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Virtual Labs for Undergraduate Engineering: Does Virtual Reality have any advantages over a web-based simulation or traditional homework assignment?

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Virtual Labs for Undergraduate Engineering: Does Virtual Reality have any advantages over a web-based simulation or traditional homework assignment?

In Fall 2024, we studied the use of *ThermoLab*, a publically available virtual laboratory designed to support conceptual understanding in undergraduate thermodynamics. We conducted a randomized control experiment at a large public university in the midwest, with 163 participants, comparing the use of the web- and VR-based virtual laboratory with a business-as-usual control condition. The purpose of this experiment is to better understand the advantages of tradeoffs of highly novel and immersive, but generally more logistically challenging Virtual Reality learning experiences, in comparison to a virtual laboratory that can be run within a web browser. We used previously validated instruments to measure thermodynamics conceptual understanding, perceived usefulness, usability, as well as researcher developed instruments for enjoyment. The results showed that the *ThermoLab* virtual laboratory supported increases in student understanding of thermodynamics concepts, but only in the web version. Both versions performed better than the control in terms of enjoyment, and perceived usefulness. This study therefore demonstrates the value of the *ThermoLab* virtual laboratory in undergraduate engineering education, but cautions that VR may not be worth the additional challenges it brings.

Importance of Introductory Thermodynamics and Challenges in Education

Introductory undergraduate thermodynamics is a cornerstone course in engineering and science curricula. Often considered a “rite of passage” for engineering students [1], it serves as a critical determinant of students’ interest and capability in their chosen fields early in their academic journey. In some cases, it functions as a “weed-out” course, with significant implications for retention in STEM programs [2].

The complexity of thermodynamics poses unique challenges for both students and instructors. The subject is conceptually rich, demanding mastery of domain-specific vocabulary and the integration of multiple fundamental principles to solve intricate problems. Thermodynamics often relies on the interpretation of extensive reference tables and diagrams [3] to understand how the system will respond and when it will change how it behaves. This interplay of conceptual understanding and applied problem-solving is further compounded by the need for proficiency in complex mathematics, a combination that frequently frustrates learners and hinders their academic success.

The consequences of these challenges are reflected in concerning academic outcomes; for instance, a longitudinal study at the University of Texas, San Antonio, revealed that less than 53% of students completed introductory thermodynamics on their first attempt, with even lower success rates for repeat attempts [4]. These findings underscore the urgent need for innovative strategies to enhance student engagement and learning outcomes in thermodynamics education. They also beg the question

Emerging Role of Virtual Laboratories in Engineering Education

Virtual laboratories offer a promising avenue to address the educational challenges in thermodynamics and beyond. By providing interactive, simulated environments for experimentation, virtual labs complement traditional laboratory experiences while addressing logistical constraints such as cost, scalability, and accessibility [5], [6]. Importantly, studies consistently demonstrate that virtual laboratories are as effective as physical labs in fostering students' understanding of core principles. For example, Ma and Nickerson [7] reviewed 39 studies and found no significant differences in learning outcomes between hands-on, simulated, and remote laboratories in engineering education.

Moreover, virtual laboratories afford unique benefits that physical laboratories cannot easily replicate. They enable learners to visualize unobservable phenomena, engage in complex inquiry practices, and focus on conceptual understanding without the distractions of "messy" experimental data. Research shows that students using virtual experiments often outperform their peers in conceptual assessments, as exemplified in studies of simulated electric circuits and optics [8], [9]. Additionally, virtual laboratories streamline experimentation, allowing students to dedicate more time to understanding the underlying principles rather than grappling with experimental setups [6]. These features position virtual laboratories as a transformative tool for thermodynamics education, enabling educators to address persistent challenges and improve learning outcomes at scale.

The Potential of Virtual Reality in Undergraduate Education

Virtual reality (VR) has gained attention as a tool for undergraduate education, offering immersive and interactive environments that may enhance student engagement and support learning. Researchers have explored its applications across various disciplines, including engineering, health sciences, and the natural sciences, highlighting its potential to address complex educational challenges. VR environments allow learners to engage with abstract concepts, conduct simulated experiments, and practice skills in ways that may complement or extend traditional classroom approaches.

In physics, VR environments have been reported to help students visualize abstract phenomena, such as electric fields and wave propagation, potentially improving their understanding of fundamental principles [10]. In the health sciences, VR-based training environments are used to introduce students to anatomical structures and procedural tasks in a safe, repeatable manner. These applications offer opportunities for students to develop spatial understanding and practical skills that may otherwise require direct access to clinical settings [11]. Virtual experiments have also been employed to help students explore unobservable phenomena, such as electric currents or subatomic processes, which could support the development of conceptual knowledge [12].

Despite its promise, the use of VR in education comes with limitations and challenges. Evidence for its effectiveness in improving learning outcomes is mixed, with some studies reporting no significant differences compared to traditional methods [13]. Some researchers, such as [14] suggest that while VR environments can enhance student engagement and presence, they may not always lead to improved comprehension. Hardware costs, technical limitations, and the availability of well-designed instructional materials further complicate its adoption.

The Importance of this Study

Undergraduate engineering educators need empirical evidence about which technologies and learning experiences are best suited for teaching the different components of their courses. Given the importance of Introductory Thermodynamics in many students' engineering careers, individual learning activities need to be effective, easy to implement, and optimally enjoyable. Students, especially struggling students, need activities that help them learn the fundamental concepts that will guide their reasoning when they are later performing calculations. Learning technology developers need to understand which technologies and approaches are the most promising so they know where to invest their efforts.

In this paper, we provide some empirical evidence that may help instructors and designers make these decisions. We explore the development, deployment, use and student outcomes of using two versions of a virtual laboratory to teach thermodynamics concepts and report on the outcomes in terms of student learning as well as percieved experience.

Method

Software Development. *ThermoLab* was developed over several years and with the involvement of a community of thermodynamics instructors. The initial prototype was developed using a small innovation grant provided by the researchers home university. The majority of this effort was to demonstrate that a working implementation of the thermodynamic states of water could be created from the IAPWS-95 and IAPWS-97 equation of state and be performant within the limited computational resources available in a consumer VR headset. This initial version of the project was piloted with five students during the fall 2020 semester. Each participant interacted with the prototype application for approximately one hour, becoming familiar with its functionality and carrying out the assigned activities. During the spring 2021 semester, a larger pilot was conducted with 48 students. Over the period of two-weeks, each student utilized the prototype as part of their coursework, requiring a scheduled visit to the local College of Engineering's Visualization Studio to check out devices. Following use, they took a survey to allow us to gauge their perceptions of the prototype virtual laboratory's usability, learning value, value to improve their grade and their enjoyment, with very promising results [15].

These early prototypes enabled the project to receive additional National Science Foundation funding in 2022. After addressing lingering technical and simulation issues, a cohort of seven additional thermodynamics instructors from a diverse range of engineering colleges joined the team as codesigners and initial users. Along with the authors and developers, these additional instructors met in Chicago in early Fall of 2023 for a full day working meeting to learn about the project, explain their unique needs and contexts, and to inform the future design and development efforts. Following the meeting, each instructor facilitated small pilot studies of the VR-based *ThermoLab* application with approximately 5 students. They provided feedback on the design and potential use in their courses which was utilized by the design team to develop the 1.0 version of the virtual lab that also included a new guided laboratory activity in addition to the open "sandbox" simulation mode. By this point in the project, the VR and Web-based virtual lab had been publicly released and tested with a number of instructors in various undergraduate contexts.

Instrument Development. A collection of previously published and validated instruments as well as researcher created instruments were utilized to capture student conceptual understanding as well as their perceptions of the learning experience. *Usefulness for Learning* (Usefulness) was measured using a 10-item instrument developed by [16]. *Usability* was measured with the 10-item System Usability Scale [17] *Enjoyment* was measured using a 6-item scale developed by the authors. The thermodynamics *Conceptual Inventory* (CI) measure included 13 questions and were also developed by the authors, based on prior work by [18]

Research Questions. Three research questions guide this investigation. They are:

Research Question 1. Do either of the *ThermoLab* interventions support greater conceptual learning than the control?

Research Question 2. Does *ThermoLab* help struggling students (i.e. students with the lowest pre-test scores) improve their conceptual understanding?

Research Question 3. Are there differences in how students reported their enjoyment, usability and perceived the usefulness of each *ThermoLab* intervention?

Participants and Recruitment. Participants were recruited from 215 Students enrolled across three sections of the Fall 2024 *Introduction to Thermodynamics* course being taught at a large public university in the Midwest. Two sections were taught by one instructor and one section was taught by a second instructor. As part of a weekly assignment, students were invited to become participants in the study and consent and have their data used for research. Participation in the study had no influence on the work they needed to do for the assignment, nor any influence on their grade. The instructors were not informed about which students provided consent. In total, 190 students elected to be included in the study and allow their de-identified data to be shared openly for research.

Implementation. The conceptual homework was assigned to students during the fourth week of the course and students were given one full week to complete the assignment, which was graded (complete or incomplete) and factors into their final course grade. Within the course management system, each student was randomly assigned to one of three learning activities for the week, regardless of their participation in the research, as part of normal instructional improvement and evaluation. Each assignment included a survey to be taken before the activity, an approximately hour-long learning activity, and a survey to be taken after completing the activity.

Both versions (Web and VR) of the virtual laboratory contained four guided activities: Tools & Constants, Properties of Regions, Boundaries & Points of Interest, and Cycles & Processes. For each of these activities, students would control a simulated piston-cylinder system allowing them to heat and cool the system, add a weight or spring to the top of the piston, set stops to limit the maximum or minimum volume of the system, apply any amount of insulation, and set the temperature and pressure of the surrounding environment. The state of the simulation responds in real time through a visualization of the piston-cylinder, as well as a 3d plot of Pressure, Temperature and Specific Volume. Some of the prompts within the activity require the student to reach a specific state (e.g. “Set the temperature to 300 degrees K”), and others included a multiple choice selections (e.g. “In the liquid region, as the temperature rises, the volume: increases slightly, increases, decreases, decreases slightly”). The students were free to navigate to any part of the activity at any time, even if they hadn’t successfully completed a component.

Figure 1: A screenshot of the Web based version of *ThermoLab*

For students assigned to the Web activity, they were given a 2 minute video explaining how to use the virtual laboratory. And links to the pre-survey, web-based activity, and post-survey. The web-based activity was designed and tested to work on any non-mobile web browser such as a desktop or laptop computer. A vast majority of students own their own personal computer that could be used. Alternatively, they could use any of the various computer labs on campus.

For students assigned to the VR activity, a few additional steps were required. First, they needed to sign up for a specific 2-hour time slot to use a shared VR device at a campus building near to the course lecture hall. Six devices were available for each timeslot, which ran from 9am until 5pm for the five weekdays before the assignment was due. Alternately, students were invited to install the free app on their own device using the Meta App Store. Second, they were provided an additional 5 minute video to orientate them to the unique controls and interfaces they would have to use in the VR version of the lab. Finally, they needed to travel to the location where devices could be used during their timeslot.

To facilitate the access and support of the VR devices, we leveraged support from a local campus makerspace which is tasked with supporting student VR development efforts. The makerspace provided 12 devices, ensuring that while up to six devices were being used, another set could be charging for the next group. They also provided a support person in case any students ran into any technical issues. Surprisingly, not a single student required support. The VR headsets were neatly laid out on a charging station in one corner of a large room reserved for this activity during the week. Printed instructions provided students with links to the support videos, and pre and post surveys. Six studio chairs provided students with a place to sit while using the virtual lab.

For students assigned to the control assignment, the links were similar to the Web-based virtual laboratory except the removal of the orientation video. The control activity included a collection of 23 questions, directly translated from the prompts and questions used within the virtual laboratories, but presented within a google form without any sort of simulator. Instead, these questions required the student to use thermodynamic lookup tables for water as well as conceptualize how the thermodynamic properties would change on their own. None of the questions required the students to perform any calculations. Following is an example question:

> Question 4. A piston-cylinder arrangement containing water is initially in equilibrium with the ambient pressure 300 kPa. It is in perfect thermal contact (no insulation) with the ambient surroundings at 400 C. The piston can move freely, with no friction. A weight is added to the top of the piston. What property remains constant as the weight is added to the top of the piston?
> [] Pressure
> [] Temperature
> [] Specific Volume

Data Collection. Data from the pre- and post-tests was collected using an IRB approved web-based survey tool. Metadata included the datetime of beginning and submitting the survey as well as an IP address of where the survey was taken. Records were linked using the student name, which was unique among the participants. For the virtual laboratory interventions, telemetry data was also collected that recorded every action taken by the players using the Open Game Data research infrastructure [19]. These data include an anonymous code that allows a specific session to be linked to the student surveys.

Data Preparation and Filtering. Data from the survey tool was imported into Python for processing. Several rounds of linking and filtering were conducted. After removing any students who did not consent to be part of the study, the pre and post surveys were combined into one dataframe and names were replaced with random participant codes. The conceptual inventory items were scored with either a 0 (incorrect response) or a 1 (correct response), then summed together for a total score which ranged from 0 to 18. For the other instruments, individual items were 0-scaled so neutral responses to the likert items would be recorded as a 0, positive responses range from 1 to 3, and negative responses range from -1 to -3, being careful to factor for any questions which are written in the negative and needed to be inverted. The individual items were then summed together to produce one number for each instrument: enjoyment, usefulness and usability.

11 participants were removed because they reported a different group in the post test than they were formally assigned. 3 participants were removed by having outlying pre- Concept Inventory scores (z-scores less than -3). 2 participants were removed for having students with pre-test dates later than their post-test dates. 6 participants were removed for having outlying pre-test durations (z-scores greater than 3). 3 participants were removed for open ended comments left during the post-test that would indicate their data may not be trustworthy. For example, one particularly honest participant reported: “I was slightly hung over while taking this, which may affect your results. I apologize!” After all filtering and matching, 163 participants' data was included in the study.

Analysis. A few confirmatory tests were conducted to ensure the remaining data reflected key assumptions of the study. First, Cronbach’s Alpha was calculated to ensure the reliability of the researcher created conceptual inventory measure. This score was reported as alpha = 0.72 which is acceptable. Second, boxplots and a t-test were conducted to ensure that no significant differences existed between students between the two instructors in terms of their pre-test conceptual inventory scores. This assumption was confirmed, with the students of each instructor performing very similarly.

Histograms were developed to visualize the overall “shape” of each measure and visually confirm that values were normally distributed. Box-plots allowed for visual comparisons between the groups and many were included in the results. T-tests and ANOVAs were used to determine if groups were statistically different. One linear regression model was developed to understand the relationship between pre-test Conceptual Inventory scores and the change in Conceptual Inventory scores.

Results

Change in Conceptual Inventory (CI) scores between pre- and post-test, reported enjoyment, reported usability, and perceived usefulness are reported in Figure 1 as boxplots and Table 1 as values. For the Change in Conceptual Inventory (CI) score, a t-test for each group was conducted to identify any conditions where the change between the pre and post populations were significant. Only one condition, Web-based Virtual Lab demonstrated a significant change in scores ($p=0.006$), the other two changes were not significant.

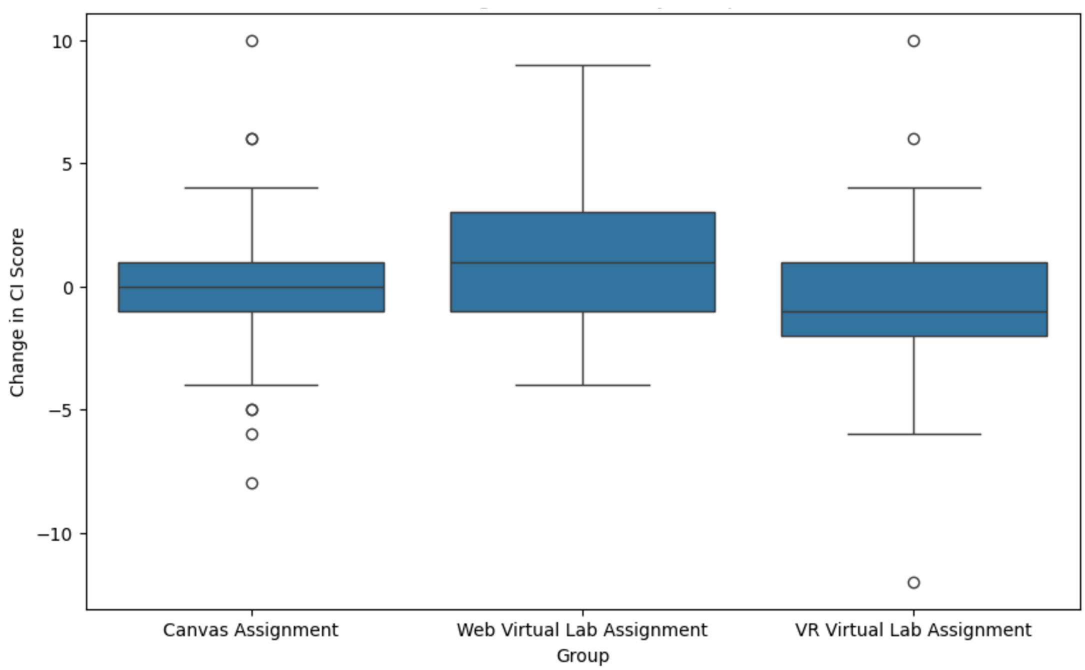

Figure 2: Box plot of the Change in Conceptual Inventory Scores of each intervention

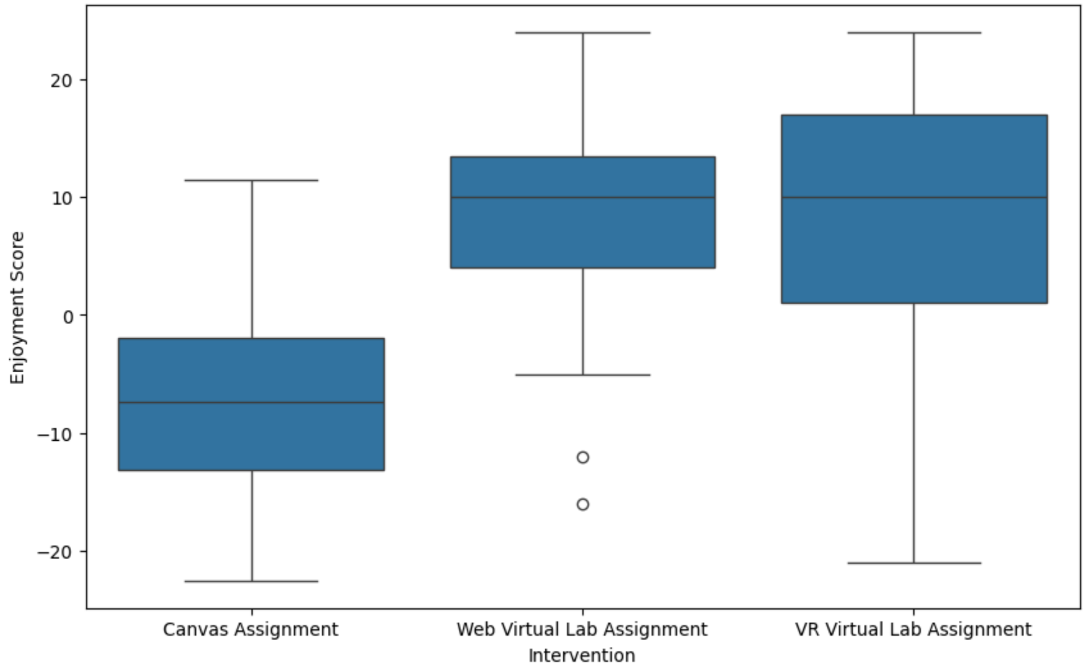

Figure 3: Box plot of the reported Enjoyability of each intervention

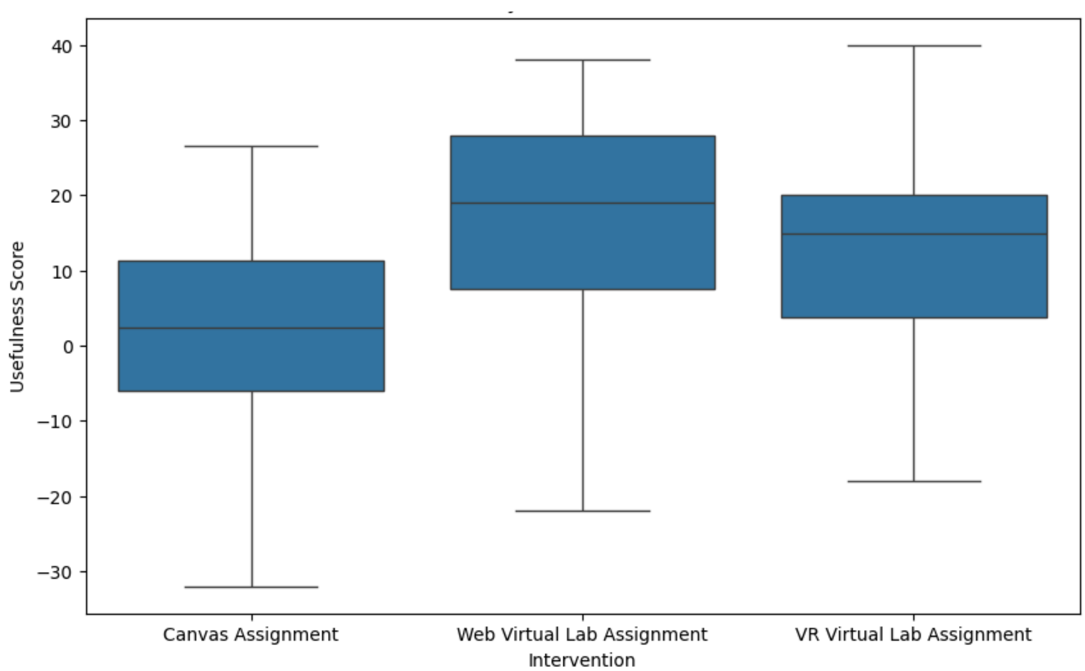

Figure 4: Box plot of the reported Usefulness of each intervention

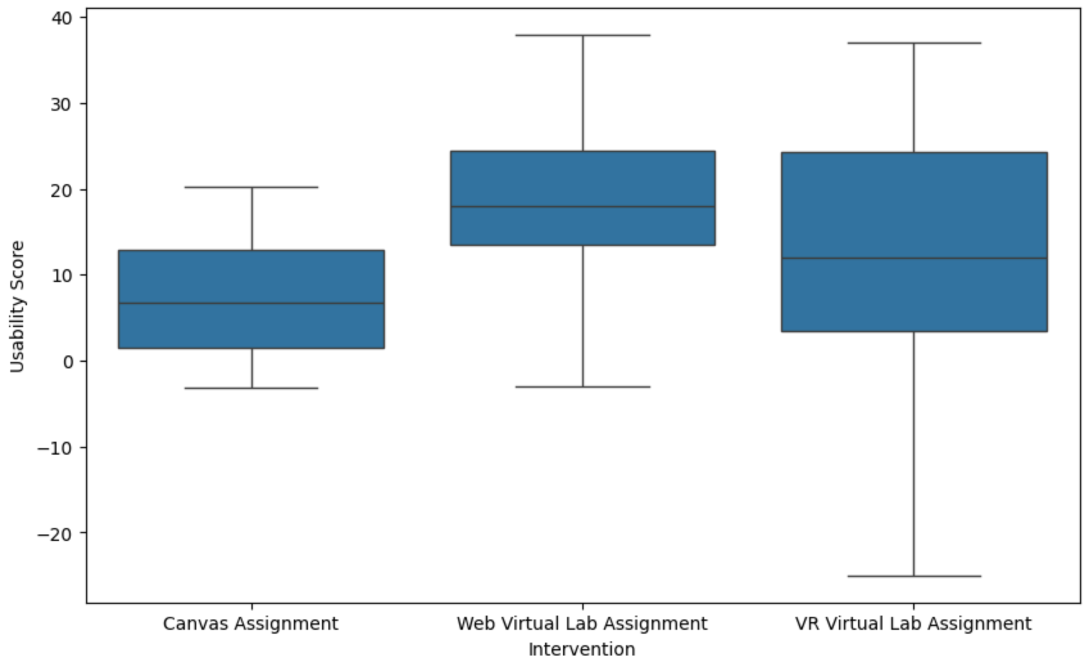

Figure 5: Box plot of the reported Usability of each intervention

A linear regression (See Figure 6) demonstrates that a significant relationship exists between the students' initial conceptual understanding and their improvement after using the for the Web-Based Virtual Lab (R sq = 0.274, F=18.51). Students with the lowest initial scores saw the largest improvement.

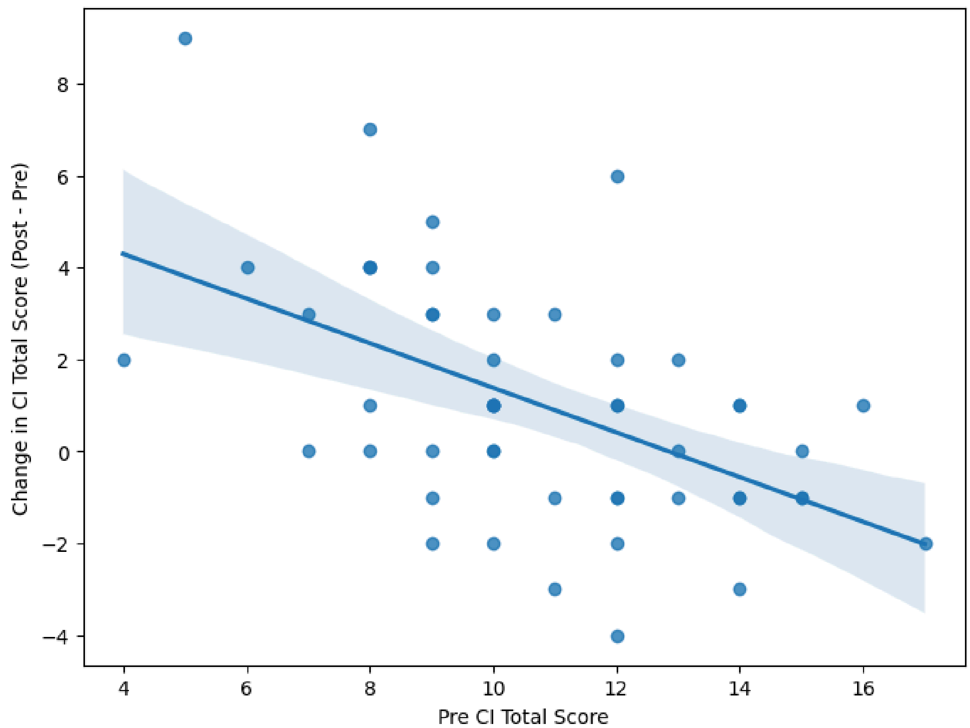

Figure 6: Change in Conceptual Inventory scores in relation to Pretest Conceptual Inventory Score with regression

One-way ANOVA tests were run to determine if significant differences exist between students who had the business-as-usual canvas intervention, the VR Virtual Lab or the Web-based Virtual Lab. All four tests demonstrate significance. Students in the Web-based Virtual Labs had the highest scores for each of the tests. See the bottom row of Table 1 for F and P-values.

Table 1: Mean and Std. Deviation for Changes in Conceptual Inventory, Enjoyment, Usefulness and Usability

Condition	**Change in CI Score**			**Enjoyment**		**Usability**		**Perceived Usefulness**	
	Mean	**S.D.**	**P-value**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
Canvas Assignment n= 56	0.018	2.908	0.963	-7.893	7.945	7.03	6.321	1.97	12.682
Virtual Lab (VR) n= 56	-0.553	3.133	0.191	**8.339**	11.234	11.214	14.876	11.839	11.157
Virtual Lab (Web) n= 51	**1.040**	**2.630**	**0.006**	**8.784**	8.348	**17.941**	9.57	**17.686**	14.031
ANOVA comparison between conditions	**F=4.088 P=0.019**			**F=57.25 p<0.001**		**F=13.58 p<0.001**		**F=19.29 p<0.001**	

To attempt to correct for issues with using the VR technology itself, a second level of analysis was conducted focusing only on students who identified as frequent VR users. The assumption is that these students would be comfortable with the various issues that were observed during the pilot, such as issues with charging, intermittent controller connection, selecting and navigating apps, and using the controllers. Unfortunately, only 5 students in the VR Group self-identified as frequent users. A Welch's T-Test with unequal variances was conducted for each construct to investigate differences between Web-based and Frequent VR users in the VR Virtual Lab. No significant differences were found between the groups.

Discussion and Conclusion

This study answered each of the three research questions adequately. **Research Question 1, "Did either of the *ThermoLab* interventions support greater conceptual learning than the control?" is answered in the affirmative.** The results shown above strongly suggest that the web-based version of *ThermoLab* supports undergraduate students in learning thermodynamics concepts. Additionally, students found the experience enjoyable, usable, and useful. Somewhat surprisingly, the web-based version of the *ThermoLab* performed better than the VR version in all aspects. This is a convenient finding for instructors as well. It is a much simpler task to post a link to an online resource than it is to manage the logistics necessary to ensure every student has access to a pre-configured VR device.

Research Question 2, "Did *ThermoLab* help struggling students (i.e. students with the lowest pre-test scores)?" is also answered in the affirmative. A significant relationship exists between the size of the improvement and a student's initial conceptual inventory score. Students starting with the lowest scores saw the greatest gains. This is a very encouraging finding, as it was one of the primary reasons for conducting the project: to support students that may have fruitful engineering careers if they could only have some early successes. This relationship should be further explored, as richer instruments to identify "struggling students" are possible, potentially even by using other parts of the existing survey and course data.

Finally, **Research Question 3, "Are there statistical differences in how students reported their enjoyment, usability and perceived the usefulness of each intervention?" is also answered in the affirmative**. Upon reflection on the overall student experience of each of the conditions (traditional homework, web-based and VR virtual laboratory) it is easy to imagine how students would find the web-based activity more usable and useful. Engineering students are known for having demanding course schedules. Extra effort is required by students who used the VR version of *ThermoLab*. While the web users likely only needed to click a link from their instructor to get started, the VR users needed to reserve a timeslot, travel to the facility to check out a device, and more often than not, learn a new and entirely new interface. Combined, these extra steps required more planning, thinking and time.

Enjoyment scores, on the other hand, were very close between the different versions of *ThermoLab* and both were significantly higher than the traditional written assignment. In both cases, the virtual lab was found to be more enjoyable than a traditional assignment.

The reason why conceptual learning was not as high for VR participants is still unknown. While there is not enough data to conclude that familiarity with VR generally is not the reason, it still seems likely that given the lower usability scores, some aspect of the interface is involved. One explanation would be that students were distracted by the extra effort required to access the VR devices and use the interfaces. It is also possible that the particular implementation of *ThermoLab* is a factor. For example, it could be that the choice to have students use their hands to grab virtual slides on the control panel is simply not as natural of an interface as some other option, leading to frustration and distraction. In order to better answer these questions, more qualitative, specifically interview work is likely required.

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