

Instructors used the Lt® online learning platform for anatomy and physiology lab delivery (Stokes & Silverthorn, 2021). This platform integrates pre-made online lectures with computer data acquisition hardware and transducers (used to collect physiological data), questions, background material, hardware configurations, and data analysis tools. To align with their course's learning objectives more effectively, instructors can modify the lessons by adding or removing content. The platform offers a wide range of question types with features such as suggestions, immediate feedback, multiple attempts, and automated grading. Students can engage in the lessons individually or in small groups.

A digital electronics visual tutor was employed in an electrical and computer engineering course to enhance the learning experience for introductory digital electronics topics. Visual Tutor is an online learning tool that offers interactive modules that cover various concepts in digital electronics (George, 2020). It also includes a port-mapping tool for digital logic design, allowing students to learn about port mapping practically and apply their knowledge in a practical setting. This port-mapping tool is important for students learning about high-speed integrated circuit hardware description language. Additionally, the tutor provides a variety of mock quizzes to assess understanding and a newly developed course book tailored specifically for the course (George, 2020).

The strategies discussed thus far were implemented early in the pandemic when institutions were closed completely and academic continuity was maintained using remote approaches. However, one study explored the remote partner model introduced in the bacteriology and mycology lab for an infection microbiology course later in the pandemic, specifically from December 2020 to March 2021 (Koort & Åvall-Jääskeläinen, 2021). This lab consisted of introduction and summary lectures on Zoom and SafeLab online self-study modules combined with hybrid in-person/online experimentation. Students worked in pairs in this model, one working virtually online and the other physically in the lab. The students took turns to ensure that all were allowed to work in the lab. Students who experimented in the in-person lab were given physical instruction. At the same time, the remote partner used Zoom to record observations, perform calculations, and draw conclusions about the experiments. Online video recordings were provided to students to help them comprehend the fundamental ideas (Hamed & Aljanazrah, 2020). At the same time, simulations were incorporated to give students the experience of working on the experiments virtually before experimenting in the in-person lab (Hamed & Aljanazrah, 2020).

Instructors used simulations as an alternative pedagogy for implementing online labs that included interactive physical elements such as computers or smartphones. Through these virtual lab simulations, students participated in lab experiments or modeled physical phenomena (Fox et al., 2020). They completed all these steps by interacting with the models of the experiment on their computers or smartphones (Jones et al., 2021). For instance, in a simulated chemistry Buffers lab, students created a buffer (an acid-base pair), prepared the solutions, collected, and independently analyzed the data obtained by measuring the pH values of all solutions (Jones et al., 2021). These students could "get the feel" of working on the experiment by adjusting the apparatus, pouring solutions, and measuring the variables by systematically controlling the simulation platform from their computers. However, students were deprived of the chance to gain genuine hands-on experience through these simulations, which is crucial in STEMM fields. Few studies made the simulation labs more engaging by adding supplement videos that were either pre-recorded or from commercial platforms (Aguirre & Selampinar, 2020; Hamed & Aljanazrah, 2020; Jones et al., 2021; Liang et al., 2020; Wasmer, 2021).

Unlike video recordings and simulations, instructors assigned home labs to provide students with hands-on activities (Ediger & Rockwell, 2020; R. Gao et al., 2020; Liang et al., 2020). These labs used readily available smartphones/laptops and software, kitchen utensils, common materials/ingredients found at home, and inexpensive lab kits mailed to the students. For example, a mechanical measurements engineering course used heating devices like electric and gas stoves at students' homes to investigate the characteristics of thermocouples (Liang et al., 2020). While home labs could replace some lab experiences, not every lab could be replicated at home. Some labs required expert supervision, whereas others utilized expensive, specialized equipment students could not access at home.

Two studies have investigated substituting practical lab work with alternative approaches, such as online panel formats (J. Gao et al., 2021) or replacing laboratory work solely with previous data analysis (Dietrich et al., 2020). The online panel format divided students into tutorial and learning teams (J. Gao et al., 2021). Tutorial teams consisted of students who had already finished the in-person lab activities, while learning groups consisted of students who still needed to perform them. This format implemented a team-based approach where tutorial teams created mini-lessons that provided specific and in-depth information about the experiments for the learning teams. This strategy leveraged skills taught before distance learning to enhance learning during the pandemic.

Other strategies used by instructors to replace in-person lab experiences were a remote machine learning module, remote programming lab, remote titration unit, online learning platform with data acquisition equipment, a visual tutor, and hybrid in-person and online labs. In the remote machine learning module, instructors provided interactive materials that introduced students to big data principles, allowing them to conduct hands-on experiments with accessible resources (Leung et al., 2020). For example, an engineering dynamics system lab used a machine learning module focused on basic statistics, data analysis techniques, and machine learning concepts using MATLAB live script. MATLAB live script is an interactive document created by MathWorks® to combine codes and output/graphics with texts and equations (Nevaranta et al., 2019). The instructors provided interactive materials that allowed students to conduct experiments with available resources like smartphones to gather motion data to classify human activities and make subsequent analyses using machine learning algorithms (Leung et al., 2020).

Remote programming lab infrastructure used in a software engineering lab comprised an open source computer monitoring system (Veyon), a virtual private network, remote lab scripts for restarting and installing the remote labs gathering information about all lab attendants, and a Web conferencing platform (Garcia et al., 2021). The monitoring system allowed instructors to monitor students' computers and even lock them when needed while conducting exams. The web conferencing system facilitated the synchronous delivery of remote labs. Instructors could explain the lab tasks, engage with students through audio and chat, have one-on-one conversations, and share lab resources. Additionally, the system allowed instructors to receive student uploads and utilize screen sharing and whiteboard features. After the instructor explained the programming problem using a Web conferencing platform, the students worked on the lab activity while being monitored (Garcia et al., 2021).

A remote titration unit utilizing a Raspberry Pi architecture equipped with a webcam and a servo motor allowed students in a chemistry lab to control the experimental unit remotely (Soong et al., 2021). This procedure included selecting the titrant volume to be added to the solution and monitoring the titration progress via the webcam. This approach allowed students to participate remotely in a true laboratory setting. Additionally, this remote lab configuration had excellent potential to solve accessibility issues by enabling students to engage in a laboratory activity in an environment suitable for their learning requirements.

Instructors used the Lt online learning platform for an anatomy and physiology lab delivery (Stokes & Silverthorn, 2021). This platform integrates pre-made online lectures with computer data acquisition hardware and transducers (used to collect physiological data), questions, background material, hardware configurations, and data analysis tools. To align with their course's learning objectives more effectively, instructors can modify the lessons by adding or removing content. The platform offers a wide range of question types with features such as suggestions, immediate feedback, multiple attempts, and automated grading. Students can engage in the lessons individually or in small groups.

A digital electronics visual tutor was employed in an electrical and computer engineering course to enhance the learning experience for introductory digital electronics topics. This online learning tool offers interactive modules covering various digital electronics concepts (George, 2020). It also includes a port-mapping tool for digital logic design, allowing students to learn about port mapping practically and apply their knowledge in a practical setting. This port-mapping tool is important for students learning about high-speed integrated circuit hardware description language. Additionally, the tutor provides a variety of mock quizzes to assess understanding and a newly developed course book tailored specifically for the course (George, 2020).

The strategies discussed thus far were implemented early in the pandemic when institutions were closed completely. However, one study explored the remote partner model introduced in the bacteriology and mycology lab for an infection microbiology course later in the pandemic, specifically from December 2020 to March 2021 (Koort & Åvall-Jääskeläinen, 2021). This lab consisted of introduction and summary lectures on Zoom and SafeLab online self-study modules combined with hybrid in-person/online experimentation. Students worked in pairs in this model, one working virtually online and the other physically in the lab. The students took turns to ensure that all were allowed to work in the lab. Students who experimented in the in-person lab were given physical instruction. At the same time, the remote partner used Zoom to record observations, perform calculations, and draw conclusions about the experiments. Online video recordings were provided to students to help them comprehend the fundamental ideas (Hamed & Aljanazrah, 2020). At the same time, simulations were incorporated to give students the experience of working on the experiments virtually before conducting the study in the in-person lab (Hamed & Aljanazrah, 2020).

Effectiveness in the Transition of Labs

Studies evaluating the impact of educational tools and technology focused on two main aspects: the effectiveness of the tool in teaching students and the user's experience with the system (Jenkinson, 2009). The researchers evaluated the effectiveness of these strategies identified in previous section as IHEs transitioned to online platforms by investigating student learning outcomes and instructor/student satisfaction/perceptions across the various online labs.

Learning Outcomes

Of the 34 articles reviewed, only 14 evaluated learning outcomes attained across online labs using assessment tools like pre and post-tests, assignments, exams and quizzes, and task safety and performance. Of the 14 articles that evaluated learning outcomes:

- Two studies examined labs that integrated video recordings and desktop simulations.
- Two studies focused on labs that used only video recordings.
- Two studies looked at labs that were conducted using home labs.
- Two studies explored labs that used a hybrid approach.
- One study each investigated labs using desktop simulations, live stream videos, remote programming labs, online panel formats, learning platforms with data acquisition equipment, and visual tutors with video recordings.

Online labs that integrated video recordings and desktop simulations: The studies that included both videos and simulations identified that the learning outcomes achieved by the students remained the same after the implementation of online labs. One study assessed learning outcomes by comparing the average scores of the final tests conducted on the online platform to the scores from the previous year's in-person chemistry labs (Aguirre & Selampinar, 2020). To accomplish this, the experimental study used the same final examination questions from an earlier semester and then analyzed and compared the outcomes. In another study, student performance was analyzed in two distinct virtual labs that focused on laboratory experiments related to circuits (Liang et al., 2020). These labs utilized a remote-control platform called ELF-BOX3 and an open-source virtual breadboard called Breadboard Simulator. After completing their labs on the online platform, students were required to write lab reports. The average score of these reports was analyzed and found to be greater than 80%.

Online labs that implemented video recordings: Labs implemented using video recordings have also achieved learning outcomes similar to traditional labs (Davy & Quane, 2021; Tran et al., 2020). The post-lab assessment scores achieved during remote delivery were compared to those obtained during in-person lab sessions in an organic chemistry course (Tran et al., 2020). Various components were considered in the organic chemistry in-person lab assessments, including prelab quizzes, lab completion, post-lab assignments, and exams. Usually, the lab's completion and the reaction product's yield would contribute 25% to the overall grade. However, due to the transition to remote learning, adjustments were made to the grading system. The study reassigned the 25% weightage to new post-lab assignments to address the absence of laboratory work and product yield. This study found that remote assignments primarily focused on examining and evaluating the results rather than completing the lab. As a result, these assignments emphasized scientific concepts more than practical skills, leading to an increased post-lab assessment score (Tran et al., 2020). In a study conducted on a titration lab and a Synthesis and Purification Lab Exercise in an undergraduate chemistry course, pre-COVID learning outcomes were compared with labs delivered by video recordings (Davy & Quane, 2021). After completing the online labs, student performance was assessed in several areas: making and recording observations, performing relevant calculations, making decisions about the proper endpoint, assessing the quality of the results, deciding if results were not adequate, processing and analyzing samples, and experiencing the analysis of real-world samples. Instructors then analyzed and compared which learning outcomes were achieved on the online platform and traditional in-person labs.

Online labs that implemented home labs: One study included home labs covering thermocouples' operating characteristics, determining strain in cantilever beams, and using accelerometers to measure dynamic mechanical systems. Upon finishing their labs online, students had to submit lab reports. The analysis of the average score of these reports revealed that it was over 80% (Liang et al., 2020). One study examined student performance in an introductory chemistry course (R. Gao et al., 2020). Students submitted lab reports after performing the copper chemistry experiment using a kitchen chemistry lab. These reports were then analyzed and compared with lab reports from the previous year. This comparison showed that students received higher grades using the kitchen chemistry lab. It should be noted that these observations are derived from a single kitchen chemistry lab and should be considered a partial assessment of kitchen chemistry experiments.

Online labs that implemented a hybrid approach: A study of a remote partner model that utilized both onsite and online platforms found that the practical exam scores for a microbiology course were similar between the pre-pandemic and pandemic periods (Koort & Åvall-Jääskeläinen, 2021). Towards the end of the lab, teachers evaluated students' proficiency in hands-on microbiological laboratory skills through a practical exam. During this exam, students worked in pairs and were tasked with identifying an unknown bacterium. The results obtained from this practical exam were compared to those from previous years (2018-2020) when traditional on-site laboratory learning was the norm. The results indicate that the combination of in-person and online lab platforms worked well together, making it a good option for lab classes with limited capacity for in-person attendance (Koort & Åvall-Jääskeläinen, 2021). Another study also identified no significant differences in students' level of achievement in a physics lab between an experimental group (using videos and simulations for theoretical presentation followed by in-person practical work) and the control group using the traditional method (face-to-face theoretical presentation followed by practical work) (Hamed & Aljanazrah, 2020). Data on students' performance during the hands-on experiments in the real lab were collected through observation. Both the experimental and control groups were observed while conducting the experiments. The control group consisted of students who participated in face-to-face theoretical presentations followed by practical work. The experimental group consisted of students who participated in virtual sessions followed by practical work. During the practical exams, the observation was focused on several aspects. These included the students' grouping and their discussions, the level of support provided by teaching assistants (including the type and amount of help), the support received from peers, the ability to identify the required equipment and construct experiments, the proficiency in collecting data and conducting experiments within the expected timeframe and pace, as well as students’ body language (Hamed & Aljanazrah, 2020).

Online labs that implemented desktop simulations: One study presented data demonstrating improved learning outcomes across labs incorporating simulations (R. Gao et al., 2020). Students completed the online lab using McGraw Hill's LearnSmart Lab®

series, which allowed them to perform experiments using virtual simulations and complete multiple-choice or matching questions to gain conceptual knowledge. After completing a LearnSmart Lab session, students received a performance report covering experimental operation and conceptual understanding. These reports were compared with the performance reports from the previous year's in-person labs. This study identified that students' performance in virtual biochemistry laboratories in the spring of 2020 was nearly identical to that of students in comparable in-person activities in the fall of 2017 (R. Gao et al., 2020). The study claimed that the enhanced learning outcomes might be attributed to the capability of configuring and personalizing simulations to facilitate student learning. This approach enabled students to repeat their experiments multiple times, allowing them to achieve satisfactory results before submitting their final reports.

Online labs that used live streaming videos: In a study examining a titration lab and a Synthesis and Purification Lab Exercise in an undergraduate chemistry course, pre-COVID learning outcomes were compared with those conducted using live streaming videos (Davy & Quane, 2021). After completing the online labs, student performance was evaluated in various areas, including making and recording observations, performing relevant calculations, determining the correct endpoint, assessing result quality, deciding if results were inadequate, processing and analyzing samples, and analyzing real-world samples. Instructors then compared the achievement of these learning outcomes in the online platform and traditional in-person labs. A comparison was also made to analyze the delivery of pre-COVID-19 learning outcomes using video recordings and live-stream videos. It appeared that live stream delivery achieved more learning outcomes than recorded videos.

Online labs that used remote programming: A study conducted in a software engineering lab solving programming problems found that student grades over nine years (2011-2020) remained unchanged within a 95% confidence interval (Garcia et al., 2021). The main goal of this remote lab was to address programming problems by utilizing different language features and paradigms. This result suggests that a synchronous remote lab is effective for courses that can be completed on computers that do not require basic experimental skills of other STEMM domains.

Online labs that used online panel format: In a chemical engineering lab, implementing an online panel format involving teaching and learning teams revealed that students' performance remained consistent with previous years. After completing the online lab, students submitted oral and written lab reports, which were analyzed and compared with lab reports of earlier years. The student's primary focus was demonstrating a comprehensive understanding of fundamental concepts and exhibiting effective communication and teamwork skills (J. Gao et al., 2021).

Online labs that used learning platforms with data acquisition equipment: In a study conducted in the anatomy and physiology lab, students' performance on laboratory reports for virtual laboratories was negatively affected (Stokes & Silverthorn, 2021). In-person laboratories had assessments for individual effort (pre-laboratory work) and group work (group quiz, data analysis, and laboratory report). Virtual labs had prework and the laboratory report combined into a single lesson that could be completed anytime. These virtual labs did not include group quizzes, and participation in the instructor-led virtual session was optional. On average, the virtual labs received lower scores, with a particularly significant decline observed in the endocrinology lab. Student comments indicated that the solitary online format made the virtual labs seem more difficult. Interestingly, when endocrinology lab grades were analyzed based on how students chose to complete the lab, those who participated in the interactive online session with the instructor performed better than those who completed the lab independently (Stokes & Silverthorn, 2021).

Online labs that used visual tutors with video recordings: The student performance in final examination quizzes in the electrical and computer engineering course, utilizing the digital electronics visual tutor, remained consistent with the performance observed in previous in-person sessions (George, 2020). Students had to take online quizzes after completing the labs on the online platform. These quizzes consisted of structured essay-type questions on the MyElearning course page, where students had to provide solutions in designated fields. Students were allowed multiple attempts at the quizzes, which were manually graded upon completion. The quiz grades were then compared with student performance grades collected over a period of five years.

In general, while the studies reviewed here indicate that learning outcomes can be achieved online, care needs to be taken to identify the purpose of the lab and the most effective strategy for achieving it. Labs involving basic experimental skills are more effective if incorporated into the online environment via simulations, live stream videos, and home labs rather than relying only on recorded videos.

Student and Instructor Perceptions

A second aspect of identifying the effectiveness of online labs involved the perceptions of both the instructors and students using them. Of the 34 articles reviewed, 23 evaluated student and instructor perceptions across online lab configurations using surveys, observations, and interviews. These studies incorporated:

- Six studies examined labs that integrated Video recordings
- Three studies focused on labs that used only Live-streamed videos
- Three studies examined labs that used a combination of videos and simulations
- Two studies explored labs that used only desktop simulations
- Two studies each looked at labs that were conducted using home labs, remote programming labs and hybrid in-person and online
- One study each investigated labs that used an online panel format, online learning platform with data acquisition equipment and visual tutor

Online labs that used video recordings: Six studies have investigated the efficacy of video recordings in facilitating online laboratory sessions through the use of surveys (Anstey et al., 2020; Franklin et al., 2021; Lacey & Wall, 2021; Leung et al., 2020; Petillion & McNeil, 2021; Wang & Ren, 2020). The overarching theme from the student feedback surveys indicates that video recordings have been effective in helping students learn scientific concepts. Students appreciated being able to watch the videos multiple times, which helped them understand the concepts at their own pace. To provide a specific example, students from a physics lab watched videos demonstrating the process of establishing a relationship between a pendulum's length and time period to derive the relevant equations. The study findings suggested that repeated viewing enhanced a student's ability to calculate acceleration due to gravity (Hamed & Aljanazrah, 2020). After watching lab recordings of data collection, students reported that they understood the concepts better by seeing the equipment and the types of measurements taken. This study also identified that 83% of physics students found the videos to help them understand the experiments before and during the hands-on laboratories (Hamed & Aljanazrah, 2020). The videos were effective in presenting concepts and explaining the experimental process. Survey results also reflected the negative feedback regarding the passive approach associated with using video recordings (Anstey et al., 2020; Leung et al., 2020; Petillion & McNeil, 2021; Wang & Ren, 2020). Incorporating interactive lab videos could be a possible solution (Wang & Ren, 2020).

Online labs that used live streaming videos: Three studies conducted in the domain of chemistry examined the effectiveness of live-streamed videos in delivering online labs, using surveys and semi-structured interviews to collect feedback on student satisfaction (Davy & Quane, 2021; Petillion & McNeil, 2021; Woelk & Whitefield, 2020). The survey results identified that students valued the live-streamed videos for creating a sense of participation during lab activities. While pre-recorded videos were generally preferred, live-streamed videos were effective for offering real-time learning experiences and opportunities to observe procedural errors. However, concerns were raised about the effectiveness of live lab demonstrations in understanding specific lab equipment. Issues such as blurry videos and occasional lag were also mentioned. Students preferred a two-camera setup during online courses, using a smartphone to film the instructor and a separate web camera for a close-up view of the chemistry experiments. Overall, the results highlight the importance of providing real-time and engaging lab demonstrations to enhance the learning experience and student engagement.

Online labs that integrated video recordings and desktop simulations: Three articles examined the effectiveness of online labs integrating videos and simulations. Student and instructor perceptions were collected through student feedback surveys and instructor observations (Huang, 2020; Liang et al., 2020; Zhou, 2020). Based on instructors’ observations, the videos enabled students to understand the critical experimental protocol, principles, and precautions, while the simulations allowed them to conduct virtual experiments (Zhou, 2020). This approach enhanced various abilities essential for multiple experiments, favoring the use of this strategy for several real-world experiments. These instructor observations are supported by the students' perceptions, with 93% of students rating this method as excellent and 7% as very good in a study conducted to identify the success and challenges encountered during the full implementation of online chemistry instruction (Huang, 2020). The student survey conducted in a mechanical measurements course revealed that students were satisfied with the remote teaching platform, which incorporated breadboard simulations and video demonstrations (Liang et al., 2020). A vital component of this platform was Breadboard Simulator, an open-source virtual breadboard software. It allowed students to understand the features of breadboards and utilize a virtual breadboard to connect and construct electrical circuits, enabling them to get the feel of working with actual circuits.

Online labs that used desktop simulations: Two studies collected survey data to analyze students' perceptions of using simulations (Anstey et al., 2020; R. Gao et al., 2020). In an organic chemistry class, students utilized a simulation platform to virtually perform and grasp the concept of electrophilic aromatic substitution reactions. Further, they were given mock laboratory notebook pages and analytical data as an exercise to identify potential errors. While students appreciated this experiment's collaborative and creative nature, they longed for hands-on experimentation opportunities unavailable in the remote setting (Anstey et al., 2020). One study examined that 67% of the juniors and seniors (n =10) in a biochemistry lab were pleased with their overall remote learning experience incorporating simulations, while 33% were neutral. Further, when asked to compare their experience of online laboratories to in-person instructions, most students reported that virtual labs were effective (17%) or somewhat effective (50%). In comparison, 33% considered them less effective (R. Gao et al., 2020). Overall, students found simulations beneficial for understanding concepts and practicing skills, particularly in scenarios where hands-on experimentation was not feasible. However, there was a clear preference for in-person labs, with students valuing the hands-on aspects of traditional laboratory settings. This highlights the importance of balancing the use of simulations with opportunities for hands-on learning to provide an effective learning experience for students.

Online labs that used home lab kits: A study in a mechanical measurements course to determine strain in cantilever beams found that students preferred online labs incorporating home labs because they could work on physical equipment and experience its touch and feel. Student survey results indicated they rated home labs higher than online labs (Liang et al., 2020). One study conducted a post-course survey to rate student perceptions of how efficient learning was through the kitchen chemistry lab (R. Gao et al., 2020). While most students found conducting a kitchen chemistry lab effective, a few raised concerns regarding safety. For example, in the kitchen chemistry lab, students might use household chemicals or conduct experiments involving heat sources. One safety concern could be ensuring that students are properly trained in handling these chemicals and equipment to prevent accidents or injuries. The overarching theme identified from these studies is that students value the hands-on experience with physical equipment in home labs. However, addressing safety concerns and ensuring that home labs provide students with a safe and effective learning environment is essential.

Online labs that used remote programming lab: Two studies in the engineering domain analyzed the effectiveness of remote programming labs using a survey (Garcia et al., 2021; Leung et al., 2020). The Likert scale was used to analyze student opinions of a synchronous online platform used in a software engineering lab to solve programming problems using object-oriented and parallel programming. The results showed that students rated questions related to installation simplicity and infrastructure suitability for meeting each lab's goals the highest. In contrast, the question regarding using remote labs to prevent cheating received the lowest. The anonymous survey with a 17% voluntary response rate on student satisfaction with a machine-learning module found that 85% preferred it over the video-recorded labs. This lab used at-home devices like smartphones to gather human motion data and subsequent analysis using machine learning modules. All students agreed that this module helped them review statistics and grasp the fundamentals of machine learning (Leung et al., 2020). These results indicate that incorporating remote programming labs can enhance student learning and satisfaction. However, measures should be taken to address concerns about preventing cheating in online lab environments.

Online labs that used an online panel format: One study surveyed student perceptions about using their online panel format (tutorial team and learning team) in a chemical engineering lab (J. Gao et al., 2021). Nearly 92% of the students mentioned that the collaboration and communication between the two groups aided their understanding of the experiment's nature and requirements. In comparison, 87% commented that the online panel format enhanced their data interpretation and analysis ability. According to 73% of students from the tutorial teams, discussing the questions in advance and participating in the question-and-answer sessions following the presentation helped them better comprehend and understand the experiments. In addition, 87% of the students agreed that the tutorial presentation of the lesson improved their core understanding of the procedure and helped them grasp the experiments. In the learning teams, 79% of the students responded that they felt more prepared to conduct these experiments than during their conventional pre-experiment preparation. Based on the findings from the student survey, this panel structure allowed for interactive dialogue between the tutorial and learning teams, which was substantially more effective than passive listening.

Online labs that used online learning platforms with data acquisition equipment: Student feedback surveys on the perceptions of the Lt learning platform used in an anatomy and physiology lab were overwhelmingly positive, with students recognizing that the technology significantly enhanced their learning experience (Stokes & Silverthorn, 2021).

When comparing in-person labs to the online format with the integration of the learning platform, students found the online version much easier to follow. However, some students expressed negative feedback regarding specific experiments, finding them boring, confusing, or difficult in the virtual format. Whether using paper handouts in face-to-face delivery or computer-based learning in the virtual platform, they found the online version more organized. The comments from students regarding the two virtual laboratories, specifically the endocrinology and anatomy and histology labs, at the end of the course highlighted the importance of instructor participation and collaborative work in the online format (Stokes & Silverthorn, 2021).

Online labs that used visual tutors with video recordings: Based on student feedback collected using a survey in an electrical and computer engineering course using a digital electronics visual tutor, students expressed increased confidence in engaging in self-study while guided by the instructor (George, 2020). Students appreciated the wide range of learning resources available on the online platform, including the visual tutor and the newly introduced course textbook.

Online labs that used analysis of previous year data to replace lab work: Feedback from students who participated in online education during the lockdown semesters of two different groups of a 5-year program in Chemistry, Environment, and Chemical Engineering was collected using an online survey to identify the success and challenges during online education. Due to the pandemic, some practical lab work had to be canceled. This decision received mixed responses from the students, with 33.3% considering it a good solution, 28.6% disagreeing, and 38.1% remaining neutral. Students mentioned that the attempts to maintain the continuity of lab work proved to be more time-consuming and exhausting. The approach of replacing laboratory work with just the analysis of previous data was rejected by 61.2% of the students because this merely involved numerical calculations performed autonomously (Dietrich et al., 2020). However, the same approach with the presence of an educator through video conferencing in small groups was appreciated by 44.7% of the students. It was observed that students studying disciplines related to engineering science, where hands-on practical work is crucial, were particularly frustrated by the loss of the practical aspect of the lab work. On the other hand, some students highlighted that the theoretical aspect was covered in greater depth, leading to a better understanding of the course material.

Based on the analyses of these studies, integrating various methods, such as video recordings with interactive elements, live-streamed videos, simulations, and home labs, can enhance student learning and engagement in online labs. Nevertheless, a hybrid approach that combines in-person and online experiments can be ideal, even in traditional classroom settings, as it saves time and provides an enhanced learning environment for the student.

Challenges Faced by Institutions in Transitioning to Online Platforms

The unexpected transition to online delivery of labs caused by the COVID-19 pandemic led to several challenges across STEMM education. The significant barriers in the studies reviewed included technological challenges, workload and expertise constraints, academic integrity, and lack of student engagement.

Lack of access to technology: The articles reported that the lack of access to the internet and the technology needed for the online delivery of labs was identified as an ongoing challenge during the pandemic (Aguirre & Selampinar, 2020; Anstey et al., 2020; Anzovino et al., 2020; Chierichetti & Backer, 2021; Choate et al., 2021; R. Gao et al., 2020; Huang, 2020; Kolack et al., 2020; Tran et al., 2020). As both instructors and students moved to remote teaching and learning, access to institutional services was lost. Some areas, particularly remote ones and those serving marginalized populations need the Internet and network technology to support online education (Englund et al., 2017; Huda et al., 2018). More than two-thirds of students had problems with intermittent Internet connectivity during the spring of 2020. More than 50% of the students needed more physical study space, and webcams were unavailable (Chierichetti & Backer, 2021). Students often shared laptops with family members as they worked or attended school remotely. Furthermore, internet access was limited as students' access to high-quality Wi-Fi was not as readily available at home as at campus - an especially prominent issue in remote areas and underserved communities. These issues were mitigated to a certain extent by instructors providing loaner laptops and portable Wi-Fi connections (Anstey et al., 2020; Anzovino et al., 2020; Kolack et al., 2020; Tran et al., 2020; Zhou, 2020).

Workload and expertise constraints: Workload and expertise constraints were challenges impacting an effective and efficient transition to an online platform for instructors and students (Aguirre & Selampinar, 2020; Chierichetti & Backer, 2021; Choate et al., 2021; Tran et al., 2020). Instructors were required to use skills and expertise outside their education and teaching experience (Chierichetti & Backer, 2021). This study further documented that more instructors reported using audio and video conferencing tools, followed by webcams, online videos or tutorials, and YouTube after shifting to the online platform. The study also identified that 70.4 % of the instructors responded that they had to spend more time preparing the online course materials than traditional in-person methods. Reformatting/reinventing the labs and the need to provide technology support for their less experienced teaching assistants and students added to the instructors' workload. In addition, it was difficult for students to quickly adapt to new learning formats, which posed challenges in becoming accustomed to online platforms. The students described their experience as more negative because their perceptions of the classes in spring 2020 were different. After classes transitioned to online mode in April 2020, a survey of students at a prominent Texas institution reported that 71% of respondents reported increased stress and anxiety, while almost 90% experienced difficulty maintaining focus (Son et al., 2020). More students started scheduling one-on-one meetings with the instructors, mainly because they required emotional support and academic help (Aguirre & Selampinar, 2020; Chierichetti & Backer, 2021). To help with the transition, instructors also supplied a wealth of materials on online learning, time management, and stress management.

Academic integrity: Some of the articles identified a lack of online proctoring guidelines, raising academic integrity issues (Aguirre & Selampinar, 2020; Anzovino et al., 2020; Chang et al., 2021; Choate et al., 2021; Dietrich et al., 2020; Garcia et al., 2021; Huang, 2020; Stokes & Silverthorn, 2021). Students were inconvenienced by the need to use two electronic devices, one to complete an exam, for example, and another to monitor themselves (Huang, 2020). Several recommendations for addressing academic integrity issues are provided. For instance, one study found that using a computer monitoring system (Veyon) across remote labs was effective for recording students during lab exams. In contrast, others generated a 360-degree scan of the room where the students took the exams or used lockdown browsers to ensure integrity (Aguirre & Selampinar, 2020; Anzovino et al., 2020; Chang et al., 2021). Other instructors adapted to using presentations rather than closed-book lab exams and assignments (Choate et al., 2021; Dietrich et al., 2020; Stokes & Silverthorn, 2021). These presentations offer the added benefit of improving communication skills while ensuring students have a solid comprehension of the concepts.

Lack of student engagement: Finally, irrespective of the platform, none of the online labs could engage the students in a complete lab experience that included both technical skills and non-technical experiences (Buchberger et al., 2020; Choate et al., 2021; Huang, 2020; Liang et al., 2020; Wang & Ren, 2020). For example, virtual labs took a lot of work to provide an authentic lab experience to the students, involving apparatus selection, washing and handling glassware, waste disposal, and using goggles and gloves (R. Gao et al., 2020). The challenges of virtual learning were amplified by the reduced interaction between instructors and students, the absence of real-time feedback, and the lack of opportunities for teamwork, making it difficult to provide a fully authentic lab experience.

The lab transition from in-person to online platforms was undoubtedly challenging. IHEs made considerable efforts to navigate through the difficulties brought on by the pandemic. Among the various challenges faced, the lack of access to technology stood out as the most prominent concern, highlighted by nine out of the 34 studies reviewed.

However, the IHEs were proactive in finding timely solutions to address this issue and also made efforts to maintain academic integrity to a certain extent. However, dealing with the workload and expertise constraints and ensuring a comprehensive lab experience with adequate student engagement required additional effort and careful planning to overcome these challenges.

Discussion

In this section, we synthesize the findings from reviewed literature on how educational institutions mitigated challenges related to enhancing the learning experience and student engagement in lab courses, technology and software competency, and academic integrity during the pandemic to ensure academic continuity for students. The synthesized findings have been incorporated into guidelines that institutions may implement to maintain academic continuity. These guidelines focus on developing an academic continuity plan with a primary emphasis on maintaining teaching and learning. 1) Plan to select or develop evidence-based digital learning tools and software that support learning outcomes 2) Provide opportunities for synchronous and asynchronous sessions and select evidence-based digital learning tools and resources to facilitate student engagement; 3) Provide training in software and technology for instructors and students to prepare them for current technologies; 4) Develop clear instructions and guidelines for assessments to uphold academic integrity; 5) Continuously improve online lab courses by integrating student and instructor feedback and addressing any challenges encountered.

Plan to select or develop evidence-based digital learning tools and software that support learning outcomes

The findings from this review reflect that the instructor employed video recordings, desktop simulations, and home labs individually or in combination to continue teaching and learning. It is worth considering expanding the availability of well-planned commercial lab kits across various domains to provide more opportunities for hands-on practice. Institutions may need to finalize during the academic continuity planning phase, including provisions for transitioning to commercial kits when necessary. Safety concerns from home lab kits can be addressed using Extended Reality (XR) technologies. XR technology is a broad term that includes various immersive technologies like Augmented Reality (AR) and Virtual Reality (VR) (Kwok & Koh, 2021). By employing XR technologies, students can engage in simulated laboratory environments that provide a sense of working with real equipment while minimizing safety risks. This suggestion is supported by studies emphasizing the importance of XR technologies in enabling learners to safely familiarize themselves with procedures such as handling hazardous chemicals (Broyer et al., 2021) or performing surgery on patients (Lohre et al., 2020). Another approach to offering authentic experiences involves incorporating AR or VR techniques into remote experimentation, creating Extended Reality Remote Laboratories (Silva et al., 2023). However, XR technologies have disadvantages related to lack of familiarity with the technology, motion sickness and cost (Hoffman, 2020).

Provide opportunities for synchronous and asynchronous sessions and select evidence-based digital learning tools and resources to facilitate student engagement

Maintaining student engagement in online platforms is challenging but can be addressed through direct interactions with instructors and peers. While synchronous, real-time, video-based delivery can facilitate such interactions, it may only sometimes be feasible due to factors like differing time zones or technology issues. In these instances, instructors found it practical to use synchronous or asynchronous methods or integrate them effectively. These strategies are consistent with recommendations from another study, emphasizing the use of technological tools synchronously, asynchronously, or in an integrated manner to maintain student engagement and involvement in the course effectively (García-Morales et al., 2021). Another potential strategy is providing online team collaboration spaces, collaborative activities, group discussions, and other forms of student interaction to enhance student engagement. This finding is supported by studies suggesting the creation of a virtual community of practice to enhance peer engagement and collaborative learning experiences among students (Carolan et al., 2020; Gamage et al., 2020; Müller & Ferreira, 2005). Müller and Ferreira (Müller & Ferreira, 2005) discuss the need for student interactions in online labs to acquire soft skills like teamwork and cooperation and to integrate the know-how of others to accomplish a task. They emphasize that delivering online labs solely through asynchronous modes can significantly limit or prevent collaboration and skill development opportunities. Breakout rooms from video conferencing software such as Zoom provide a feature for online team collaboration. Using this feature, students can discuss their projects in smaller groups without being interrupted or distracted by other groups. To ensure a balanced and well-coordinated learning experience, instructors should carefully plan and communicate the duration of Zoom sessions and collaborative activities. This helps prevent students from becoming disengaged due to lengthy sessions. This finding is consistent with the study highlighting the need to consider the duration of synchronous Zoom sessions based on the amount of content to be covered (Lockee, 2021).

Develop clear instructions and guidelines for assessments to uphold academic integrity

During the pandemic, students and instructors faced additional pressure as they had to learn to use new technologies and software. Providing software and technology training to instructors can help them create and implement engaging simulations and effectively use web conferencing platforms like Zoom. These training sessions can enable the instructors to navigate any disruptions caused in the future efficiently. These findings are consistent with the study on maintaining academic continuity, paying attention to the digitalization of learning processes, and offering specific technical training to professors, administrative staff, and students (García-Morales et al., 2021).

Continuously improve online lab courses by integrating student and instructor feedback and addressing any challenges encountered

Academic dishonesty in online or remote courses is a significant concern for IHEs. Understanding the types and causes of academic dishonesty can make it possible to develop effective methods to promote academic integrity (Holden et al., 2021). To address these issues, IHEs may need to establish guidelines and rules during the initial planning phase of online education. One effective prevention method is using the Multiple Attempts Format

(MAF) in online assessments (Estidola et al., 2021). Students reported that MAF allows them to improve their scores honestly and strengthens their commitment to academic integrity. Teachers agreed that MAF teaches students about responsibility, decision-making, and risk-taking to enhance their scores. Fostering self-regulated learning skills, where learners set goals and manage their learning, can contribute to increasing academic integrity (McAllister & Watkins, 2012). Course design strategies such as reducing exam weight, randomizing exam questions, and providing prompt feedback are recommended for maintaining academic integrity.

In conclusion, this review reveals that integrating video recordings, desktop simulations, and expanding commercial lab kits offers a comprehensive laboratory experience in online education. As an insight from this review, considering XR technologies can further enhance the overall learning experience. Strategies like direct interactions, synchronous and asynchronous methods, and collaborative activities are essential for student engagement. It is equally important to establish clear guidelines to maintain academic integrity. These findings highlight the necessity of adapting to new technologies and strategies to ensure effective teaching and learning on online platforms.

Conclusion

This systematic literature review investigated articles from across various domains of STEMM. The studies focused on identifying the effective strategies for transitioning labs to online platforms and the challenges faced during the phase. However, this study has a few limitations. Only English-language publications were reviewed; thus, our data may need to be completed because we did not include articles published in other languages. Due to the limited time frame of data collection (September to October 2021) and the focus on articles published during the COVID-19 pandemic, the available data could be much higher. In addition, our results on the strategies implemented for online labs also focused on qualitative data. Results on quantitative data were minimal.

Despite these drawbacks, the review answered the preliminary research questions. The review indicates that combining video recordings, simulations, and home labs is more effective for remotely conducting STEMM labs than using any of these approaches in isolation. This strategy can be useful in various scenarios, such as inclement weather or future pandemics, that necessitate the shift of STEMM labs to an online platform. Future research using controlled experimental studies could provide more comprehensive information on the effectiveness of online labs. The studies considered support evidence for the importance of synchronous sessions. Nevertheless, additional research is required to assess the learning outcomes achieved across synchronous and asynchronous sessions.

CHAPTER THREE

A STRUCTURED PROCESS FOR TRANSITIONING LAB COURSES TO ONLINE PLATFORMS

Introduction

Transitioning lab courses from in-person to online platforms can be challenging. The literature review identified how institutions utilized various strategies to conduct online labs. Many relied on readily available simulations or recorded videos of their lab demonstrations. However, personalizing the labs according to the instructors' or institution's specific goals could enhance the learning experience instead of solely relying on available resources. A framework for creating online labs is proposed, which institutions can use to tailor their labs. The product design and development framework was used to create this framework for developing online labs (Ulrich et al., 2008). The existing framework has been translated into the educational domain, focusing on developing online labs. A visual representation of the framework and its various phases is illustrated in Figure 3.1. A brief explanation of each phase is provided below, and an illustration showing the activities and outcomes associated with each phase is presented in Figure 3.1.

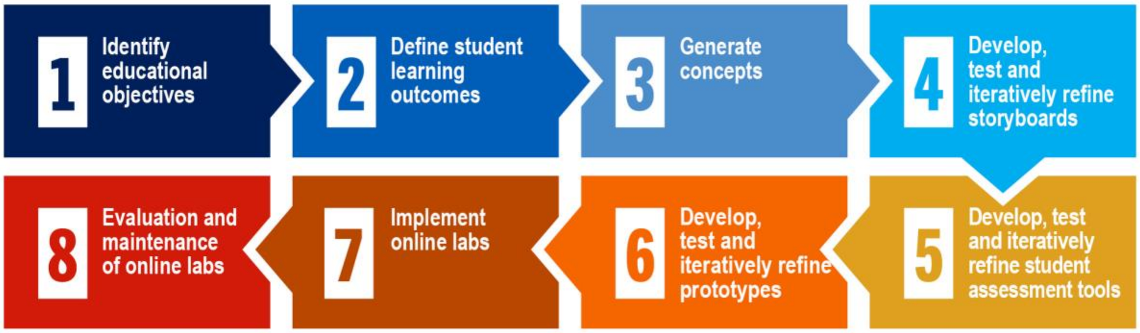


Figure 3.1: Phases in developing an online lab course

Phases in developing an online lab course

Phase 1 - Identify educational objectives

The objectives outline what an instructor or program aims for. These objectives can be identified by reviewing accreditation criteria and conducting Cognitive task analysis (CTA) of subject matter experts (SMEs) and industry partners. CTA is developed by conducting observational studies, focus groups, and interviews to understand the demands placed on the student, as well as the knowledge and specific skills required for working in the labs (Clark & Estes, 1996). These insights help educators create more relevant learning experiences and streamline learning objectives, ultimately supporting students in achieving academic and professional success.

Phase 2 - Define student learning outcomes

Learning outcomes refer to the knowledge, skills, and abilities students acquire during their studies. Instructors must identify specific and measurable learning outcomes consistent with the course's goals, level, and content while considering the student's needs and expectations, encompassing the cognitive, affective, and psychomotor domains. Utilizing frameworks like Bloom's Taxonomy (Bloom et al., 1956) can help create comprehensive and appropriately challenging learning outcomes beneficial for students in completing highly kinesthetic STEMM labs. Bloom’s taxonomy (1956) is a hierarchical model that categorizes thinking into six cognitive levels of complexity. The lower three levels are knowledge, comprehension, and application, while the higher are analysis, synthesis, and evaluation. In the context of lab courses, some examples of learning outcomes may include identifying and analyzing the basic principles behind the experiments, demonstrating the ability to conduct appropriate experiments, collecting and analyzing data, formulating results, and effectively communicating findings through well-written lab reports.

Phase 3 - Generate concepts

Educators can conduct external research by interviewing lead users and experts, conducting literature reviews, or performing patent searches to identify feasible strategies for conducting online labs. This external research can help them develop initial concepts for the online lab platform and determine the best strategy for transitioning the lab to an online platform. The literature review identified several strategies for conducting online labs, including video recordings, desktop simulations, live stream videos, and home labs. Educators can also leverage existing content libraries such as Open Educational Resources (OER) Commons, Massachusetts Institute of Technology (MIT) OpenCourseWare, and Skills Commons to select appropriate educational materials for their needs. Educators can then discuss and refine the strategies generated to ensure that the final learning outcomes align with the course goals and are accessible to all students. These concepts can be presented through sketches of the proposed strategies and brief textual descriptions. In this phase, the research team must ensure that the strategy selected adheres to ADA guidelines.

Phase 4 – Develop, test, and iteratively refine storyboards

Storyboarding is a widely used technique in Human-computer interaction design to showcase images that communicate a temporal sequence of actions involving particular lab courses (Ulrich et al., 2008). This method can provide a practical means to modify designs, allowing for changes to be made before virtual lab software development begins. Storyboarding can be highly beneficial in planning, organizing, and creating educational materials. It also enables teams to evaluate potential content for inclusion in online laboratory platforms. Sketches, videos, and animations can be used to create storyboards based on the content generated in the concept phase, aligning with the desired learning outcomes. The storyboarding phase undergoes several iterations and refinements based on the CTA and learning outcomes, with feedback from SMEs. Through this process, educators can develop models of immersive simulations, desktop simulations, and video recordings that effectively demonstrate how users can interact with the system.

Phase 5 – Develop, test, and iteratively refine student assessment tools

As part of the development process, educators can use assessment tools to collect and analyze data to evaluate student outcomes and achievement levels. Technology-based tools such as learning management systems (LMS) can administer quizzes, compile lab reports, and provide feedback. In addition to LMS, other digital tools like Kahoot! can combine game dynamics with the ability to monitor student learning (Correia & Santos, 2017). Kahoot allows teachers to create interactive quizzes, surveys, and discussions involving students in learning content knowledge through a competitive and engaging game format (Dellos, 2015). Formative assessment can provide students with feedback on their learning progress throughout the learning process (Glazer, 2014). It encompasses various assessment methods such as open-ended response questions, essays, and performance tasks like poster presentations and projects. It can also include closed-ended questions like multiple-choice questions. On the other hand, summative assessment can be used for grading, evaluation, or certification purposes and measures students' learning outcomes at the end of a term, semester, or year. Summative assessment includes closed-ended questions such as multiple-choice questions, true or false statements, and fill-in-the-blank exercises (Glazer, 2014). Methods like Rasch analysis may also be used to analyze the learning gains (Benjamin D. Wright & Stone, 1979).

Phase 6 – Develop, test, and iteratively refine online lab prototypes

Institutions can employ multiple digital technologies and software that simulate real-world laboratory experiences to provide students with flexible and convenient practical learning opportunities. For instance, simulations can be built using software like Unity, and augmented reality (AR) and VR equipment can be used to provide an immersive experience. Similarly, video recordings can be produced using high-quality cameras, and home lab kits can be developed and distributed to students' homes on a larger scale. These online labs are designed based on the organization and sequence of the lab procedures finalized in the storyboarding phase. Methods such as Learning Tools Interoperability LTI®-enabled modules can integrate any LMS product with any learning tool. During the testing and refinement phase, the online lab prototype can be put through multiple evaluations to improve its usability and functionality (Ulrich et al., 2008). Educators and SMEs can analyze the simulations, video recordings, and other digital platforms to identify usability problems. These usability evaluations can be done using heuristic evaluations (Nielsen, 1994) and subjective assessment tools like the System Usability Scale (SUS) (Brooke, 1996). The design team can then refine and modify the initial digital platform developed based on the feedback received.

Phase 7 – Implement online labs

In the implementation phase, online labs are made available to instructors and students using various digital tools and techniques available on the platform. The design team can create tutorials to help stakeholders understand how to use the online labs. These tutorials can provide instructions on implementing the various software and navigating the online lab platform. This may require additional testing to ensure the online labs function as intended during the testing phase. This phase would also help to understand how real users interact with the product.

Phase 8 – Evaluation and maintenance of online labs

This phase includes an assessment of the online labs post-launch, focusing on improving the development process for future courses. As part of implementing online labs, it is essential to analyze assessment results, update the labs, train instructors, monitor student progress, and consider student feedback and data to evaluate the effectiveness of any updates made to the system.

1 IDENTIFY EDUCATIONAL OBJECTIVES

- Identify the course objectives the instructor aims to achieve in the course.
- Align curriculum with required standards.
- Identify all stakeholders involved in implementing the online course, including teachers, students, IT department, industry partners.
- Determine the implementation timeline.
- Explore potential hosting avenues for implementing this system which may include classroom setting, online platforms, on the job training sessions.
- Identify necessary technologies and software for developing and implementing online labs.

2 DEFINE STUDENT LEARNING OUTCOMES

- Identify the observable and measurable aspects of knowledge, skill and abilities a student will be able to apply as a result of completing the online lab learning process.

3 GENERATE CONCEPTS

- Design and refine the various ideas generated to align with the established learning outcomes.
- Ensure ADA guideline adherence.

4 DEVELOP, TEST AND ITERATIVELY REFINE STORYBOARDS

- Create an outline communicating a temporal sequence of actions involving a particular online lab course.

5 DEVELOP, TEST AND ITERATIVELY REFINE STUDENT ASSESSMENT TOOLS

- Identify appropriate assessment tools for formative and summative assessments to measure learning progress.

6 DEVELOP, TEST AND ITERATIVELY REFINE PROTOTYPES

- Develop online labs based on the process flow identified in the storyboard phase.
- Ensure required technologies and supporting software are made available for implementation of online labs.
- Provide list of finalized assessment tools.
- Test and iteratively refine the online lab prototypes.
- Uncover usability issues using heuristic evaluations and subjective assessment tools.

7 IMPLEMENT ONLINE LABS

- Make the online labs available to instructors and students.
- Perform additional testing if required.

8 EVALUATION AND MAINTENANCE OF ONLINE LABS

- Train instructors, monitor student progress and repeat the process to ensure the labs continue to meet student needs.
- Identify areas for continuous improvement.
- Collect and analyze long-term analytics to evaluate the success of the online lab platform and identify opportunities for future development.

Figure 3.2: A process for transitioning labs to online platforms

The example below illustrates the development process for an online lab course focusing on fluid lines and fittings as taught in aviation maintenance technician schools.

Identify Educational Objectives

According to the CTA of the AMTS faculties and aviation industry partners, this course enables learners to identify the common materials, applications, preparation, installation, and repair of rigid fluid lines used in an airplane's various pressurized fluid systems. This knowledge is necessary for the technician to properly inspect, maintain, and repair an airplane’s various fluid lines to ensure the reliable operation of the different fluid systems during flight. The stakeholders for this online course include instructors and students at AMTS and partners within the aviation industry. The potential hosting platforms for these online labs include both traditional and online academic settings. This online lab can also be a supplementary learning tool for on-the-job training sites in aviation maintenance.

Define Student Learning Outcomes

After completing this course, the learner will be able to:

- Identify the common materials, types, sizes, and construction categories used in manufacturing rigid fluid line assemblies. Discuss their characteristics, typical applications, and compatibility concerns with each material and construction type.
- Choose the appropriate rigid tube material type, size, and fittings as determined by product, pressure, vibration, heat, and risk of foreign object damage.
- Apply the correct repair method for leaky, faulty, or failed rigid tube fittings.

- Inspect fluid line assemblies and installation for signs of damage or failure and determine if a repair can be made or if the assembly will need to be replaced.
- Evaluate and identify the correct fabrication procedure for replacement rigid or tube assemblies, including selecting the correct bending procedures, tubing material selection, and fitting preparation.
- Identify correct installation of the rigid tube assemblies, including providing adequate support, clearance, slack, flex, and bends where appropriate and ensuring an absence of twists and excessive bends.

Generate Concepts

The literature review identified several strategies for conducting online labs, including video recordings, desktop simulations, live stream videos, and home labs. The research team and the AMT faculty then discussed and refined the concepts generated to ensure that the final learning outcomes align with the course goals and are accessible to all students.

Develop, test, and iteratively refine storyboards

Based on the strategies identified, a storyboard was created utilizing PowerPoint slides. This phase underwent multiple iterations based on the CTA and learning outcomes with feedback from the AMT professor and the research team members. Through this process, the research team created models of online labs delivered using video lectures, video demonstrations and desktop simulations.

Develop, test, and iteratively refine student assessment tools

A formative assessment tool was employed in this course to assess student learning progress. In consensus with the AMTS faculty, the research team designed the pre-and post-test questionnaires to ensure students' learning progress after completing the course.

Develop, test, and iteratively refine online lab prototypes

Based on the storyboard, the research team developed models for the video lectures, video demonstrations, and desktop simulations. Video lectures and video demonstrations were created using Camtasia and Murph.ai. The simulations were developed using Unity. The formative assessment was administered using the Qualtrics survey suite. These online lab prototypes and the formative assessment questionnaires were integrated into an online learning platform (EducateWorkforce). EducateWorkforce is a learning management system offering industry-tested course materials to prepare learners for technical careers. These online lab prototypes were iteratively refined based on the usability evaluations done using heuristic evaluations.

Implement online labs

The final online lab platform course consisted of video lectures, demonstrations, and desktop simulations. The online lab course was made available to the instructors and students through an online platform. Additional testing was done to ensure the online labs functioned as intended during the testing phase.

Evaluation and maintenance of online labs

A research study, as articulated in Chapter 4, was conducted to evaluate the effectiveness of utilizing this online lab course. The study aimed to identify the effectiveness of simulations in training aviation maintenance technicians. The experiment results provided insights for planning further improvements and enhancements for future course delivery.

CHAPTER FOUR

EFFICACY OF USING VIRTUAL REALITY SIMULATIONS IN TRAINING AVIATION MAINTENANCE TECHNICIANS IN PROCEDURAL TASKS

Introduction

A skilled team of aviation maintenance professionals is necessary for air travel safety. To train the next generation of aircraft maintenance technicians, AMTs traditionally relied on hands-on training (Shakour et al., 2021). However, students nationwide experienced program disruption due to the COVID-19 pandemic. Because lab courses demand substantial hands-on participation, which is challenging to provide in a virtual setting, IHEs had to develop new instructional strategies. Administrators and teachers at aviation maintenance technology programs faced the challenge of teaching students while maintaining accreditation standards (Shakour et al., 2021). The Federal Aviation Administration oversees these programs under Federal Aviation Regulation Part 147, which sets requirements for AMTs programs. The quick transition of labs to the online environment was a complex process, requiring careful planning, development, and coordination.

Computer-based training in the form of desktop VR simulations can be used for training the students, offering them a secure, risk-free, flexible, location- and time-independent teaching experience on the online platform (Abidi et al., 2019). Although early VR technologies faced challenges, the rapid advancement in computer processing power enabled the widespread adoption of desktop-based VR technology in K-12 and higher education (Merchant et al., 2014). These VR simulations give learners practical training in a virtual lab using computer-generated pictures and animations (Choi et al., 2015). The rapid increase in the use of desktop-based VR technology in education is based on the belief in its ability to enhance learners' cognitive skills (Merchant et al., 2014). Consequently, many educators have integrated various desktop-based virtual reality technologies into instruction.

Online labs can cater to individuals with diverse accessibility needs. These labs allowed the students to conduct online experiments multiple times at their convenience. Typically, converting lab courses to an online platform relied heavily on lecture slides and video recordings. These pre-recorded videos and lecture slides helped teach students about the operation of the instruments and observing the experiment; however, they needed more interactivity as students became passive observers unable to engage in hands-on activities. However, these VR simulations allow students to perform lab experiments using their computers or smartphones virtually, providing them with hands-on experience (Fox et al., 2020).

Previous studies have investigated the efficacy of online labs, comparing those that incorporated either video demonstrations or desktop simulations separately to traditional labs (Brinson, 2015; Lacey & Wall, 2021). The studies examined how effective online labs are in transferring content knowledge across the online platform. They also found that online labs enhanced students' learning and helped them understand the principles behind the experiments. These studies primarily focused on teaching concept knowledge rather than procedural skills. A research gap exists regarding whether there are differences in gaining procedural skills between training provided through desktop simulations and video demonstrations. To bridge this gap, this study aims to compare the effectiveness of using desktop VR simulations with video demonstrations in imparting procedural knowledge.

Research Questions

1. How do desktop VR simulations compare with video demonstrations to attain learning gains?
2. How does the students's task performance compare with desktop VR simulations and video demonstrations?
3. How do the perceived workload and usability compare with desktop VR simulations and video demonstrations?

Method

Study Sample

This study used purposive sampling to select participants from the College of Engineering, Computing, and Applied Sciences. An a priori power analysis was conducted using G*Power to determine the required sample size. A large effect size (Cohen's d = 0.8) was assumed, with a significance level of 0.05 and a desired power of 0.80. A total of 52 participants (26 each for both conditions), aged between 20 and 40 (M = 25.12, SD = 3.54), participated in the study. A large effect size was assumed because it implies practical significance across the conditions (Cohen, 1988). The demographic information of the participants is presented in Table 4.1.

Table 4.1: Demographic information of participants

	N	%
Age (*M* = 25.12, *SD* = 3.54)	52	
Gender		
Female	7	13.47
Male	45	86.53
Race		
African American	1	1.92
Asian	36	69.23
Caucasian/White	13	25
Hispanic/Latino	1	1.92
Prefer not to say	1	1.92
Level of education completed.		
4-year degree	35	67.35
Professional degree (MD, JD, MS, etc.)	8	15.35
Some college	9	17.3
How often do you use a computer?		
Daily	49	94.23
4-6 times a week	3	5.77
Have you ever played video games or computer games?		
Yes	50	96.15
No	2	3.85
Have you had any experience using virtual reality?		
Yes	35	67.3
No	17	32.7
Have you had any experience watching video demonstrations?		
Yes	48	92.31
No	4	7.69
Have you had any experience watching video lectures?		
Yes	52	100

Inclusion Criteria

The participants had to satisfy the following three conditions to participate in this research study: The inclusion criteria were also mentioned in the consent form to ensure their confirmation.

- At least 18 years of age
- Should have or be enrolled in a mechanical/automotive/aeronautical engineering degree
- Comfortable using computers
- Should not be color blind
- Should have 20/20 or corrected vision

Study Design

This study used a between-subjects design. The experimental setup required the participants to fabricate a rigid fluid line, as shown in Figure 4.1, in the controlled lab settings based on the assigned instruction method.

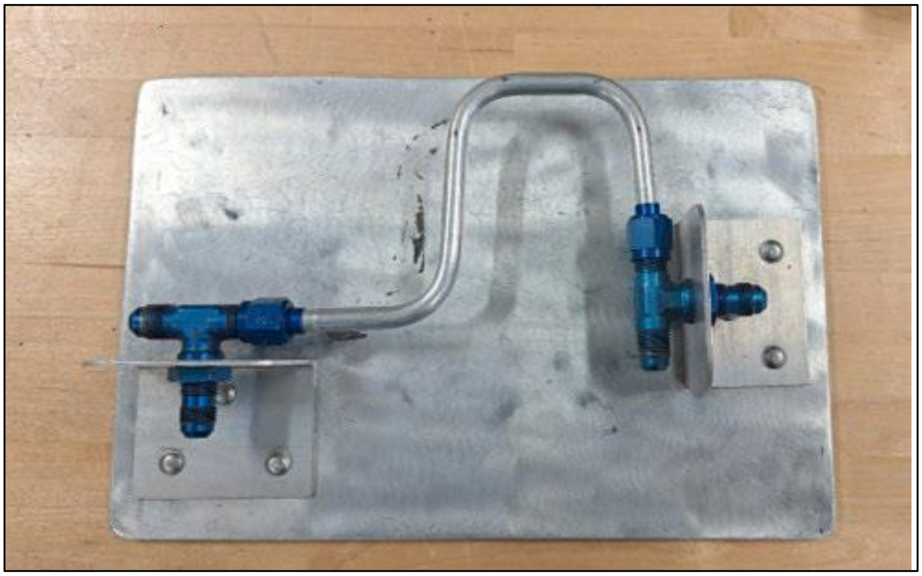
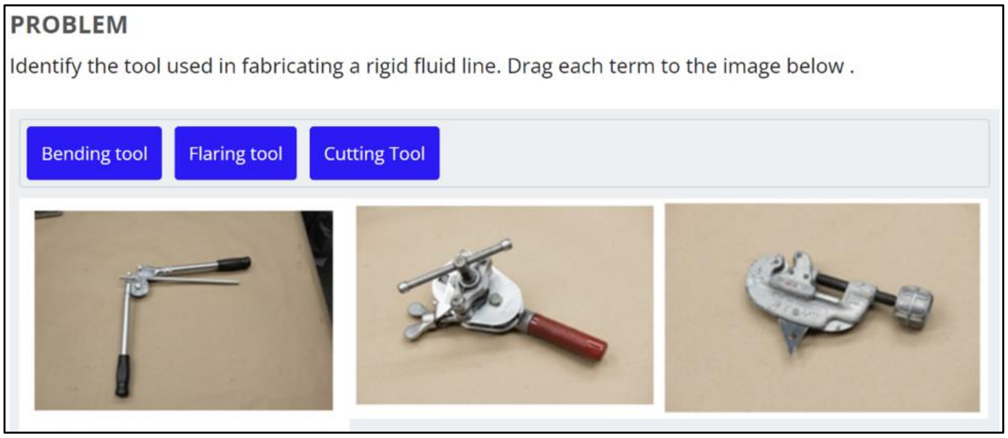


Figure 4.1: Fabricated rigid fluid line

The independent variable for this study was the medium of instruction with two different levels: a) *Video demonstration*: The participants viewed the video lecture followed by a video demonstration of the professor performing the task b) *Desktop VR simulation:* The participants viewed the video lecture followed by performing the task on a simulation platform. The two training modalities were integrated into the EducateWorkforce platform as two separate courses.

The video lecture was a 17-minute video recording of a lecture delivered by an aviation maintenance professor. It covered the basic theoretical concepts, provided an overview of the steps in fabricating the rigid fluid line, and highlighted a few critical points to be careful of while performing the task. The video lecture was common to both conditions.

The video demonstration was a 21-minute video of the aviation maintenance professor demonstrating the process of fabricating the rigid fluid line. The demonstration included a terminology phase, during which the professor showed each instrument and provided a brief explanation of its use. Explanations and the performance of various steps in the process followed this. The professor highlighted the critical points, emphasizing the implications of incorrectly following a particular step. The video demonstration was followed by a drag-and-drop activity, where the participants had to drag and drop the correct sequence of steps for each phase in the process. They had the option to perform the activity until they corrected all the steps in the sequence. The interface provided feedback if the participant placed the wrong option. The screenshot of the drag-and-drop activity is shown below in Figure 4.2.

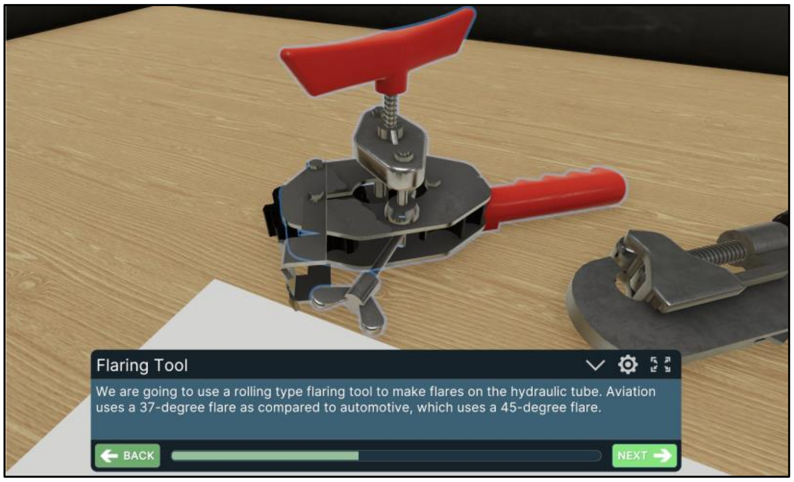


PROBLEM

Identify the tool used in fabricating a rigid fluid line. Drag each term to the image below .

Figure 4.2: Screenshot of the drag-and-drop activity

The simulation medium included three main phases: terminology, guided practice, and open exercise. In the terminology phase, the names of the instruments are included, along with a brief textual description of what each instrument is used for. In the guided practice, the instructions were provided as text at the bottom of the screen. Participants used their hands to interact with the virtual objects to complete each step, and the simulation highlighted the next button at the bottom of the screen, indicating to the user to proceed to the next step. In the open exercise, participants were not provided with step-by-step instructions; instead, they needed guidance to complete the process. Participants could click on the question mark icon on the simulation if they need to remember the next step. They received feedback if a step was incorrect, which made them aware of the error. The screenshots of the terminology phase, guided practice, and open exercise phase are shown below in Figure 4.3, Figure 4.4, and Figure 4.5.



Flaring Tool

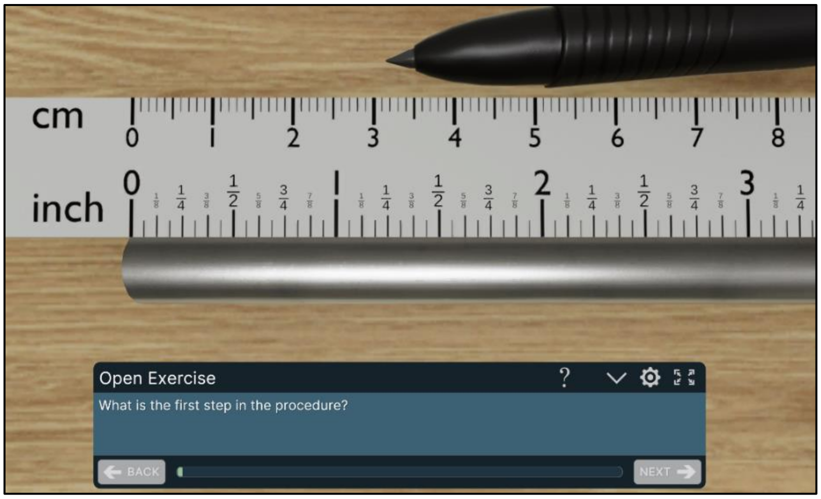
We are going to use a rolling type flaring tool to make flares on the hydraulic tube. Aviation uses a 37-degree flare as compared to automotive, which uses a 45-degree flare.

Figure 4.3: Screenshot of the terminology phase

Measuring

Let's make our first mark. Click the tube at 2 $^{5}/_{8}$" to make a small mark.

Figure 4.4: Screenshot of the guided practice phase



What is the first step in the procedure?

Figure 4.5: Screenshot of the open exercise phase

The dependent variables for this study were.

Learning gains: The knowledge gain was measured by comparing the pre-test and post-test results, each containing ten multiple-choice questions. The pre-test and post-test questionnaires are provided in Appendix C and D. Six questions were identical on the pre-test and post-test questionnaires. The remaining four questions were slightly modified between the pre-test and post-test. However, it was ensured that the question type and the construct they measured remained the same.

Performance: Performance was computed by identifying the time to complete the task and the number of errors made. Errors were classified based on the human performance framework, distinguishing between skill-, rule-, and knowledge-based performance (Rasmussen, 1983). Performance was also evaluated based on whether the participants successfully completed the task.

Workload: Perceived workload was measured using the NASA Task Load Index (TLX) survey (Hart & Staveland, 1988) consisting of numerical rating and pairwise comparison questions. NASA TLX survey is provided in Appendix E.

Usability: Perceived usability was measured using IBM CSUQ (Lewis, 1995) questionnaires. IBM CSUQ survey is provided in Appendix F.

Procedure

The participants were asked to sign the consent form and randomly assigned to one of the two instruction modes. This was followed by a demographic survey, which queried age, gender, and experience with desktop VR simulations and video demonstrations. The demographic survey is presented in Appendix B. The participants then completed the pre-test questionnaire. The participants then attended the training hosted on the EducateWorkforce platform per their assigned conditions. The participants then completed the post-test questionnaire, NASA-TLX, and IBM-CSUQ questionnaires. The demographic survey, pre-test and post-test questionnaire, NASA-TLX, and IBM-CSUQ surveys were administered using the Qualtrics survey suite. The participants then fabricated the rigid fluid line in the physical workplace. Their performance was video recorded to identify the number of errors made and the time to complete the task. The videos were then analyzed, coded, and summed up based on the SRK framework identified through the task analysis. The research team members individually coded the errors, and later, disagreements were discussed, and consensus was formed based on mutual consensus. Task analysis is presented in Appendix G. The unique errors identified as skill-, rule- and knowledge-based performance are presented in Table 4.2. While participants were informed that they could consult a paper manual if required for each step, they were instructed to refer only when necessary. The action of referring to the instruction manual was considered requesting help, so the researcher noted and counted how many times each participant referred to the manual. A semi-structured interview then followed the task performance. The semi-structured interview questions are presented in Appendix H. The semi-structured interviews were audio-recorded and transcribed using Otter.ai. The study procedure is shown in Figure 4.6.

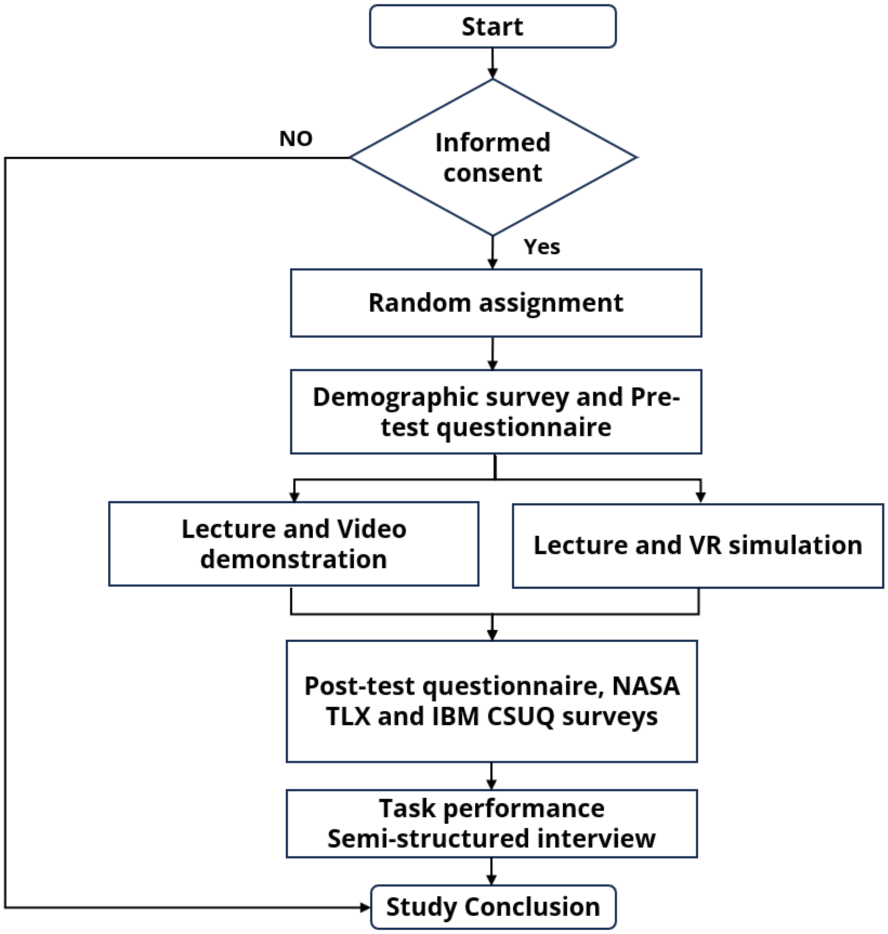


Figure 4.6: Flowchart of the study procedure

Table 4.2: SRK based errors

#	Types of errors
	Skill-based errors
1	Bend not on same plane
2	Inaccurate end B measurement
3	Inaccurate square cut
4	Inaccurate bending
5	Inaccurate cut and flare
6	Flaring inaccurate
	Rule-based errors
1	Missed to mark arrows for bending
2	Missed deburring and sanding
3	Improper use of cutting tool
4	Missed to match tube template
5	Improper use of flaring tool
6	Improper cutting of end B
7	Improper use of bending tool
8	Improper measurement marking
9	Incorrect order of deburring and sanding
10	Incorrect sequence of operation
11	Missed to insert fitting nut on tube
12	Missed to insert sleeve on tube
13	Missed to fix tube end A on jig to cut end B
14	Improper marking and cut of end B
15	Improper orientation of the sleeve
	Knowledge-based errors
1	Bend in the wrong direction

Skill-based errors are specific errors made by participants due to their lack of skill in performing a particular task. For example, participants may know they need to cut, but they need to learn to make it a neat, square cut.

Participants make rule-based errors when they miss a step in the procedure, perform a step in the wrong sequence, or improperly use a tool. For example, participants perform deburring and sanding before bending instead of performing it after bending as required.

Knowledge-based errors are specific errors made by participants due to their lack of knowledge. For example, participants might know they need to bend in a particular direction, but they need to be made aware of which direction it should be.

Data Analysis

Statistical analysis was conducted using IBM SPSS statistics version 29.0. To test for significant differences in learning gains and time taken to complete the task, a between-subjects independent sample t-test with α=.05 was conducted. A Custom negative binomial regression was performed to analyze the errors made by the participants across both conditions. Custom negative binomial regression is an option in SPSS to get a closer estimate of the amount of over or under-dispersion. A Custom negative binomial regression was conducted to identify the number of times participants asked for help and the training condition. A nonparametric Mann-Whitney U test was used to determine significant differences across conditions for perceived workload and perceived usability of the system. Mann-Whitney U tests are conducted when the t-test assumptions are not met. Using Winsteps software, the Rasch model was utilized to determine the Rasch Learning Gains (RLG). The Rasch model is a probabilistic model that explains item responses as an interaction between a person's ability and the difficulty of the item (Benjamin D. Wright & Stone, 1979). The Rasch analysis determines the reliability of the pre-test and post-test items and participant reliability. To use the Rasch model to show changes in measures over time, the data needs to be restructured by stacking the data (B. D. Wright, 2003). Stacking involves appending the person measures for the post-questionnaire onto the pre-test measures, doubling the number of persons measured. The interview data was transcribed using Otter.ai to generate themes and identify associated barriers. Analysis conducted for each dependent variable is shown in Table 4.3.

Table 4.3: Analysis methods

Dependent variable	Analysis methods
Learning gains	
Rasch learning gains between the conditions	Independent sample t-test
Learning gains within the condition	Paired-sample t-test
Performance	
Number of errors made	Custom Negative Binomial regression
Time taken to complete the task	Independent sample t-test
Perceived workload of the system	Mann-Whitney U test
Perceived usability of the system	Mann-Whitney U test

Results

Learning gains across the conditions

The reliability of the pre-and post-test items and participant reliability were calculated using the Rasch analysis. The test items were found to have a reliability rating of 0.80 with a separation of 2.01, indicating that the survey was designed to have approximately two difficulty levels. The participant reliability was found to be low, with a reliability of 0.51 and a separation of 1.03, indicating that our participant pool consisted of participants with just one ability level. The pre-and post-test scores were later stacked to calculate the pre-and post-test student ability scores, representing student ability scores by θ. RLG was calculated using the equation: RLG = $\theta post\text{-}score - \theta pre\text{-}score$. An independent-sample t-test was conducted on RLG to determine whether the two training conditions had statistically significant differences in learning gains. Learning gain scores for each level of training were normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.05$). There was homogeneity of variances, as assessed by Levene's test for equality of variances ($p = 0.60$). However, there was no statistical significance in final scores across the training conditions, simulation ($M = 2.56$, $SD = 2.12$), and video ($M = 2.20$, $SD = 1.98$). Learning gains were also calculated by considering only four questions, which were different across pre-and post-test questionnaires. Learning gain scores for each level of training were normally distributed as assessed by the Normal Q-Q plot. There was homogeneity of variances, as assessed by Levene's test for equality of variances ($p = 0.57$). However, there was no statistical significance in final scores across the training conditions, simulation ($M = 0.68$, $SD = 1.31$), and video ($M = 0.80$, $SD = 1.22$).

A paired-sample t-test was used to determine whether there was a statistically significant mean difference between the pre and post-test scores of the participants attending training through the video condition. The assumption of normality was not violated, as assessed by Shapiro-Wilk's test ($p = 0.45$). Post-test scores were high ($M = 7.16$, $SD = 1.51$) as opposed to the pre-test scores ($M = 4.96$, $SD = 1.57$), a statistically significant mean increase of 2.2, 95% CI [1.38, 3.02], $t(24) = 5.56$, $p < 0.001$, $d = 1.11$.

A paired-sample t-test was used to determine whether there was a statistically significant mean difference between the pre and post-test scores of the participants attending training through the simulation condition. The assumption of normality was not violated, as assessed by Shapiro-Wilk's test ($p = 0.16$). Post-test scores were high ($M = 7.04$, $SD = 1.37$) as opposed to the pre-test scores ($M = 4.56$, $SD = 1.53$), a statistically significant mean increase of 2.48, 95% CI [1.50, 3.46], $t(24) = 5.24$, $p < 0.001$, $d = 1.05$.

The results suggested that participants performed equally well in both training conditions. The participants scored better on the post-test scores across both conditions, indicating they understood the concepts better after the training intervention.

Time taken to complete the task

The raw task times were converted using a log transformation, the mean of the transformed values was found, and then the conversion back to the original scale was done by exponentiating. An independent sample t-test was run to determine whether there were statistically significant differences in the time taken to complete the task between the two training modalities. Duration for each level of training was normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.05$), and there was homogeneity of variances, as assessed by Levene's test for equality of variances ($p = 0.47$). The time taken was more in the video condition ($M = 3.43$, $SD = 0.29$) than in the simulation condition ($M = 3.21$, $SD = 0.32$), with a statistically significant difference, ($M = 0.22$, 95% CI [0.04, 0.40], $t(49) = 2.39$, $p = 0.01$, $d = 0.68$.

Participants had to perform the procedural task after completing the training in both the video demonstration and simulation conditions. The results indicated that participants in the video condition took more time to complete the task. This suggests that participants in the simulation condition had a clearer understanding of the task procedures and steps, making them more efficient in completing the task in less time.

Number of errors made

A Poisson regression was performed to ascertain the errors between the training conditions. The Pearson chi-square value/df = 24.40 showed overdispersion. Then, a Negative binomial regression was done, and the Pearson Chi-Square value/df = 0.68 showed under-dispersion. Custom negative binomial regression indicated the Pearson Chi-Square value/df = 1.32. For every one error in the simulation condition, 2.95 (95% CI, 1.19 to 4.54) times more errors were made in the video condition, a statistically significant result, $p = 0.001$.

A Poisson regression was performed to ascertain the relationship between the number of skill-based errors and the training condition. The Pearson Chi-Square value/df = 2.49 showed overdispersion. Then, a Negative binomial regression was done, and the Pearson Chi-Square value/df = 1.33. For every one error in the simulation condition, 4.71 (95% CI, 1.45 to 15.30) times more skill-based errors were made in the video condition, a statistically significant result, $p = 0.010$.

A Poisson regression was performed to establish the relationship between the number of rule-based errors and the training condition. The Pearson Chi-Square value/df = 18.51 showed overdispersion. Then, a Negative binomial regression was done, and the Pearson Chi-Square value/df = 0.68. Further performed Custom negative binomial regression and showed Pearson Chi-Square value/df = 1.34. For every one error in the simulation condition, 2.89 (95% CI, 1.88 to 4.47) times more rule-based errors were made in the video condition, a statistically significant result, $p = 0.001$.

A Poisson regression was performed to ascertain the relationship between the number of knowledge-based errors and the training condition. The result suggested that in the test of model effects p = 0.68, the condition is not statistically significant for the total number of knowledge-based errors made.

The results suggested that when participants' performance was analyzed based on skill-based and rule-based errors, those in the simulation condition showed better skill and rule-based learning, resulting in fewer errors. Knowledge-based learning remained equally effective in both conditions, consistent with earlier finding of no significant difference in knowledge-based learning gains between the two conditions.

Number of times help was requested.

A Poisson regression was performed to ascertain the dependence on training conditions and the number of help requests by the participant in completing the task. The Pearson Chi-Square value/df = 4.20 showed overdispersion. Then, a Negative binomial regression was done, and the Pearson Chi-Square value/df = 2.34 showed overdispersion. Further, we performed Custom negative binomial regression and showed the Pearson Chi-Square value/df = 0.92. However, there was no statistical difference (p = 0.34) across training conditions and in the number of help requests by the participants.

Perceived workload of the system

A Mann-Whitney U test was performed to determine if there were differences in mental demand, physical demand, temporal demand, performance, effort, and frustration score between the two training conditions. Distributions of all scores for video and simulation conditions were not statistically different. Distribution scores are shown in Table 4.4.

Table 4.4: Mann-Whitney test results

Dependent Variable	Mean Score		Mann-Whitney U	Standardized Test Statistic	p-value
	Video	Simulation			
Mental demand	25.9	27.1	353.5	0.28	0.77
Physical demand	22.69	30.31	437	1.87	0.06
Temporal demand	28.94	24.06	274.5	-1.16	0.25
Performance	28.62	24.38	283	-1.01	0.31
Effort	26.65	26.35	334	-0.07	0.94
Frustration	27.62	25.38	309	-0.54	0.59

An independent-sample t-test was run to determine if there were differences in the total workload of the system between the two training conditions. Total workload scores for each level of training modality were normally distributed, as assessed by Shapiro-Wilk's test (p >0 .05), and there was homogeneity of variances, as assessed by Levene's test for equality of variances ($p = 0.25$). However, there were no statistically significant differences between the total workload for the two conditions, simulation ($M = 40.36$, $SD = 15.81$) and video ($M = 42.87$, $SD = 18.73$).

The results suggested that irrespective of the training condition, the participants felt the workload associated with the system with respect to the mental demand, physical demand, temporal demand, performance, effort, and frustration to be equally effective.

Perceived usability of the system

A Mann- Whitney U test was performed to determine whether the two training conditions differed in perceived overall usability, system usability, information quality, and interface quality scores. Distributions of the scores for video and simulation conditions were not similar, and only perceived usability, system usability, and information quality were found to be statistically significant across the groups. Lower mean scores in the simulation condition are considered better, as the Likert scale was designed with lower values indicating better scores. This suggests that perceived usability, system usability, and information quality were found to be better in the simulation condition. Distribution scores are shown in Table 4.5.

Table 4.5: Mann-Whitney test results

Dependent Variable	Mean Score		Mann-Whitney U	Standardized Test Statistic	p-value
	Video	Simulation			
Overall usability	31.23	21.77	215	-2.25	0.024
System usability	31.15	21.85	217	-2.23	0.026
Information quality	32.83	20.17	173.5	-3.01	0.003
Interface quality	30.33	22.67	238.5	-1.85	0.064

The interview responses were coded line by line to identify themes. Primary themes focused on two main areas: barriers and facilitators in learning through the assigned condition. The participant quotes are referred to as V for the video demonstration condition and S for the simulation condition. The numerical following is the participant number.

Lecture and Video demonstration

The participants reported three facilitators and five barriers using the video demonstration. Eighteen of the 26 participants valued the video demonstrations, with participants finding them clear and enjoyable.

> *Participant quote:* "*So why this must be done, and what is the result of doing this? So even for novices and experienced learners, whomever we still learn will get a clear idea of what's happening*". *– V1*

The visual aspect of seeing tasks performed aided in a better understanding of the process and tool usage. Although some considered the drag-and-drop activity tedious, 11 participants found it beneficial in reinforcing the steps. This activity allowed them to test their understanding and learn from their mistakes.

> *Participant quote: "For me, I personally did one thing wrong, and it told me that this answer is incorrect. So I could test which sequence is correct. It was helpful, and I would say I would say that it helped me through the process".- V5*

The major barrier across the lecture and video condition was that 15 participants expressed difficulties with the visual aids and clarity of instruction in the videos. They noted a need for pointers at the start of the video lecture, making it unclear where the professor was referring to specifically. For instance, there were multiple arrows on the same slide, but it needed to be clarified which particular arrow the professor referred to.

> *Participant quote: "At the start, you're confused. I'm like, he's pointing it somewhere. I don't see where exactly it is pointing because there's no pointer". V20*

Improvements to the video demonstration's graphics, diagrams, and camera angles were suggested for better understanding. Nine Participants expressed a preference for in-person instruction, citing benefits such as immediate clarification of questions and a better understanding of the task.

> *Participant quote: "If we have, like, many doubts, it's better if it's cleared on the spot. So, I don't think that through these videos and lectures, it can be possible. So, this can be possible in-person where the lecture is there and when he explains and clears all the doubts."- V8*

One participant expressed concern that online learning might be less beneficial for newcomers without prior experience. Seven participants found certain aspects of the drag-and-drop activity, such as small window size, scrolling issues, and text readability, difficult. They perceived the drag-and-drop activity as tedious and not very helpful. The participants might have found it tedious due to the time they spent on the training to finish the lecture and video demonstration. They might need more patience and focus when they reach the drag-and-drop activity, making it tedious. Two participants noted that some tools, primarily flaring, were initially complex and challenging.

> *Participant quote:* "*But in the drag and drop, I mean, I don't think I necessarily got anything out of it."- V15*

Lecture and Desktop simulation

The participants reported four facilitators and two barriers using the simulation. 19 of the 26 participants found that the simulation provided a clear understanding of the tasks.

They also appreciated the combination of lecture videos and simulations, finding it advantageous for learning.

Participant quote: "I think this is pretty good and clear because at least I have like both visual and step-by-step procedure." – S6

The guided practice in the simulation was enjoyable and effective, providing a virtual hands-on experience that helped with memorization. Participants also found the interactive walkthrough on the screen helpful and described the simulation experience as exciting. Eight Participants appreciated hands-on experience with physical tasks, finding it the most interesting part of learning. They also valued the opportunity to apply what they learned to reinforce learning immediately.

Participant quote: "This type is very advantageous. I watched it once, and then I did it practically."- S14

Three participants appreciated the time-saving aspect of the online medium, seeing it as beneficial for both teaching and learning communities. They found the medium of instruction efficient in terms of time spent explaining and performing virtual tasks, which they believed helped save time on actual task performance.

Participant quote: "It is time-saving for both the employer and the employee."*- S9*

Nine participants found that some aspects of the simulation could have been more intuitive, particularly when clicking in specific spots for certain actions. They also mentioned that the simulation made tasks seem more accessible than they might be, as it doesn't replicate the physical pressure and ergonomics involved in using tools.

Participant quote: "It was easier on the simulation ergonomically it should be shown." – S1

Six participants felt the process was lengthy and time-consuming, especially for precision tasks.

Participant quote: "I think it took me like an hour to finish all the instructional stuff."- S8

Discussion

The first research question explored which instruction medium leads to more significant learning gains among learners fabricating a rigid fluid line process. Results indicate no significant differences in Rasch learning gains across the two conditions. Despite no significant differences, the post-test scores for each condition were significantly higher than the pre-test scores, indicating that both conditions contributed to an increase in learner's knowledge, which is consistent with the findings of the previous studies (Bertrand et al., 2017, 2015; Bhargava et al., 2018; Madathil et al., 2017; Upadhyay et al., 2023). The lack of significant difference in learning gains between the two conditions may be due to common video lectures. These lectures explained theoretical knowledge, which remained consistent across both groups. In contrast, the video demonstration and simulation focused more on practical task performance. Participants' familiarity with the pre-test questionnaire may have led them to search for answers to those specific questions while attending the training. Combining lectures with simulations and lectures with demonstrations was perceived as advantageous for learning, as indicated by the qualitative interview results and findings consistent with the previous study (Upadhyay et al., 2023). Participants mentioned that the lecture enhanced their theoretical knowledge. They also had the chance to reinforce this knowledge further by performing tasks virtually through guided and open exercises during the simulation. In the video demonstration condition, participants mentioned that they gained theoretical knowledge through the lectures and developed a better understanding by watching the video demonstrations and performing the drag-and-drop activity. Overall, the findings suggest that both training conditions helped the participants gain theoretical knowledge.

The second research question investigated which instructional medium yields better task performance for a procedural task such as fabricating a rigid fluid line. Task performance was assessed through the total errors and time taken to complete the tasks. Participants' total errors were analyzed and categorized into skill-, rule-, and knowledge-errors. The results showed that more skill-based and rule-based errors occurred in the video condition compared to the simulation condition. There was no statistical significance in the number of knowledge-based errors. The experiential learning theory can provide a potential explanation of the number of skill, rule, and knowledge-based errors. The theory emphasizes the importance of learning through experience, reflection, conceptualization, and experimentation (Kolb & Kolb, 2009). Participants in the simulation condition might have had a more comprehensive experiential learning cycle, allowing them to experience the task, reflect on their actions, understand the underlying concepts, and apply their knowledge effectively. This could have led to fewer skill-based and rule-based errors compared to the video condition, where the lack of hands-on experience and immediate feedback might have hindered the development of practical skills. The lack of statistical significance in knowledge-based errors between the two conditions suggests that both instructional mediums effectively convey theoretical knowledge. Based on the skill and rule-based errors, the total errors were fewer in the simulation condition, findings consistent with previous study (Ahlberg et al., 2007). Participants had the opportunity for virtual practice through guided and open exercises on the simulation, which helped them remember the tasks and prevented them from repeating errors while performing the task. Interviews revealed that guided simulation practice was enjoyable and effective, providing a virtual hands-on experience. The open exercises in the simulations reinforced task repetition, aiding memorization. This led to fewer skill-based and rule-based errors, as participants gained virtual hands-on practice and became well-versed in the process and specific skills required, such as making proper square cuts and measuring and cutting tubes accurately. The overall findings suggest that students in the simulation-based training made fewer errors while performing the actual task. Therefore, simulation-based training might be more effective for teaching procedural tasks online.

The time taken to complete the tasks was significantly less in the simulation than in the video condition. This finding differs from previous study that explored the time taken to complete the task in video-, VR-, and AR-based conditions (Daling et al., 2023). In this study, participants had the opportunity to perform the task two times during the training phase, which helped them become familiar with the process in all training conditions. This familiarity might be the reason for the lack of significant differences in task completion times across the conditions. (Daling et al., 2023) . The significance of the time taken to complete the task in this study may arise from adding video lectures to the simulation condition, which provided additional knowledge and highlighted critical points. The video lecture's brief introduction to the procedures provided a basic understanding of the process, followed by virtual hands-on practice through simulations. This approach allowed participants to engage with the material through lectures, guided practice, and open exercises, offering multiple learning modalities. Consequently, participants were better able to remember the process due to the varied and comprehensive nature of the learning experience, which made them do the task much quicker. On the other hand, in the video demonstration condition, participants had similar engagement through lectures but could not virtually perform the task as in guided simulations. Regarding the drag-and-drop activity, compared to the open exercise on simulation, it only allowed the interaction of dragging and dropping the item, which was less involved in each step than with the open exercise. Further interview results also suggested that the user interface on the drag and drop could have been better, as it felt tedious instead of reinforcing the learning experience. The study findings conclude that students in the simulation-based training took less time to complete the actual task, indicating that procedural tasks can be effectively taught using simulation rather than passive video demonstrations.

The third research question explored the perceived workload and usability compared between desktop simulations and video demonstrations. The absence of significant differences in the perceived workload emphasizes that the workload during online learning is not influenced by the technology used. Despite participants appreciating the medium of instruction for its clear explanation of concepts, stepwise procedures, and consequences of flaws, the difficulty of the course content itself may contribute to the workload. The significant difference in overall usability, system usability, and information quality observed in the simulation condition may be attributed to the interactive nature of the experience, allowing participants to work virtually on the task and giving them a sense of performing it. The finding aligns with another study that observed higher levels of engagement, usability and satisfaction among students using VR and traditional training methods compared to those using photo-based training (Madathil et al., 2017). In contrast, participants in the video condition may feel less engaged with the system as they are passive observers. The overall findings suggest that simulation-based training provides an opportunity for an interactive experience, giving students a sense of performing the task and making them feel more engaged.

In conclusion, the study suggests that instructors might adopt desktop-based VR simulations to teach students procedural tasks rather than relying on video demonstrations. In fields within the STEMM domain that involve laboratory practicals, teaching these lab practicals online is feasible by providing virtual hands-on practice through simulations. Students can benefit from this approach by practicing as many times as needed on these simulations, leading to fewer errors and a better understanding of the task procedures before performing the task in the physical lab. Additionally, as students who completed the simulation-based training required less time to perform the actual task, this extra time can be utilized for additional reading and collaborative activities, enhancing the overall learning experience for students. A further recommendation is to increase the availability of simulation-based training to engage students better on the online platform, leveraging the specific interactive nature of simulations. However, unlike desktop-based VR simulations, a study also suggests that immersive VR provides a more effective environment for higher-level cognitive tasks, potentially leading to better skill transfer in real-world tasks (Parmar et al., 2016).

Future work

Although this study yields significant implications for establishing a connection between the type of instruction medium and performance achieved in the procedural task, it also has a few limitations. The study did not consider how individual differences in student learning, their attitudes, and personal learning goals might influence learning performance. Participants' familiarity with the pre-test questionnaire may affect their post-test scores. This is because participants tend to focus more on the pre-test questions during the training session, potentially impacting their performance on the post-test. Additionally, while the questions used to assess learning gains focused on theoretical knowledge acquisition, future work can investigate the analytical and inquiry skills gained by the participants. These skills can be measured using assessment methods such as formal lab reports, open-ended quiz questions on data interpretation, original data analysis to answer a research question, and oral interviews with learners regarding data interpretation. Future studies could explore the effectiveness of training when combining video demonstration and simulation in online settings, comparing it to the efficacy of using only video demonstrations or simulations.

Conclusion

The COVID-19 pandemic has necessitated the increased use of video and simulation labs for online STEMM lab instruction. While previous studies have mainly focused on attaining learning gains, especially concerning knowledge and understanding, the transfer of learning gains associated with procedural skills has been minimally studied. Furthermore, any differences in training conditions associated with attaining greater procedural skills have yet to be thoroughly explored. The findings highlight the effectiveness of well-defined simulations in enhancing student learning and preparing them for task performance with reduced errors in real-world settings. The study's approach, which included video lectures, guided and open exercises for virtual practice, and hands-on task performance, was well-received. This comprehensive approach enriched the learning experience by allowing students to apply their knowledge immediately.

CHAPTER FIVE

CONCLUSION

The thesis explores the effectiveness of VR simulations in training aviation maintenance technicians on procedural tasks. To begin with, we conducted a literature review to examine challenges faced by the IHEs in transitioning the STEMM labs to the online platform during the pandemic, strategies employed for online labs, and their effectiveness, focusing on learning outcomes and student and instructor perceptions. The review highlighted video demonstrations and desktop simulations as feasible strategies for online labs. Based on the identified challenges, we also proposed a few guidelines IHEs can implement to maintain academic continuity. We further proposed a human-centered design framework that may enhance the development of online labs for effective learning experiences on the online platform.

Secondly, to address gaps in the literature regarding online procedural skill transfer, we conducted a study comparing VR simulations with video recordings in training participants on a procedural task. While past studies mainly focused on content knowledge, this study aims to assess procedural skill transfer online to determine the most effective method. By bridging this gap, the thesis aims to contribute to the advancement of online STEM education, providing insights into effective online lab strategies and enhancing procedural skill transfer in virtual environments.

This thesis provides a comprehensive exploration of implementing various strategies for conducting online labs, including using video recordings, simulations, home lab kits, or immersive VR, individually or in combination, to enhance student learning effectively. The review suggests potential ways by which instructors may enhance student interaction. The review indicated that instructors found practicality in using technology tools synchronously or asynchronously or integrating them most effectively, with findings aligning with the previous study (García-Morales et al., 2021). The review also suggests using online team collaboration spaces, collaborative activities, and group discussions to enhance students' interaction, findings aligning with previous studies (Carolan et al., 2020; Müller & Ferreira, 2005). Providing technology and software training to instructors and students and measures to maintain academic integrity were also significant in the literature review; this finding aligns with previous studies (García-Morales et al., 2021). The human-centered design framework used in the thesis to develop online labs may enhance the effective transition of STEMM labs to online platforms, enabling the IHEs to increase the likelihood of a smooth and successful transition.

The study contributed to the effectiveness of using simulations in transferring procedural skills through online training. It was found that participants made fewer errors in the simulation condition compared to the video, highlighting the benefits of using VR simulations in educational settings to improve procedural skills. This finding is consistent with another study that highlighted fewer errors in the VR condition on the participant's first ten laparoscopic cholecystectomies (Ahlberg et al., 2007). Our analysis suggests that institutions may increase the use of simulations in teaching lab courses.

The study aimed to explore whether the condition would affect the probability of participants completing the task, expecting a good fit for this hypothesis. However, no significant interaction effect was found between the times participants asked for help and completed the task based on the conditions.

The guidelines and the framework developed in the literature review sections provide measures for the administrators and instructors to maintain academic continuity during disruptions. Instructors and administrators may focus on creating engaging online resources, including video recordings, desktop simulations, and home labs, to ensure that students can continue to engage in meaningful laboratory experiences remotely. Instructors may use VR simulations to teach procedural tasks and video recordings to transfer content knowledge. Both instructors and administrators may prioritize training in digital tools and platforms to facilitate effective online instruction and ensure that instructors are equipped to deliver engaging and interactive online lab courses. Both instructors and administrators should engage in ongoing evaluation and refinement of online lab courses, incorporating feedback from students and faculty to enhance the effectiveness and accessibility of remote lab instruction. Administrators may work with instructors to develop appropriate assessment strategies for online labs, ensuring they effectively measure student learning outcomes while maintaining academic integrity. Administrators may ensure that all students have access to the necessary technology and resources to participate in online labs and support students who may face challenges in remote learning. Instructors may explore innovative strategies to maintain student engagement online, such as incorporating synchronous discussions, interactive simulations, and collaborative projects.

The research mainly concentrated on qualitative data regarding strategies for online labs, with minimal emphasis on quantitative data measuring learning outcomes.

Additionally, the studies primarily focused on learning outcomes related to concept knowledge transfer and did not extensively explore measuring students' performance skills in lab experiments. This study's limitations include not considering individual differences in student learning and attitudes and not assessing analytical and inquiry skills gained. Participants' familiarity with the pre-test questionnaire may affect their post-test scores. This is because participants tend to focus more on the pre-test questions during the training session, potentially impacting their performance on the post-test.

Further controlled experimental studies are needed to assess the effectiveness of online labs more comprehensively in transferring practical skills on the online platform. Future studies could explore the effectiveness of training when combining video demonstration and simulation in online settings, comparing it to the efficacy of using only video demonstrations or simulations. Future work can investigate the analytical and inquiry skills gained by the participants. These skills can be measured using assessment methods such as formal lab reports, open-ended quiz questions on data interpretation, original data analysis to answer a research question, and oral interviews with learners regarding data interpretation.

APPENDICES

Appendix A

Study Design and Measures

Author and Journal	Place and Domain	Study Design	Measures
R. Gao et al., 2020, Journal of Chemical Education	United States, Chemistry	Experimental: Students participated in lab work. They also had to take the lab exams.	Students' post-laboratory questionnaires, instructors' observations, and the grading of laboratory reports served as the means of completing the course evaluations.
Tran et al., 2020, Journal of Chemical Education	United States, Chemistry	Experimental: Students participated in lab work. They also had to take the lab exams.	A Venn graphic compared the common difficulties that analytical and organic chemistry lab courses encountered when they switched to distance learning. Post-lab tests were used to gauge how well students adapted to the laboratories.
Garcia et al., 2021, IEEE Transactions on Learning Technologies	Spain, Software Engineering	Experimental: where the students work in programming labs. They also had to take the lab exams.	A survey was conducted to separate analyses, which were also performed for students taking lab tests during the previous nine years, including pass and

			fail rates. A different analysis and graph were put together to analyze the network and internet availability produced by the Veyon master.
Buchberger et al., 2020, Journal of chemistry education	United States, Analytical Chemistry	Observational: where students participated in the project labs.	A post-project feedback form was used to gather student feedback, and teachers were polled to get their impressions.
Woelk & Whitefield, 2020, Journal of Chemistry Education	United States, Chemistry	Experimental: The lab experiments were live-streamed by the teaching staff. Students record the observations and data.	The effectiveness of the live-streamed lab activities was identified by instructor reflection and student comments.
Davy & Quane, 2021, Journal of Chemistry Education	Canada, Chemistry	Experimental: Students participated in lab work.	1) A survey compared student satisfaction with varied audio, video, and overall quality. 2) Evaluate the effectiveness of various remote delivery options (narrative laboratories, third-party recordings, and real-time delivery).

Dietrich et al., 2020, Journal of Chemistry Education	France, Chemistry	Observational: This study is based on an inventory of the various strategies educators devised, implemented, and used throughout the semester.	1) After the semester, a 16-question online survey in French was administered to students, who were asked to grade each method using a Likert 5 scale. 2)A 10-question online poll was used to consult teachers as well.
Kolack et al., 2020, Journal of Chemistry Education	United States, Chemistry	Experimental: Students participated in lab work. Students' grades are compared face-to-face and online.	1) Student evaluations were compared based on lab exam results from the spring and fall of 2019 and discovered mixed performance. 2) Scores from the three courses' lecture exams from the spring 2020 and fall of 2019 were also compared as a percentage. 3) Comparisons of lecture withdrawal rates for Fall 2019 and Spring 2020 were also tallied.
Wasmer 2021, Journal of Teaching and Learning with Technology	United States, Aviation maintenance technology	Observational study	Experiences and observations of the author.

Almetwazi et al., 2020, Saudi Pharmaceutical Journal	Saudi Arabia, Pharmaceutical Sciences	Observational study	Feedback was collected from students regarding what they had learned, liked, disliked, and how to apply what was learned in practice.
Anstey et al., 2020, Journal of Chemical Education	United States, Chemistry	Observations: Various instructors used observation to identify the most effective teaching techniques.	Feedback from students.
George, 2020, Journal of Educational Technology	West Indies, Engineering	Experimental: Students attended an introductory digital electronics course. Students' performance in the course is compared in the past five years, from 2015 to 2020.	The data is collected for Quiz 1 (Combinational Logic Circuits), Quiz 2 (Intro to VHDL), and the Final exam over five years. This data is then compared and analyzed to assess student performance.
Chierichetti & Backer, 2021, Education Sciences	United States, Engineering	Observation: Faculty members were asked to complete a survey on two primary topics: their personal experiences and psychological health in the spring of 2020 and the pedagogies and resources they used to switch to emergency online instruction. How did you do in your classes in the spring of 2020? And How did SJSU as a whole do during this changeover were the two main topics of the interview.	Survey data were analyzed, combined, and represented in graphs with characteristics like "moving to 100%online," "felt you were rushing, felt you were under deadline pressure, and so on. Testing and assessment, experience, teaching methodology, and

			hands-on laboratories were all examined in the interview results.
Franklin et al., 2021, Life	United States, Medical Education	Experimental: Students participated in an experimental setting, receiving primary patient care via telemedicine and Aquifer Simulations.	Data were collected through a cross-sectional, multi-method survey. The data was analyzed and assembled into graphs.
Chang et al., 2021, Journal of Dental Sciences	Dental educators from around the globe, Medical Education	Observation: Through an online symposium, dental educators discussed how they had to adjust to the pandemic's innovations.	Dentistry educators from many nations were invited to present and converse about knowledge and experience about the innovation of dental education during the pandemic through three online symposiums.
Anzovino et al., 2020, Journal of Chemical Education	United States, Chemistry	Experimental: Students participated in online labs employing simulations and YouTube videos.	Rates of dropouts for two courses, when delivered in person and remotely, organic chemistry one and two, were compared.
Choate et al., 2021, Advances in Physiology Education	An international group of 10 physiology educators, Biology-Physiology	Observation: Narratives in writing.	The written narratives examined the educators' transitions to online platforms, pre-covid attitudes, and experiences with virtual laboratories.

			Teachers were also questioned for their thoughts on how well their students engaged in online learning. There was no student evaluation of the instruction.
Zhou, 2020, Biochemistry and Molecular Biology Education	United States, Biology-Genetic course	Experimental: Students participated in online labs with educational videos and simulation exercises.	The information was gathered based on the author's observation.
J. Gao et al., 2021, Chemical Engineering Education	United States, Chemical Engineering	Experimental: where students were divided into two teams (tutorial and learning teams) and assigned tasks accordingly.	By gathering feedback from instructors and students, it was possible to evaluate how well the shift from in-person to virtual instruction worked. 1) Information about the instructor's viewpoint was gathered from the course grades and their own experiences and comparisons to previous semesters. 2) A survey was used to assess student perspectives (on a scale of 1 to 5, with 1 being "Strongly Disagree" and 5 being "Strongly Agree"), and the results were

			compiled into graphs.
Leung et al., 2020, Advances in Engineering Education	United States, Mechanical Engineering	Experimental: A week-long senior-level Dynamics System Laboratory course was taught online and included two options.	An anonymous survey then determined the students' preference for the two techniques. Six out of seven students (with a voluntary response rate of 17%) prefer the machine learning module to the video-recorded labs.
Ediger & Rockwell, 2020, Journal of the Human Anatomy and Physiology Society	United States, Biology-Anatomy and Physiology	Experimental: Students used home lab kits to engage in virtual laboratories.	Observation: Assessments of the virtual lab sessions and lab tests by the instructors.
Wang & Ren, 2020, Journal of Chemical Education	United States, Chemistry	Experimental: Students completed the lab on the "Origin of Color" experiment both in-person (Spring 2019) and remotely (Spring 2020).	Surveys were given to students to evaluate teaching effectiveness. The survey was conducted on the student experience in the lab and rated as " No answer, Strongly Disagree, Disagree, Somewhat Agree, Agree, Strongly Agree. Students were also asked to provide suggestions for improving the

			online lab experience.
Koort & Åvall-Jääskeläinen, 2021, FEMS Microbiology Letters	Finland, Microbiology	Experimental: For an experiment for the "Infection Microbiology Lab Course," students engaged in a remote partner model (one person in the lab and another online).	The learning outcomes of the new model (2021) were compared to the face-to-face performance of the prior year (2018-20) using practical tests and surveys.2) Task safety was assessed on a scale of 0–6, and task performance was graded on a 0–3. 3) The student experience with the more partner approach was later evaluated using a five-point Likert scale. 4) A comparison of 2021 student experiences with onsite and remote components was also made using a 5-point Likert scale.
Petillion & McNeil, 2021, Journal of Chemical Education	Canada, Chemistry	Experimental: Students gathered on Zoom to view a taped video of the laboratory technique with a teaching assistant, and students gathered on Zoom to watch a live stream of the teaching assistant experimenting in the lab. These two online	1) A survey was used to compare the two delivery systems' student satisfaction ratings. 2) Semi-structured interviews probed students' experiences using online labs more

		distribution methods were used.	deeply. 7 Likert scale questions and two open-ended questions were included in the surveys. In-depth semi-structured interviews examined how students felt about receiving their online labs.
Huang, 2020, Journal of Chemical Education	China, Chemistry	The study is based on the survey.	Questions about their experiences with online chemistry teaching and learning and the effects of online education were posed to teachers and students (in years 1 and 2). The feedback was then rated as follows: excellent (80–100%), very good (70–79%), good (60-69%) and average (50–59%), and below average. QQ, a well-liked messaging app in China, delivered the questionnaires; 56 teachers and 432 pupils responded.
Jones et al., 2021, Journal of Chemical Education	United States, Chemistry	Experimental: A synchronous online delivery (SOD) approach to laboratory education was used to create and deploy two general chemistry laboratory	With the help of survey information from 123 students, student experiences in these courses were preliminary

		courses in the summer of 2020.	evaluated. The post-test format for the SOD course's Meaningful Learning in Laboratory Instrument (MLLI) served as a basis for the survey. Online surveying was done for this utilizing Qualtrics.
Dukes, 2020, Journal of Chemical Education	United States, Chemistry-Instrumental analysis	Experimental: Students performed virtual labs 1) made data from the previous year available to experiment. 2) Replicating an instrument using a simulation.	Although feedback was needed, a better lab technique was determined based on students' questions after analyzing the data from both solutions.
Aguirre & Selampinar, 2020, Journal of Chemical Education	United States, Chemistry	Experimental: 1) students completed the labs at Storrs using the prelab videos and tests typically used during in-person classes. They additionally utilized simulations. 2) Students at the Hartford campus watched YouTube videos with experiments that matched their requirements.	1) Respondus Lockdown Browser and Monitor were used to examine students on both campuses. 2) The final test and quiz averages were compared to the prior year's averages.
Hamed & Aljanazrah, 2020, Journal of Information Technology Education: Research	Palestine, Physics	The experimental group (Virtual lab-45 students) and control group (Traditional lab-45 students) attended the general physics lab.	SPSS and descriptive statistics were used to analyze quantitative data. The observation collected student performance data during the real lab (hands-on

			experiments). Semi-structured interviews were also conducted to analyze students' views about virtual experiments.
Liang et al., 2020, Advances in Engineering Education	China, Engineering - Mechanical Measurements	Experimental: Through remote control platforms, virtual simulation software, and pocket labs, students conducted experiments.	1) The findings of a poll on student satisfaction were evaluated on a scale of "Very satisfied," "Satisfied," "Less satisfied," and "Not satisfied." 2) Exams were used to analyze student performance in the new lab sessions, and the resulting grades were then turned into graphs.
Soong et al., 2021, Journal of Chemical Education	Canada, Chemistry	Case study - remote titration unit.	Author's observation.
Stokes & Silverthorn, 2021, Advances in Physiology Education	United States, Anatomy and Physiology	Experimental: Students participated in virtual labs.	1) Based on survey results, student impression of the learning platform for the 2019 and 2020 school years was evaluated on a Likert scale, with 1 denoting strongly disagree, 2 denoting somewhat disagree, 3 denoting neutrals, 4 denoting somewhat agree, and 5 denoting strongly agree. 2)

			Additional remarks regarding their ranking were also allowed. Graphs showing the differences between online and in-person lab report grades. 3) Comparisons are also made between students' summative assessment results.
Lacey & Wall, 2021, FEMS Microbiology Letters	Ireland, Microbiology	Experimental: Three B.Sc. undergraduate student groups were chosen to receive feedback using an experimental "quantitative study design.	1) The feedback from the students following the laboratory sessions was used to evaluate the effectiveness of the videos in the classroom. 2) After the COVID-19 shutdown, fourth-year students completed an anonymous online survey, while input from second-and third-year students was gathered utilizing an anonymous questionnaire from the class. 3) The survey results were then extrapolated into bar graphs to analyze the effectiveness of video-based learning. 4) The

			increased use of video-learning resources was evaluated by adding monthly and total views for all videos from May 2019 to October 2020. 5) Daily video views by third-year students (AY) 2018–19 (N = 87) from the start of the 2019–20 academic year at NUI Galway to the final test in May 2020 were also examined.
O˙zadowicz, 2020, Education Sciences	Poland, Automation Engineering	Case Study: Modified blended learning implemented across two groups of students taking the Automation Laboratory course	Experiences gathered by the author as a lecturer and lab assistant. Student perspectives were collected through a survey.

Appendix B

Demographic Questionnaire

Q1 Participant Number (Filled out by the Researcher)

____

Q2 What is your year of birth?

____

Q3 Gender
- Male
- Female
- Other
- Prefer not to say

Q4 Race
- African American
- Asian
- Caucasian/White
- American Indian or Alaska Native
- Native Hawaiian or Other Pacific Islander
- Hispanic/Latino
- Other____________________________
- Prefer not to say

Q5 Level of Education Completed
- Some college
- 2 year degree
- 4 year degree
- Professional degree (MD, JD, M.S., etc)
- Doctorate

Q6 How often do you use a computer?
- Daily
- 4-6 times a week
- 2-3 times a week
- Once a week
- Never

Q7 Have you ever play video games or computer games?

- Yes
- No
- Don't wish to answer

Q8 Have you had any experience using Virtual Reality?

- Yes
- No

Q9 Have you had any experience watching Video demonstrations?

- Yes
- No

Q10 Have you had any experience watching Video lectures?

- Yes
- No

Appendix C

Pre-test Questionnaire

Participant ID (Consult with the researcher)

Q1 The best tool to use when cutting aluminum tubing, or any tubing of moderately soft metal is

- hand-operated wheel-type tubing cutter
- circular saw equipped with an abrasive cutting wheel

Q2 Choose the correct tool that is depicted in the picture.

- Rolling Single Flaring Tool
- Impact Single Flaring Tool
- Impact Double Flaring Tool
- Beading Tool
- Bending Tool
- Cutting Tool

Q3 When flaring aluminum tubing for use with aerospace fittings, the flare angle must be

- 37 degree
- 39 degree
- 45 degree

Q4 When fabricating the rigid fluid line what specific measurement should the initial bend be made?

- 3 and 1/2 inches
- 2 and 5/8 inches

Q5 What is an advantage of a double flare on aluminum tubing?

- Ease of construction
- More resistant to damage when the joint is tightened
- Can be applied to any size and wall-thickness of tubing

Q6 Choose the correct sequence for inserting the components before the final flare.

- Insert the sleeve first, followed by the fitting nut
- Insert the fitting nut first, followed by the sleeve

Q7 While inserting the sleeve, ensure the thick end of the sleeve always points away from the tube.

- True
- False

Q8 Persian blue dye is typically used to make a repair.

- True
- False

Q9 Look at the picture below and select the correct step in the tube bending process.

- Insert tubing into correct groove size
- Pull the handle with a steady motion
- Measure bend locations
- Align zeroes, keeping tube marking aligned with the L line
- Stop when the zero mark lines up with the desired bend angle

Q10 Choose the correct tool that is depicted in the picture.

- Rolling Single Flaring Tool
- Impact Single Flaring Tool
- Impact Double Flaring Tool
- Beading Tool
- Bending Tool
- Cutting Tool

Appendix D

Post-test Questionnaire

Participant ID (Consult with the researcher)

Q1 The best tool to use when cutting aluminum tubing, or any tubing of moderately soft metal is

- Hand operated wheel-type tubing cutter
- A deburring tool
- Circular-saw equipped with an abrasive cutting wheel

Q2 Choose the correct tool that is depicted in the picture.

- Rolling Single Flaring Tool
- Impact Single Flaring Tool
- Impact Double Flaring Tool
- Beading Tool
- Bending Tool
- Cutting Tool

Q3 When flaring aluminum tubing for use with aerospace fittings, the flare angle must be

- 37 degrees
- 39 degrees
- 45 degrees

Q4 When marking measurements, what specific value should the second measurement be made?

- 3 and 1/2 inches
- 2 and 5/8 inches

Q5 What is an advantage of a double flare on aluminum tubing?

- Ease of construction
- More resistant to damage when the joint is tightened
- Can be applied to any size and wall-thickness of tubing

Q6 Choose the correct sequence for inserting the components before the final flare.

- Insert the sleeve first, followed by the fitting nut
- Insert the fitting nut first, followed by the sleeve

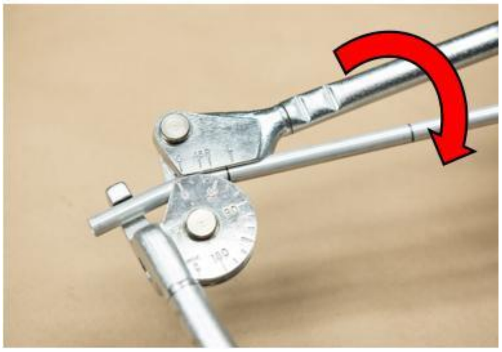
Q7 Ensure both the top and bottom dies of the flaring tool are set to 1/4"

- True
- False

Q8 Persian blue dye is typically used to make a repair.

- True
- False

Q9 Look at the picture below and select the correct step in the tube bending process.



- Insert tubing into correct groove size
- Pull the handle with a steady motion
- Measure bend locations
- Align zeroes, keeping tube marking aligned with the L line
- Stop when the zero mark lines up with the desired bend angle

Q10 Choose the correct tool that is depicted in the picture.

- Rolling Single Flaring Tool
- Impact Single Flaring Tool
- Impact Double Flaring Tool
- Beading Tool
- Bending Tool
- Cutting Tool

Appendix E

NASA-TLX Workload Instrument

Definition of Task Demand Factor

Mental demand

How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Physical demand

How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Temporal demand

How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

Performance

How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Frustration level

How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Effort

How hard did you have to work (mentally and physically) to accomplish your level of performance?

NASA-TLX Mental Workload Rating Scale

Please place an “X” along each scale at the point that best indicates your experience with the display configuration.

Mental Demand

Low High

Physical Demand

Low High

Temporal Demand

Low High

Performance

Good Poor

Effort

Low High

Frustration

Low High

For each of the pairs listed below, circle the scale title that represents the more important contributor to workload in the display.

Mental Demand or Physical Demand

Mental Demand or Temporal Demand

Mental Demand or Performance

Mental Demand or Effort

Mental Demand or Frustration

Physical Demand or Temporal Demand

Physical Demand or Performance

Physical Demand or Effort

Physical Demand or Frustration

Temporal Demand or Performance

Temporal Demand or Frustration

Temporal Demand or Effort

Performance or Frustration

Performance or Effort

Frustration or Effort

Appendix F

Computer Systems Usability Questionnaire

Administration and Scoring. Use the CSUQ rather than the PSSUQ when the usability study is in a non-laboratory setting. Appendix Table 1 contains the rules forcalculating the CSUQ and PSSUQ scores.

Appendix Table 1. Rules for Calculating CSUQ/PSSUQ Scores

Score Name	Average the Responses to:
OVERALL	Items 1 through 19
SYSUSE	Items 1 through 8
INFOQUAL	Items 9 through 15
INTERQUAL	Items 16 through 18

Average the scores from the appropriate items to obtain the scale and subscalescores. Low scores are better than high scores due to the anchors used in the 7-pointscales. If a participant does not answer an item or marks "N/A," then average the remaining item scores.

Instructions and Items. The questionnaire's instructions and items are:

This questionnaire (which starts on the following page) gives you an opportunity to express yoursatisfaction with the usability of your primary computer system. Your responses will help us understand what aspects of the system you are particularly concerned about and the aspects that satisfy you.

To as great a degree as possible, think about all the tasks that you have done with the system while you answer these questions.

Please read each statement and indicate how strongly you agree or disagree with the statement by circling a number on the scale. If a statement does not apply to you, circle N/A.

Whenever it is appropriate, please write comments to explain your

answers.Thank you!

1. Overall, I am satisfied with how easy it is to use this system.

STRONGLY								**STRONGLY**
AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**DISAGREE**

COMMENTS:

2. It is simple to use this system.

STRONGLY								**STRONGLY**
AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**DISAGREE**

COMMENTS:

3. I can effectively complete my work using this system.

STRONGLY								**STRONGLY**
AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**DISAGREE**

COMMENTS:

4. I am able to complete my work quickly using this system.

STRONGLY STRONGLY
AGREE 1 2 3 4 5 6 7 DISAGREE

COMMENTS:

5. I am able to efficiently complete my work using this system.

STRONGLY STRONGLY
AGREE 1 2 3 4 5 6 7 DISAGREE

COMMENTS:

6. I feel comfortable using this system.

STRONGLY STRONGLY
AGREE 1 2 3 4 5 6 7 DISAGREE

COMMENTS:

7. It was easy to learn to use this system.

STRONGLY STRONGLY
AGREE 1 2 3 4 5 6 7 DISAGREE

COMMENTS:

8. I believe I became productive quickly using this system.

STRONGLY STRONGLY
AGREE 1 2 3 4 5 6 7 DISAGREE

COMMENTS:

9. The system gives error messages that clearly tell me how to fix problems.

STRONGLY STRONGLY

AGREE 1 2 3 4 5 6 7 DISAGREE

COMMENTS:

10. Whenever I make a mistake using the system, I recover easily and quickly.

STRONGLY STRONGLY
AGREE 1 2 3 4 5 6 7 DISAGREE

COMMENTS:

11. The information (such as on-line help, on-screen messages and other documentation) provided with this system is clear.

STRONGLY STRONGLY
AGREE 1 2 3 4 5 6 7 DISAGREE

COMMENTS:

12. It is easy to find the information I need.

STRONGLY STRONGLY
AGREE 1 2 3 4 5 6 7 DISAGREE

COMMENTS:

13. The information provided with the system is easy to understand.

STRONGLY STRONGLY
AGREE 1 2 3 4 5 6 7 DISAGREE

COMMENTS:

14. The information is effective in helping me complete my work.

STRONGLY								**STRONGLY**
AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**DISAGREE**

COMMENTS:

15. The organization of information on the system screens is clear.

STRONGLY								**STRONGLY**
AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**DISAGREE**

COMMENTS:

16. The interface of this system is pleasant.

STRONGLY								**STRONGLY**
AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**DISAGREE**

COMMENTS:

17. I like using the interface of this system.

STRONGLY								**STRONGLY**
AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**DISAGREE**

COMMENTS:

18. This system has all the functions and capabilities I expect it to have.

STRONGLY								**STRONGLY**
AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**DISAGREE**

COMMENTS:

19. Overall, I am satisfied with this system.

STRONGLY AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**STRONGLY DISAGREE**

COMMENTS:

Appendix G

Task Analysis

Hierarchy Description

0. Fix the tube on the jig
1. Measuring the bends
    - 1.1 Align the starting end of the tube with the 0 on the ruler
    - 1.2 Measure and mark 2 and 5/8 inches; use the sleeve to extend the mark
    - 1.3 Align the first measure with the 0 on the ruler
    - 1.4 Measure and mark 3 and 1/2 inches; use the sleeve to extend the mark
    - 1.5 Align the second measure with the 0 on the ruler
    - 1.6 Measure and mark 3 and 1/2 inches; use the sleeve to extend the mark
2. Bending
    - 2.1 Place the tube in the groves of the bending tool
    - 2.2 Align the 0 on the fixed arm with the rotating arm of the bending tool
    - 2.3 Align the tube marking (2 and 5/8 inches) with the L symbol on the rotating arm
    - 2.4 Turn the handle of the bending tool down until the 0 on the rotating arm aligns with the 90-degree mark on the fixed arm
    - 2.5 Return the handle to the start position with the 0-0 aligned
    - 2.6 Pull the tube out
        - 2.6.1 Matching with the template
            - 2.6.1.1 Place the bent tube on the template

2.6.1.2 Mark the direction in which the next bend needs to be made

2.6.1.3 Remove the tube from the template

2.7 Place the tube in the groves of the bending tool. Make sure to place the tube parallel to the fixed arm to ensure the bends are in the same plane

2.8 Align the 0 on the fixed arm with the rotating arm of the bending tool

2.9 Align the tube marking (3 and 1/2 inches) with the L symbol on the rotating arm

2.10 Turn the handle of the bending tool down, until the 0 on the rotating arm aligns with the 90-degree mark on the fixed arm

2.11 Return the handle to the start position with the 0-0 aligned

2.12 Pull the tube out

2.12.1 Matching with the template

2.12.1.1 Place the bent tube on the template

2.12.1.2 Mark the direction in which the next bend needs to be made

2.12.1.3 Remove the tube from the template

2.13 Place the tube in the groves of the bending tool. Make sure to place the tube parallel to the fixed arm to ensure the bends are in the same plane

2.14 Align the 0 on the fixed arm with the rotating arm of the bending tool

2.15 Align the tube marking (3 and 1/2 inches) with the L symbol on the rotating arm

2.16 Turn the handle of the bending tool down, until the 0 on the rotating arm aligns with the 90-degree mark on the fixed arm

- 2.17 Return the handle to the start position with the 0-0 aligned
- 2.18 Pull the tube out
  - 2.18.1 Matching with the template
    - 2.18.1.1 Place the bent tube on the template
    - 2.18.1.2 Remove the tube from the template

3. Debur and Sand
   - 3.1 Deburr the end where the first measure was made using the deburring tool
   - 3.2 Sand the same end using sandpaper
4. Inserting sleeve and fitting nut
   - 4.1 Insert the sleeve with the thick end pointing away from the tube
   - 4.2 Insert the fitting nut with the threaded end towards the sleeve
5. Flaring
   - 5.1 Ensure the dies are at 3/8 inches on the flaring tool
   - 5.2 Insert the tube with the sleeve and nut end into the flaring tool
   - 5.3 Pull the wingnut out and make sure the finger touches the top of the tube
   - 5.4 Ensure the wingnut is placed back in the groove and tightened
   - 5.5 Turn the screw on the top of the tool until feels the pressure
   - 5.6 Unscrew and pull the tube out
6. Measuring the extra end to cut
   - 6.1 Place the tube on the jig
   - 6.2 Tighten the flared end on the jig, turning the fitting nut

    - 6.3 Measure the other end where the tube touches the fixture, and mark where the end contacts the first threading
    - 6.4 Remove the tube from the jig by unscrewing the fitting nut

7. Cutting, deburring, and sanding
    - 7.1 Fix the marked end between the rollers of the cutting tool
    - 7.2 Turn the tool clockwise, directing away from the user
    - 7.3 Rotate the circular portion down below the tool after each rotation of the tool
    - 7.4 Continue 7.2 and 7.3 until the tube is cut
8. Inserting sleeve and fitting nut
    - 8.1 Insert the fitting nut with the threaded end towards the end of the tube
    - 8.2 Insert the sleeve with the thick end pointing away from the tube
9. Flaring
    - 9.1 Ensure the dies are at 3/8 inches on the flaring tool
    - 9.2 Insert the tub with the sleeve and nut end into the flaring tool
    - 9.3 Pull the wingnut out and make sure the finger touches the top of the tube
    - 9.4 Ensure the wingnut is placed back in the groove and tightened
    - 9.5 Turn the screw on the top of the tool until it feels the pressure
    - 9.6 Unscrew and pull the tube out
10. Fixing the fabricated tube
    - 10.1 Fix the tub on the jig by screwing the fitting nuts on both the ends

Appendix H

Semi-Structured Interview Questions

1. Could you describe your learning experience with this medium of instruction?
2. How advantageous is this instruction medium for learning practical assembly tasks?
3. What do you think are some of the disadvantages of this instruction medium for learning practical assembly tasks?
4. Which components of this course are most enjoyable to you?
5. How do you think this medium of instruction compares to a traditional in-class teaching environment?
6. Which medium of instruction (assigned condition or traditional learning) helps with learning better for assembly tasks like the one demonstrated in the course?
7. Do you have any suggestions to improve the medium of instruction that would help other students learn the task in the course better?

REFERENCES

Abidi, M. H., Al-Ahmari, A., Ahmad, A., Ameen, W., & Alkhalefah, H. (2019). Assessment of Virtual Reality-based manufacturing assembly training system. *International Journal of Advanced Manufacturing Technology*, *105*(9), 3743–3759.

Aguirre, J. D., & Selampinar, F. (2020). Teaching Chemistry in the time of COVID-19: Memories and the classroom. *Journal of Chemical Education*, *97*(9), 2909–2912.

Ahlberg, G., Enochsson, L., Gallagher, A. G., Hedman, L., Hogman, C., McClusky, D. A., 3rd, Ramel, S., Smith, C. D., & Arvidsson, D. (2007). Proficiency-based Virtual Reality training significantly reduces the error rate for residents during their first 10 laparoscopic cholecystectomies. *American Journal of Surgery*, *193*(6), 797–804.

Almetwazi, M., Alzoman, N., Al-Massarani, S., & Alshamsan, A. (2020). COVID-19 impact on Pharmacy education in Saudi Arabia_ Challenges and opportunities. *Saudi Pharmaceutical Journal*, *28*(11), 1431–1434.

Anstey, M. R., Blauch, D. N., Carroll, F. A., Gorensek-Benitez, A. H., Hauser, C. D., Key, H. M., Myers, J. K., Stevens, E. P., Striplin, D. R., Holck, H. W., Montero-Lopez, L., & Snyder, N. L. (2020). #DavidsonTrue: Transitioning to remote teaching while maintaining our values as a liberal arts college during the COVID-19 pandemic. *Journal of Chemical Education*, *97*(9), 2800–2805.

Anzovino, M. E., Mallia, V. A., Morton, M. S., Barker Paredes, J. E., Pennington, R., Pursell, D. P., Rudd, G. E. A., Shepler, B., Villanueva, O., & Lee, S. (2020). Insights and initiatives while teaching Organic Chemistry I and II with laboratory courses in the time of COVID-19. *Journal of Chemical Education*, *97*(9), 3240–3245.

Ausburn, L. J., & Ausburn, F. B. (2004). Desktop Virtual Reality: A powerful new technology for teaching and research in industrial teacher education. *Journal of Industrial Teacher Education*, *41*(4), 1–16.

Baker, L. A., & Cavinato, A. G. (2020). Teaching Analytical Chemistry in the time of COVID-19. *Analytical Chemistry*, *92*(15), 10185–10186.

Basu, A., & Johnsen, K. (2014, March). Ubiquitous Virtual Reality ‘to-go.’ 2014 IEEE Virtual Reality (VR), Minneapolis, MN, USA.

Bertrand, J., Bhargava, A., Madathil, K. C., Gramopadhye, A., & Babu, S. V. (2017). The effects of presentation method and simulation fidelity on psychomotor education in a bimanual metrology training simulation. *2017 IEEE Symposium on 3D User*

Interfaces (3DUI). 2017 IEEE Symposium on 3D User Interfaces (3DUI), Los Angeles, CA, USA.

Bertrand, J., Brickler, D., Babu, S., Madathil, K., Zelaya, M., Wang, T., Wagner, J., Gramopadhye, A., & Luo, J. (2015). The role of dimensional symmetry on bimanual psychomotor skills education in immersive virtual environments. *2015 IEEE Virtual Reality (VR)*, 3–10.

Bhargava, A., Bertrand, J. W., Gramopadhye, A. K., Madathil, K. C., & Babu, S. V. (2018). Evaluating multiple levels of an Interaction Fidelity Continuum on performance and learning in near-field training simulations. *IEEE Transactions on Visualization and Computer Graphics*, *24*(4), 1418–1427.

Bhute, V. J., Inguva, P., Shah, U., & Brechtelsbauer, C. (2021). Transforming traditional teaching laboratories for effective remote delivery—A review. *Education for Chemical Engineers*, *35,* 96–104.

Bloom, B. S., Engelhart, M. D., Furst, E. J., Hill, W. H., & Krathwohl, D. R. (1956). others. 1956. Taxonomy of Educational Objectives: The Classification of Educational Goals. Handbook I: Cognitive Domain. New York: David McKay Company. *Inc. (7th Edition 1972)*.

Brinson, J. R. (2015). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research. *Computers & Education*, *87*, 218–237.

Brooke, J. (1996). SUS-A quick and dirty usability scale. *Usability Evaluation in Industry*, *189*(194), 4–7.

Broyer, R. M., Miller, K., Ramachandran, S., Fu, S., Howell, K., & Cutchin, S. (2021). Using Virtual Reality to demonstrate glove hygiene in Introductory Chemistry laboratories. *Journal of Chemical Education*, *98*(1), 224–229.

Buchberger, A. R., Evans, T., & Doolittle, P. (2020). Analytical Chemistry online? Lessons learned from transitioning a project lab online due to COVID-19. *Journal of Chemical Education*, *97*(9), 2976–2980.

Carolan, C., Davies, C. L., Crookes, P., McGhee, S., & Roxburgh, M. (2020). COVID 19: Disruptive impacts and transformative opportunities in undergraduate nurse education [Review of *COVID 19: Disruptive impacts and transformative opportunities in undergraduate nurse education*]. *Nurse Education in Practice*, *46,* 102807.

Chang, T.-Y., Hong, G., Paganelli, C., Phantumvanit, P., Chang, W.-J., Shieh, Y.-S., & Hsu, M.-L. (2021). Innovation of dental education during COVID-19 pandemic. *Journal of Dental Sciences*, *16*(1), 15–20.

Chen, X., Song, G., & Zhang, Y. (2010, March 11). Virtual and remote laboratory development: A review. *Earth and Space 2010. 12th Biennial International Conference on Engineering, Construction, and Operations in Challenging Environments; and Fourth NASA/ARO/ASCE Workshop on Granular Materials in Lunar and Martian Exploration*, Honolulu, Hawaii, United States.

Chierichetti, M., & Backer, P. (2021). Exploring faculty perspectives during emergency remote teaching in engineering at a large public university. *Education Sciences*, *11*(8), 419.

Choate, J., Aguilar-Roca, N., Beckett, E., Etherington, S., French, M., Gaganis, V., Haigh, C., Scott, D., Sweeney, T., & Zubek, J. (2021). International educators' attitudes, experiences, and recommendations after an abrupt transition to remote Physiology laboratories. *Advances in Physiology Education*, *45*(2), 310–321.

Choi, S., Jung, K., & Do Noh, S. (2015). Virtual reality applications in manufacturing industries: Past research, present findings, and future directions. *Concurrent Engineering: Research and Applications*, *23*(1), 40–63.

Clark, R. E., & Estes, F. (1996). Cognitive task analysis for training. *International Journal of Educational Research*, *25*(5), 403–417.

Cohen, J. (1988). *Statistical power* (pp. 273–406). Erlbaum Hillsdale, NJ.

Colclasure, B. C., Marlier, A., Durham, M. F., Brooks, T. D., & Kerr, M. (2021). Identified challenges from faculty teaching at predominantly undergraduate institutions after abrupt transition to emergency remote teaching during the COVID-19 pandemic. *Education Sciences*, *11*(9), 556.

Correia, M., & Santos, R. (2017, November). Game-based learning: The use of Kahoot in teacher education. *2017 International Symposium on Computers in Education (SIIE). 2017 International Symposium on Computers in Education (SIIE)*, Lisbon, Portugal.

Cuaton, G. P. (2020). Philippines higher education institutions in the time of COVID-19 pandemic. *Revista Romana de Statistica: Organ al Comisiei Nationale Pentru Statistica*, *XII*(1 Sup2), 61–70.

Daling, L. M., Tenbrock, M., Isenhardt, I., & Schlittmeier, S. J. (2023). Assemble it like this! – Is AR- or VR-based training an effective alternative to video-based training in manual assembly? *Applied Ergonomics*, *110*, 104021.

Dash, S., Kamath, U., Rao, G., Prakash, J., & Mishra, S. (2016). Audio-visual aid in teaching “fatty liver.” *Biochemistry and Molecular Biology Education*, *44*(3), 241–245.

Davy, E. C., & Quane, S. L. (2021). Assessment of technological setup for teaching real-time and recorded laboratories for online learning: Implications for the return to in-person learning. *Journal of Chemical Education*, *98*(7), 2221–2227.

Dellos, R. (2015). Kahoot! A digital game resource for learning. *International Journal of Instructional Technology and Distance Learning*, *12*(4), 49–52.

Dietrich, N., Kentheswaran, K., Ahmadi, A., Teychené, J., Bessière, Y., Alfenore, S., Laborie, S., Bastoul, D., Loubière, K., Guigui, C., Sperandio, M., Barna, L., Paul, E., Cabassud, C., Liné, A., & Hébrard, G. (2020). Attempts, successes, and failures of distance learning in the time of COVID-19. *Journal of Chemical Education*, *97*(9), 2448–2457.

Dukes, A. D., III. (2020). Teaching an Instrumental Analysis laboratory course without instruments during the COVID-19 pandemic. *Journal of Chemical Education*, *97*(9), 2967–2970.

Ediger, T., & Rockwell, K. (2020). Re-designing a 2-semester Anatomy and Physiology lab course for the online environment. *HAPS Educator*, *24*(3), 75–82.

Englund, C., Olofsson, A. D., & Price, L. (2017). Teaching with technology in higher education: understanding conceptual change and development in practice. *Higher Education Research & Development*, *36*(1), 73–87.

Estidola, C. A., Prudente, M. S., & Aguja, S. E. (2021, January 10). Multiple attempts in online assessments address concerns in academic honesty: Perceptions of students and teachers. *Proceedings of the 2021 12th International Conference on E-Education, E-Business, E-Management, and E-Learning*.

Faulconer, E. K., & Gruss, A. B. (2018). A review to weigh the pros and cons of online, remote, and distance science laboratory experiences. *The International Review of Research in Open and Distributed Learning*, *19*(2), 1–15.

Feisel, L. D., & Rosa, A. J. (2005). The role of the laboratory in undergraduate Engineering education. *Journal of Engineering Education*, *94*(1), 121–130.

Ferdig, R. E., Baumgartner, E., & Hartshorne, R. (2020). *Teaching, technology, and teacher education during the COVID-19 pandemic: Stories from the field*. AACE-Association for the Advancement of Computing in Education.

Fox, M. F. J., Werth, A., Hoehn, J. R., & Lewandowski, H. J. (2020). Teaching labs during a pandemic: Lessons from spring 2020 and an outlook for the future. In *arXiv [physics.ed-ph]*. arXiv. http://arxiv.org/abs/2007.01271

Franklin, G., Martin, C., Ruszaj, M., Matin, M., Kataria, A., Hu, J., Brickman, A., & Elkin, P. L. (2021). How the COVID-19 Pandemic Impacted Medical Education during the Last Year of Medical School: A Class Survey. *Life* , *11*(4).

Freina, L., & Ott, M. (2015). A literature review on Immersive Virtual Reality in education: State of the art and perspectives. *The International Scientific Conference Elearning and Software for Education*, *1*, 10–1007.

Gamage, K. A. A., Wijesuriya, D. I., Ekanayake, S. Y., Rennie, A. E. W., Lambert, C. G., & Gunawardhana, N. (2020). Online delivery of teaching and laboratory practices: Continuity of university programmes during COVID-19 pandemic. *Education Sciences*, *10*(10), 291.

Ganier, F., Hoareau, C., & Tisseau, J. (2014). Evaluation of procedural learning transfer from a virtual environment to a real situation: A case study on tank maintenance training. *Ergonomics*, *57*(6), 828–843.

Gao, J., Crossley, S. P., Nollert, M. U., & Lobban, L. L. (2021). Online teaching of a lab course amid a pandemic - A challenge and an opportunity. *Chemical Engineering Education*, *55*(2), 76–84.

Gao, R., Lloyd, J., & Kim, Y. (2020). A desirable combination for undergraduate chemistry laboratories: Face-to-face teaching with computer-aided, modifiable program for grading and assessment. *Journal of Chemical Education*, *97*(9), 3028–3032.

Garcia, M., Quiroga, J., & Ortin, F. (2021). An infrastructure to deliver synchronous remote programming labs. *IEEE Transactions on Learning Technologies*, *14*(2), 161–172.

García-Morales, V. J., Garrido-Moreno, A., & Martín-Rojas, R. (2021). The transformation of higher education after the COVID disruption: Emerging challenges in an online learning scenario. *Frontiers in Psychology*, *12*, 616059.

George, M. L. (2020). Effective teaching and examination strategies for undergraduate learning during COVID-19 school restrictions. *Journal of Educational Technology Systems*, *49*(1), 23–48.

Glazer, N. (2014). Formative plus summative assessment in large undergraduate courses: Why both? *International Journal of Teaching and Learning in Higher Education*, *26*(2), 276–286.

Gutierrez, T., Rodriguez, J., Velaz, Y., Casado, S., Suescun, A., & Sanchez, E. J. (2010, September). IMA-VR: A multimodal virtual training system for skills transfer in Industrial Maintenance and Assembly tasks. *The 19th IEEE International Symposium on Robot and Human Interactive Communication*, Viareggio, Italy.

Hamed, G., & Aljanazrah, A. (2020). The effectiveness of using virtual experiments on students' learning in the general Physics lab. *International Journal of Information and Communication Technology Education*, *19*, 977–996.

Hargrave, C. P., & Kenton, J. M. (2000). Preinstructional simulations: Implications for Science classroom teaching. *The Journal of Computers in Mathematics and Science Teaching*, *19*(1), 47–58.

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Advances in Psychology* (Vol. 52, pp. 139–183). North-Holland.

Hein, G. E. (1991). *Constructivist learning theory*. https://www.exploratorium.edu/education/ifi/constructivist-learning

Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review*, *16*(3), 235–266.

Hoffman, H. R. (2020). *The impact of Immersive VR verses desktop VR technologies on learning attainment and sense of presence*. University of South Dakota .

Hofstein, A., & Lunetta, V. N. (2004). The laboratory in Science education: Foundations for the twenty-first century. *Science Education*, *88*(1), 28–54.

Hofstein, A., & Mamlok-Naaman, R. (2007). The laboratory in science education: the state of the art. *Chemical Education Research and Practice*, *8*(2), 105–107.

Holden, O. L., Norris, M. E., & Kuhlmeier, V. A. (2021). Academic integrity in online assessment: A research review. *Frontiers in Education*, *6*, 1–13.

Huang, J. (2020). Successes and challenges: Online teaching and learning of Chemistry in higher education in China in the time of COVID-19. *Journal of Chemical Education*, *97*(9), 2810–2814.

Huda, M., Maseleno, A., Atmotiyoso, P., Siregar, M., Ahmad, R., Jasmi, K. A., & Muhamad, N. H. N. (2018). Big Data emerging technology: Insights into innovative environment for online learning resources. *International Journal of Emerging Technologies in Learning (IJET)*, *13*(01), 23.

Jenkinson, J. (2009). Measuring the effectiveness of educational technology: What are we attempting to measure? *Electronic Journal of E-Learning*, *7*(3), 273-280-pp273-280.

Jeschofnig, L., & Jeschofnig, P. (2011). *Teaching lab Science courses online: Resources for best practices, tools, and technology*. John Wiley & Sons.

Jones, E. V., Shepler, C. G., & Evans, M. J. (2021). Synchronous online-delivery: A novel approach to online lab instruction. *Journal of Chemical Education*, *98*(3), 850–857.

Kaup, S., Jain, R., Shivalli, S., Pandey, S., & Kaup, S. (2020). Sustaining academics during COVID-19 pandemic: The role of online teaching-learning. *Indian Journal of Ophthalmology*, *68*(6), 1220–1221.

Kolack, K., Hemraj-Benny, T., & Chauhan, M. (2020). Community college Chemistry instruction and research in the time of COVID-19. *Journal of Chemical Education*, *97*(9), 2889–2894.

Kolb, A. Y., & Kolb, D. A. (2009). Experiential learning theory: A dynamic, holistic approach to management learning, education and development. In *The SAGE Handbook of Management Learning, Education and Development* (pp. 42–68). SAGE Publications Ltd.

Koort, J., & Åvall-Jääskeläinen, S. (2021). Redesigning and teaching Veterinary Microbiology laboratory exercises with combined on-site and online participation during the COVID-19 pandemic. *FEMS Microbiology Letters*, *368*(16), 108.

Kwok, A. O. J., & Koh, S. G. M. (2021). COVID-19 and extended reality (XR). *Current Issues in Tourism*, *24*(14), 1935–1940.

Lacey, K., & Wall, J. G. (2021). Video-based learning to enhance teaching of practical Microbiology. *FEMS Microbiology Letters, 368*(2).

Leung, S. L., Hargrove, B. A., Marsh, E. R., Gregg, A. R., & Thole, K. A. (2020). Prompting by COVID-19 to rethink the purpose of Engineering laboratory education - Develop practical competence to solve real-world problems. *Advances in Engineering Education*, *8*(4), n4.

Lewis, J. R. (1995). IBM computer usability satisfaction questionnaires: Psychometric evaluation and instructions for use. *International Journal of Human–Computer Interaction*, *7*(1), 57–78.

Liang, D., Chen, G., Tian, H., & Lu, Q. (2020). The Labs May Be Closed, but Experiments Must Go On Innovations to Teaching Mechanical Measurements 1 during the COVID-19 Pandemic. *Advances in Engineering Education*, *8,* n4

Lockee, B. B. (2021). Online education in the post-COVID era. *Nature Electronics*, *4*(1), 5–6.

Lohre, R., Bois, A. J., Athwal, G. S., Goel, D. P., & Canadian Shoulder and Elbow Society (CSES). (2020). Improved complex skill acquisition by Immersive Virtual Reality training: A randomized controlled trial. *The Journal of Bone and Joint Surgery. American Volume*, *102*(6), e26.

Lunetta, V. N., Hofstein, A., & Clough, M. P. (2007). Learning and teaching in the school science laboratory: An analysis of research, theory, and practice. *Handbook of Research on Science Education*, *2*, 393–441.

Ma, J., & Nickerson, J. V. (2006). Hands-on, simulated, and remote laboratories: A comparative literature review. *ACM Computer Survey*, *38*(3), 7-es.

Madathil, K. C., Frady, K., Hartley, R., Bertrand, J., Alfred, M., & Gramopadhye, A. (2017). An empirical study investigating the effectiveness of integrating virtual reality-based case studies into an online asynchronous learning environment. *Computers in Education Journal*, *8*(3), 1–10.

May, D., Alves, G. R., Kist, A. A., & Zvacek, S. M. (2023). Online Laboratories in Engineering Education Research and Practice. In A. Johri (Ed.), *International Handbook of Engineering Education Research* (pp. 525–552). Routledge.

May, D., Morkos, B., Jackson, A., Hunsu, N. J., Ingalls, A., & Beyette, F. (2023). Rapid transition of traditionally hands-on labs to online instruction in engineering courses. *European Journal of Engineering Education*, *48*(5), 842–860.

McAllister, C., & Watkins, P. (2012). Increasing academic integrity in online classes by fostering the development of self-regulated learning skills. *Clearing House*, *85*(3), 96–101.

Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., & Davis, T. J. (2014). Effectiveness of Virtual Reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Computers & Education*, *70*, 29–40.

Moher, D., Altman, D. G., Liberati, A., & Tetzlaff, J. (2011). PRISMA statement [Review of *PRISMA statement*]. *Epidemiology*, *22*(1), 128.

Müller, D., & Ferreira, J. M. (2005). *Online labs and the MARVEL experience*. https://repositorio-aberto.up.pt/handle/10216/84652

Neuwirth, L. S., Jović, S., & Mukherji, B. R. (2021). Reimagining higher education during and post-COVID-19: Challenges and opportunities. *Journal of Adult and Continuing Education*, *27*(2), 141–156.

Nevaranta, N., Jaatinen, P., Grasbeck, K., & Pyrhonen, O. (2019, July). Interactive learning material for control Engineering education using matlab live scripts. 2*019 IEEE 17th International Conference on Industrial Informatics (INDIN)*, Helsinki, Finland.

Nielsen, J. (1994). Usability inspection methods. *Conference Companion on Human Factors in Computing Systems*, 413–414.

Ożadowicz, A. (2020). Modified blended learning in engineering higher education during the COVID-19 lockdown—building automation courses case study. *Education Sciences*, *10*(10), 292.

Pace, C., Pettit, S. K., & Barker, K. S. (2020). Best practices in middle level quaranteaching: Strategies, tips and resources amidst COVID-19. *Becoming: Journal of the Georgia Association for Middle Level Education*, *31*(1), 2–13.

Parmar, D., Bertrand, J., Babu, S. V., Madathil, K., Zelaya, M., Wang, T., Wagner, J., Gramopadhye, A. K., & Frady, K. (2016). A comparative evaluation of viewing metaphors on psychophysical skills education in an interactive virtual environment. *Virtual Reality*, *20*(3), 141–157.

Petillion, R. J., & McNeil, W. S. (2021). Student satisfaction with synchronous online Organic Chemistry laboratories: prerecorded video vs livestream. *Journal of Chemical Education*, *98*(9), 2861–2869.

Pratticò, F. G., & Lamberti, F. (2021). Towards the adoption of Virtual Reality training systems for the self-tuition of industrial robot operators: A case study at KUKA. *Computers in Industry*, *129*(103446), 103446.

Rasmussen, J. (1983). Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-13*(3), 257–266.

Reeves, S. M., & Crippen, K. J. (2021). Virtual laboratories in undergraduate Science and Engineering courses: A systematic review, 2009–2019. *Journal of Science Education and Technology*, *30*(1), 16–30.

Satterthwait, D. (2010). Why are'hands-on'science activities so effective for student learning? *Teaching Science*, *56*(2), 7–10.

Shakour, K., Gallagher, E., Ransom, T., Johnson, K., Short, R., Beck, J., & Chalil Madathil, K. (2021). The COVID-19 pandemic's effect on student learning at Aviation Maintenance Technology Schools. *ATEC Journal*, *43*(1).

Silva, I. N. da, García-Zubía, J., Hernández-Jayo, U., & Alves, J. B. D. M. (2023). Extended remote laboratories: A systematic review of the literature from 2000 to 2022. *IEEE Access: Practical Innovations, Open Solutions*, *11*, 94780–94804.

Son, C., Hegde, S., Smith, A., Wang, X., & Sasangohar, F. (2020). Effects of COVID-19 on college students' mental health in the United States: Interview survey study. *Journal of Medical Internet Research*, *22*(9), e21279.

Soong, R., Jenne, A., Lysak, D. H., Ghosh Biswas, R., Adamo, A., Kim, K. S., & Simpson, A. (2021). Titrate over the internet: An open-source remote-control titration unit for all students. *Journal of Chemical Education*, *98*(3), 1037–1042.

Stern, L., Barnea, N., & Shauli, S. (2008). The effect of a computerized simulation on middle school students' understanding of the kinetic molecular theory. *Journal of Science Education and Technology*, *17*(4), 305–315.

Stokes, J. A., & Silverthorn, D. U. (2021). Updating Anatomy and Physiology lab delivery: Shifting from a paper-based to an online lab instruction platform, just in time for a global pandemic. *Advances in Physiology Education*, *45*(2), 290–298.

Tobin, K. (1990). Research on Science laboratory activities: In pursuit of better questions and answers to improve learning. *School Science and Mathematics*, *90*(5), 403–418.

Toquero, C. M. (2020). Challenges and opportunities for higher education amid the COVID-19 pandemic: The Philippine context. *Pedagogical Research*, *5*(4), em0063.

Tran, K., Beshir, A., & Vaze, A. (2020). A tale of two lab courses: An account and reflection on the teaching challenges experienced by Organic and Analytical Chemistry laboratories during the COVID-19 period. *Journal of Chemical Education*, *97*(9), 3079–3084.

Ulrich, K. T., Eppinger, S. D., & Yang, M. C. (2008). *Product design and development* (Vol. 4). McGraw-Hill higher education Boston.

Upadhyay, B., Madathil, K. C., Bertrand, J., Rosopa, E., Ballato, J., Verlage, E., Saini, S., Kimerling, L. C., & Gramopadhye, A. (2023). Virtual Reality enabled asynchronous learning modules for fiber optic preform manufacturing education. *Applied Optics*, *62*(31), H1.

Wang, L.-Q., & Ren, J. (2020). Strategies, practice and lessons learned from remote teaching of the General Chemistry laboratory course at Brown University. *Journal of Chemical Education*, *97*(9), 3002–3006.

Wasmer, S. (2021). COVID-19 Attitude Correction: Rather than Crash in the Crisis, the Author Corrected Attitude and Began to Fly. *Journal of Teaching and Learning with Technology*, *10*, 50–57.

Woelk, K., & Whitefield, P. D. (2020). As close as it might get to the real lab experience - live-streamed laboratory activities. *Journal of Chemical Education*, *97*(9), 2996–3001.

Wright, B. D. (2003). Rack and Stack: Time 1 vs. Time 2. *Rasch Measurement Transactions*, *17*, 905–906.

Wright, Benjamin D., & Stone, M. H. (1979). *Best Test Design*. Atlantic Books.

Zhou, C. (2020). Lessons from the unexpected adoption of online teaching for an undergraduate Genetics course with lab classes. *Biochemistry and Molecular Biology Education*, *48*(5), 460–463.