DIGITAL ENGINEERING LEARNING TOOLS (DELTA) – LESSONS FROM THE PANDEMIC

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MOTIVATION

The COVID-19 pandemic created numerous challenges but also created opportunities for innovation. A "natural pseudo-experiment" was created, wherein students in Senior Unit Operations Lab were supported with different digital tools over time (walkthrough pre-lab videos and 3D models of the experimental equipment). We want to understand the effectiveness of these digital tools in supporting student learning, their attitudes about these tools, and how they might be improved.

RESEARCH QUESTIONS

Is there a significant difference in the performance of students in creating a Process & Instrumentation Diagram (P&ID) when supported by different digital tools? Can access to the experimental equipment be replaced by these digital tools? What are student attitudes towards these digital tools? How can their overall lab experience be supported through the use of, and the improvement of, these digital tools? Are there specific weaknesses in student learning that are encountered when physical tools are replaced with digital tools?

STUDY CONTEXT

At Clemson University, a main feature of the Unit Operations Sequence is that students are trained to write their own procedures for experiments. We consider this an important part of training them for industry, as many process engineers will be responsible for writing standard operating procedures for front line operators. The sequence includes training in creating a schematic to accompany the procedure. For the Junior Unit Operations Lab, this schematic is generally considered a 'user schematic' that is physically representative of the equipment on the floor, and that helps the user understand the connectivity of the process elements and how to execute the procedure. For the Senior Unit Operations Lab, the schematic is required to be a P&ID.

To support students in their efforts to understand the equipment and write their procedures, we have introduced different methods over time. The digital tools studied include recorded videos of faculty explaining the equipment and 3D computer models of the equipment (walkthrough pre-lab videos). However, the pandemic introduced a new variable, in that some students were prevented from physically accessing the lab to study the equipment.

This study examines the P&IDs produced by students with varying digital tools and varying access to the experimental equipment. Further, we were able to hold focus groups with students who were able to experience lab in varying modalities as the university went through various responses to the pandemic. Their receptiveness to the digital tools and the task in general is reported here.

The demographics of the department at Clemson University over the study period are shown in Figures 1 and 2. The data show that the department is majority white and majority male (averages over the study period, 80% and 70%, respectively) with declining trends over time.

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Students in the Unit Operations Sequence are assigned to lab groups (generally 3 or 4 students), which they stay with for the duration of the semester. During the study period, the procedures and P&IDs produced were submitted by an individual on behalf of the team. So while one student would receive an individual grade for the submitted work, they had the support of the team during its preparation.

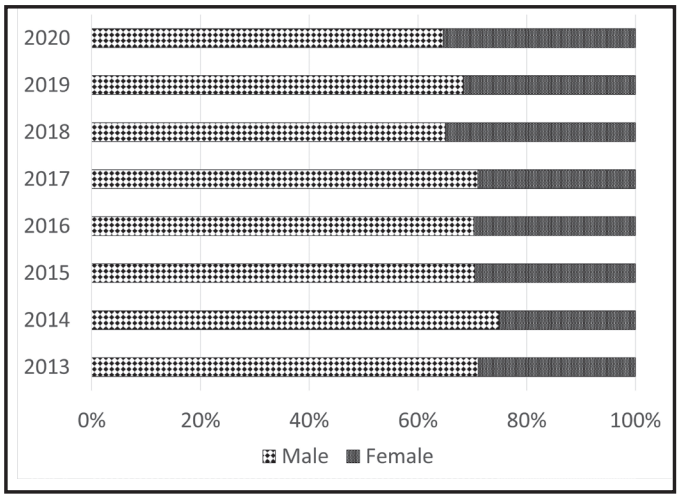

Figure 1. *Gender breakdown of the undergraduate students in the Chemical Engineering Department at Clemson during the Study Period.*

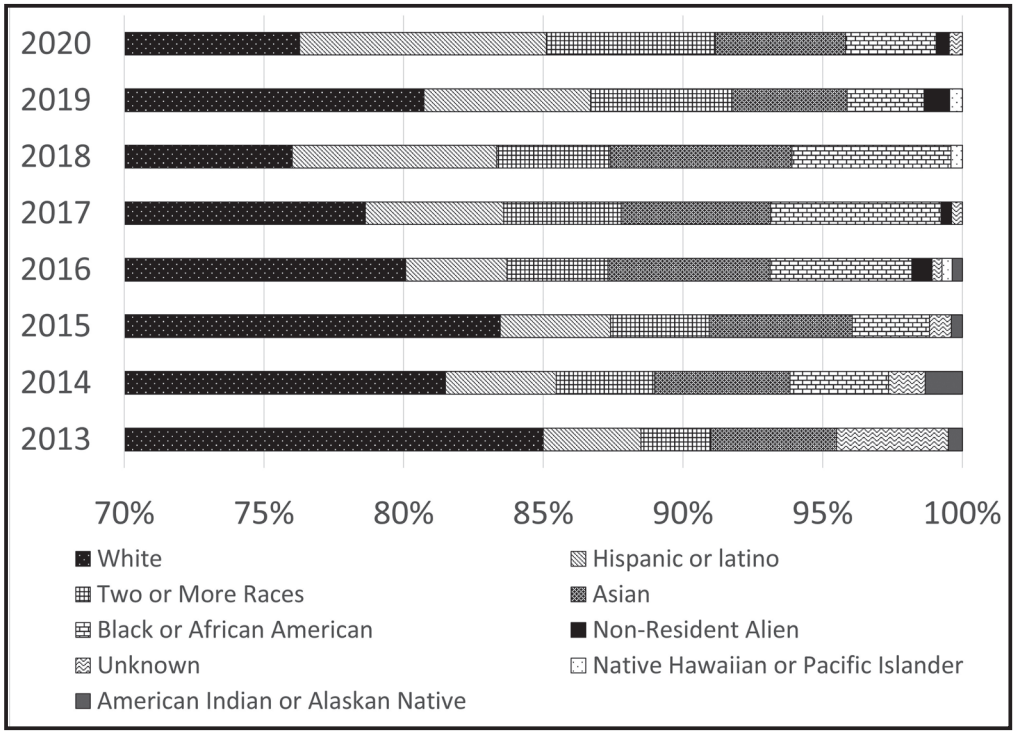

Figure 2. *Racial / Ethnicity breakdown of the undergraduate students in the Chemical Engineering Department at Clemson during the Study Period.*

METHODS

This study was conducted under an approved research protocol IRB2021-0132.

Defining Groups

Initially students met in-person with faculty in the lab, where the faculty would discuss different features of the equipment, and the students were allowed to ask questions. Students also had physical access to the lab, meaning they could spend time studying the equipment. For the purposes of this article, we will refer to this group of students, and the work they produced, as being in Group 1. The study started with 20 student submissions in Group 1, which were submitted between 2013 and 2017.

As technology became more available, it was determined that the discussion by the faculty could be done more efficiently if it were a recorded video. These walkthrough pre-lab videos ensured a more consistent discussion of the apparatus and experiment, saved faculty time and effort, and further enabled students to begin their study of the equipment prior to a meeting with the faculty mentor and to review the information as needed during their project. During this period of time, students also had physical access to the lab. For the purposes of this article, we will refer to this group of students, and the work they produced, as being in Group 2. There were 20 student submissions in Group 2, which were submitted between 2018 and 2019.

When the COVID-19 pandemic shut the university, the faculty began to work on how to overcome challenges posed by the Unit Operations Sequence. In the Fall 2020 semester, the Chemical & Biomolecular Engineering Department was set to offer Unit Ops in person and on campus for all students who wanted to come to campus and take the course. However, at the last minute, the university administration determined that the COVID testing protocols were not sufficient to ensure the safety and well-being of campus and kept campus

shut for an additional month past the traditional start of classes in August. This forced a change in modality for one of the experiments that was planned for the semester; students were still required to create procedures and P&IDs for the experiment, although they would not be able to execute the experiment. Instead, they were evaluated on the procedure but provided with a data set that was generated by the faculty for the purposes of analysis. To support the students in this task, they were provided with a 3D computer model of the equipment, in addition to the walkthrough pre-lab video of the faculty discussion of the experiment, but they were not allowed physical access to the lab at all. We will refer to this group of students, and the work they produced, as being in Group 3. There were 13 student submissions in Group 3, all submitted in Fall 2020.

We collected the P&IDs created by students from these three different groups and stripped the P&IDs of identifying information. A masked evaluation was done of the submissions before sorting the evaluations into the three groups described above. All student submissions were for the same experiment that involves the use of membranes to separate a compressed air stream into one stream enriched in oxygen and another stream enriched in nitrogen (Figure 3). The experimental equipment involves complex piping, four flowmeters, four pressure regulators, a pressure gauge mounted to a manifold with five different connection points to various measurement locations, an oxygen sensor and local display, two membrane separation modules, and three four-way valves, as well as a large number of other valves.

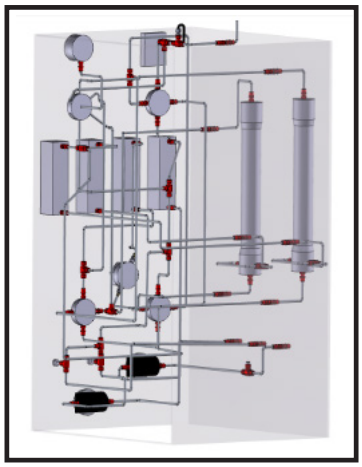

Figure 3. *3D Computer Model of the Gas Membrane Separations Experiment.*

Students from Group 3 were later able to finish Fall 2020 in person and had prior experiences in Junior Unit Ops Lab in previous semesters, parts of which were unaffected by the pandemic; during these times, they had access to the equipment as an aid to understanding the experiment. We conducted focus groups with volunteers that helped put the results into context and provided valuable feedback on the tools provided. Three groups of students who had been in a lab group together participated in separate focus groups (12 total students). Focus groups were conducted via Zoom® with a prepared, preapproved set of questions that prompted the discussion, but the conversation was allowed to evolve during the meeting. Zoom recorded the meetings and prepared a transcript of the discussion that was then reviewed and corrected. We then read the transcripts and conducted a thematic analysis to identify common themes.

P&ID Evaluation

The evaluation of laboratory reports is an ongoing challenge. At Clemson the experimental objective given to students is not always the same, and so students are continually challenged in writing procedures. Therefore, a truly "standard" procedure is elusive. Also, the P&ID is not evaluated separately from the procedure itself. Thus, a standard method of evaluating only the P&ID was created for this study.

This evaluation method cannot be considered a grading rubric. The feedback generated was not meant for students and does not describe the criteria across different performance levels.[1, 2] Instead, this evaluation generally counted the number of occurrences of flaws, while also incorporating a limit for deductions for a particular flaw; the magnitude of the deductions represents the importance of the flaw. This makes the evaluation tool closer to a frequency scale, as described by Brookhart.[3]

The evaluation was created with input from two other instructors who were familiar with teaching the lab and experienced in evaluating P&IDs created by students. This evaluation was broadly broken into three sections: Connectivity, Elements, and Legend.

- Under Connectivity, student submissions were evaluated to make sure they had the process lines connected correctly. It was also important that they showed directionality to process lines and that their formatting for showing pipes that go in front of / behind each other was correct.
- Under Elements, student submissions were checked to ensure that they included all process elements that are part of the apparatus, and further, that they used appropriate symbols for all elements.
- Under Legend, the legend that accompanies each P&ID was evaluated. We instruct students to give each process element a name that describes the function of the element.

The most common errors in student submissions were:

- Lack of directionality displayed on process lines
- No change of formatting for static lines
- Missing process elements
- Incorrect symbols for process equipment, such as pressure regulators
- Names assigned which do not correctly indicate the function of the process element

Statistical Methods

For each student submission the number of deductions in each category was tallied separately, and the total number of deductions was also tallied. Outliers, as determined from the total number of deductions, were removed from the study; outliers were removed if they were outside of the expected quartiles of the boxplot. This resulted in two submissions being removed from Group 1 and one submission being removed from Group 2. This left a study population of 18 submissions in Group 1, 19 submissions in Group 2, and 13 submissions in Group 3. Figure 4 shows a boxplot of the groups, based on the total number of deductions.

FINDINGS

Figure 4 shows the results of the evaluation of the P&IDs produced by the students. After the outliers were removed, we used Analysis of Variance (ANOVA) to test the null hypothesis that there was no difference between the three groups. For the total deductions we found no evidence of a significant difference among the three groups ($p = 0.663$, alpha = 0.05).

Similarly, we found no evidence of significant difference among the three groups in the categories of Connectivity ($p = 0.315$, alpha = 0.05) or Elements ($p = 0.892$, alpha = 0.05). However, there is evidence of a statistically significant difference in the category of Legend ($p = 0.002$, alpha = 0.05); the boxplot for this category (which had the outliers removed prior to analysis) is shown in Figure 5. The number of deductions in the category of Legend for Group 3 was significantly fewer than the other groups in this dimension. This suggests that students in Group 3 were better able to understand the function of the experimental equipment and assign appropriate names to them than students in other groups. However, the power of this conclusion is small, due to the non-normality of the deductions in this group and low discrimination in the data. The category of Legends generally saw fewer deductions than other categories. The result is that a statistically significant difference in this category did not also result in a significant difference at the total deductions for the groups.

Due to the non-normality of the data, we also performed Kruskal-Wallis[4] nonparametric comparison on the data. This was performed on the entire data set, including outliers which had been removed for ANOVA analysis. We also performed a Mood's median nonparametric analysis.[5] Both of these techniques showed the same results; the groups showed no statistically significant differences based on total deductions, Connectivity, or Elements, and showed a small but significant difference in the category

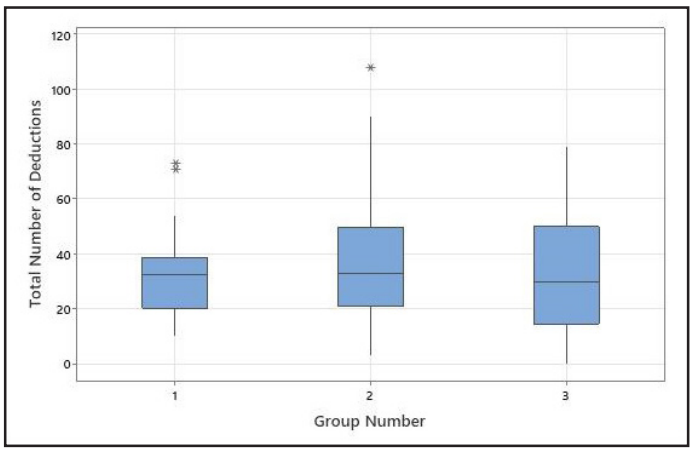

Figure 4. *A boxplot of the student submissions, based on total deductions. The middle line represents the median, the edges of the box represents the upper and lower quartiles, the ends of the whiskers represents the minimum and maximum data points which were kept in the study, and the asterisks represent the outliers which were removed from the study.*

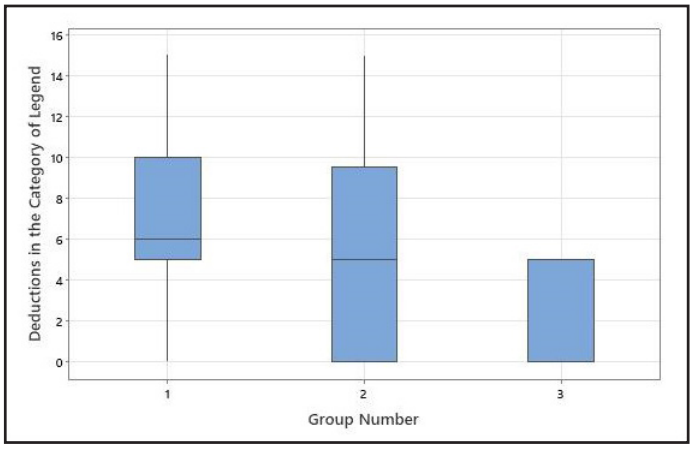

Figure 5. *A boxplot of the student submissions in the category of Legend, showing the median and quartiles. The middle line represents the median, the edges of the box represents the upper and lower quartiles, and the ends of the whiskers represents the minimum and maximum data points which were kept in the study.*

of Legend. The non-normality in the data set originates in the point values assigned in the evaluation tool used for the P&IDs. The tool listed points for deductions for each flaw, and so the measurement of deductions is limited to the precision of those point deductions, resulting in non-normal data sets and low discrimination. Figure 6 shows all of the data and illustrates how similar the Groups are in each category.

Focus groups provided valuable feedback on tools and methods. Students appreciated aspects of both in-person walkthrough meetings and pre-lab video recordings. Being in person made it easier to ask questions, and students felt they could get more

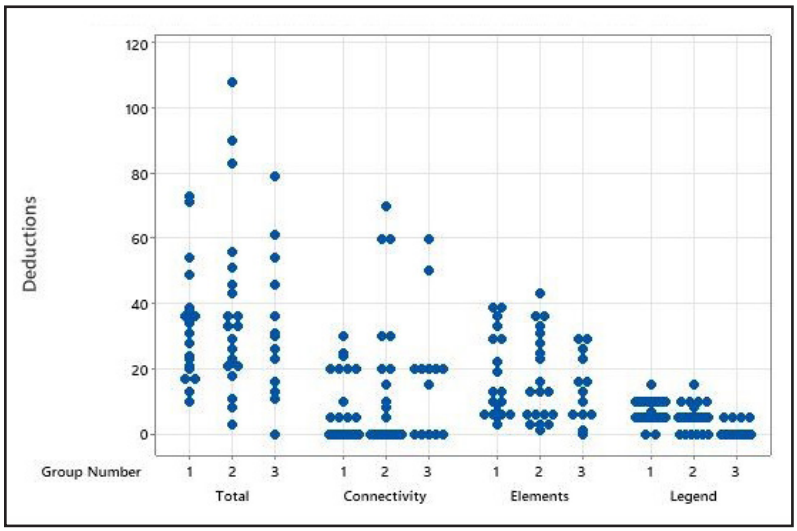

Figure 6. *The study data, including breakdowns into categories; each dot represents a student submission's score in the category. Visualizing the spread of the data provides context to the differences between the groups.*

in-depth explanations. However, video discussions made it possible to prepare questions in advance of meetings with faculty mentors and to review the discussion multiple times.

> *"…easier to ask our questions to [the faculty mentor] right there, while we were looking at the equipment. It was more helpful to see it in person and to actually see the things that you would be turning and how they're connected."*

> *"…rewatching the video because sometimes it's hard to get down all the notes like when you do ask your questions in person it's hard to write or remember everything that they say so having that video as a reference would definitely help a lot …"*

> *"… a pro of online learning is being able to go back and relisten if you miss something"*

They voiced frustrations when the walkthrough pre-lab videos didn't exactly match the equipment in the lab, which gets minor improvements on an ongoing basis. Students also thought that the videos didn't always clearly show all aspects of the equipment and that having access to both the videos and the 3D models would provide the best understanding.

> *"… some of those [videos] are a little dated … equipment has been updated … so they're not exactly a replica of what's in the lab."*

> *"I think the video walkthrough is nice before you go into the lab where you can kind of get an overview, but then I also think it's very important to be able to actually see the equipment for yourself and be in the lab with it."*

The students pointed out two significant ways that the walkthrough pre-lab videos could be improved. The discussion with the faculty has always been done with the equipment completely de-energized. This was the practice due to scheduling issues and also to avoid showing the students parts of the procedure that they should be writing. However, that made the discussion of some aspects of the experiment very abstract; for example, we had to discuss flooding in a column without an example of a flooding column. This is in-line with the findings of Wang and Ren,[6] who found that recorded "pre-lab" activities allowed for clearer and more focused images than might be possible in other settings. Students pointed out that the videos could include footage of the experiment operation, making concrete those things that were previously vague.

> *" Oh, this is what column flooding looks like …because I think that's something that's difficult whether you're in person or online"*

The students also indicated that connecting the videos with the 3D model (editing the video to include the 3D model showing the same features) would make the model more useful.

> *"I thought the videos were very helpful, but my biggest complaint with them is sometimes it's hard to see the equipment on them if the cameras in the wrong spot or there's a valve around back so maybe … if you continue to use the 3D CAD models … and made like an extra little blurb…. That way, you can show like this is what this does."*

The pre-lab walkthrough videos have been re-done to include footage of interesting experimental features (like flooding) and incorporate the 3D models. This is in-line with the suggestions of Koretsky,[7] whose meta-analysis of COVID-related literature supports considering the continued use of technology tools implemented during the pandemic to improve student learning after the resumption of in-person learning.

During the focus groups, students were asked to consider what they would conclude about the study if no evidence of significant differences were found. Students pointed out that the amount of effort required to complete the task could be very different between the groups. They argued that having physical access to the lab made the task easier, although they also admitted that being able to access the 3D model could save time in commuting, parking, etc.

> *"…as a very stubborn person I'm going to try to understand the process …if I'm in person or I'm online; granted I might be pulling out my hair lot more if its online with that 3D schematic…"*

"Especially in an engineering group I feel like people were able to you know adjust when we switched from in person to CAD so I wouldn't be surprised if there was no statistical difference."

"…objectively grading the schematics doesn't really take into account the amount of effort that it takes to produce the same schematic. You know, so if, like you know you have some straight A student who is going to put in whatever it takes to make sure they get an A on the assignment, it may be far easier for them to do it in person than with the [3D model] or vice versa. But the grading doesn't necessarily reflect that."

"…after talking through the advantages and disadvantages of each, I could see how different students would function better, with different [tools], and so I guess it would not surprise me (if there were no significant differences between Groups)."

"I think that the end result may be not statistically different between the groups, but I think the actual process of doing it is very different in terms of what the student actually does to create it."

"Especially for those people who have to drive to campus or have more strict schedules, they kind of have to go in at semi normal hours or they have to make a huge effort to go in and see something, where if it's online there is that accessibility and advantage of being able to look at it for longer and whenever you need to."

Students also brought up the usability of the 3D model. Early versions were models rendered in high resolution. These models required a lot of computing power and would often "crash" the files, causing frustration among the students and causing them to use the models less than they might have otherwise.

"It was running really slow on my computer and I'd have pipes that would disappear … it would crash, and pipes would disappear and it was really frustrating just dealing with it … I think as a tool is probably really good and whether it's as a supplement to actually going in the lab or a replacement, I think you could draw a perfectly fine schematic off of it. But my problem with it was actually dealing with it technically and I don't know if that's my computer or the format."

Newer, more stable versions of the models, rendered in lower resolution, have been created in response.

Students also raised the nuanced idea that while a standardized evaluation might be used to evaluate their performance on a task, it does not evaluate what they absorb from the experience. They argued that the in-person experience was important for their long-term retention.

"I personally think a grade doesn't really define how much you're actually learning or like I feel like it's hard to tell how much you actually are taking away from the class"

While conducting lab in-person during Fall 2020, the faculty took precautions to help protect the safety and well-being of the campus community. One of these involved limiting the number of students who could be in the lab at any one time. To accomplish this, we asked student groups to work in shifts. Most experiments can be accomplished by two people, and for years, we have observed less than full participation by all members of a four-person lab group during the experiment. Asking students to work in shifts increased the participation in the experimentation by all members of the group and reinforced the importance of a properly written lab procedure without increasing the time and effort required from the faculty and staff. Students added that they thought this made the lab less fun, and slightly more stressful; however, they had no comments about the effect on their learning, if any.

"…it made it a little bit more stressful when it was only two of us, and we were like running back and forth, and like trying to get everything done"

"I get the skill that's like comes along with that, but it's just like …We actually had some fun in lab together"

"I think it does increase appreciation for those who write the procedure and can motivate the procedure writing to be more clear"

"I honestly kind of like the shift work. I felt like [when there were four people in the lab] really only two people were doing stuff everyone else was kind of like standing around watching"

The faculty created the walkthrough pre-lab videos in part in response to a frustration with students coming to meetings unprepared. To combat this, pre-quizzes have been added to the Junior Unit Operations course that must be completed before an in-person meeting and are aligned with the information in the walkthrough pre-lab videos. This incentivizes students to prepare for their discussions with the faculty. These quizzes include the calculations that are germane to the experiment as well as issues involving the operation of the equipment. These assessment quizzes point out shortcomings in understanding to the students, which can be addressed at in-person meetings, and are similar to techniques reported by Wang and Ren.[6]

In general, these comments echo what has been found in other studies of digital tools. The advantages of flexibility, timesaving, and the ability to review and replay support students in their learning and are viewed as beneficial,[8] while the need to improve reliability remains. The suggestion that the in-person experience was critical for long-term retention

and understanding may also be related to the suggestion of Vigeant and Golightly[9] that the in-person experience may provide a more meaningful learning experience. However, this may simply reflect student preferences, as reported elsewhere,[6, 10-13] whereas this study seems to reflect a very small positive effect on student performance in the online-only modality. Anecdotal evidence at Clemson also backs up the preference for in-person experiences; when given the choice to attend lab in-person, or to remain online, the majority of students (52 of 58 in Senior Lab and 17 of 17 in Junior Lab) chose to attend in person in Fall 2020.

> *"Obviously I would prefer the in person, just for me, but I feel like I'm going to do the same either way, like my I would get the same score and my schematic would end up looking about the same either way."*

SIGNIFICANCE TO THE CHEMICAL ENGINEERING COMMUNITY

The quantitative evaluation of students' abilities to create P&IDs shows that the lack of access to the experimental apparatus does not hinder their performance on the task. However, students feel that they absorb more, and work more efficiently, when they have access to the experimental equipment. Given a situation like the pandemic, it is possible that a pervasive "Whatever It Takes" attitude drives students to similar levels of performance as during more normal periods, regardless of the tools or challenges.

Students gave good input on how to improve learning tools. Improvements to the course sequence have included pre-quizzes prior to in-person meetings, more robust and user-friendly 3D models, and new walkthrough pre-lab videos that include highlights of important operating conditions and incorporate the 3D model with the video.

The study data show that physical access to equipment can be adequately replaced by a digital tool, if required. A very small positive effect was detected in the data in the ability of students to understand the function of experimental equipment and assign appropriate names to it. Students tend to appreciate aspects of each modality to learning; for digital tools, the convenience in access and review receives positive focus, while the in-person access to the equipment is perceived to provide a more meaningful learning experience and is generally preferred by students.

The study data reveal no significant impact on student performance when using walkthrough pre-lab videos when the students also have access to the equipment. In this case, there is a clear benefit in terms of faculty time.[14] Further, the data cannot shed any light on whether certain demographics have different learning experiences when encountering these digital tools. It is possible, for social or economic reasons, that different groups would have different responses to the inclusion of more digital tools in the learning process; this study cannot make comments on such potential differences.

ACKNOWLEDGMENTS

I would like to thank Drs. Jessica Larsen and Suzanne Roat, both of Clemson University, for their help in planning the project and creating the evaluation used in the study. For her assistance with the qualitative methods used in this study, I would like to thank Dr. Shannon Stefl, and for her efforts in reviewing and strengthening this work and manuscript, I would like to thank Dr. Taimi Olsen, both of the Clemson Office of Teaching Effectiveness and Innovation. Finally, I would like to thank Mahir Kale for his efforts in creating the 3D CAD models used in the course.

REFERENCES

1. Andrade HG (2000) Using rubrics to promote thinking and learning. *Educational Leadership*. 57: 13–18 https://www.ascd.org/el/articles/using-rubrics-to-promote-thinking-and-learning. accessed October 1, 2023.
2. Arter JA and Chappuis J (2006) *Creating and Recognizing Quality Rubrics*. Pearson, Boston, MA.
3. Brookhart SM (2018) Appropriate criteria: Key to effective rubrics. *Frontiers in Education*. 3:1-12.
4. Minitab.com®. Overview for Kruskal-Wallis Test. https://support.minitab.com/en-us/minitab/21/help-and-how-to/statistics/nonparametrics/how-to/kruskal-wallis-test/before-you-start/overview/. Accessed Dec.22, 2023
5. Minitab.com®. Overview for Mood's Median Test. https://support.minitab.com/en-us/minitab/21/help-and-how-to/statistics/nonparametrics/how-to/mood-s-median-test/before-you-start/overview/ Accessed Dec.22, 2023.
6. Wang LQ and Ren J (2020) *J. Chem. Edu*. 97:3002-3006.
7. Koretsky MD (2022) Student perspectives of remote teaching during the COVID-19 pandemic. *Chem. Eng. Ed*. 56(1): 47-56. DOI: 10.18260/2-1-370.660-128227
8. Henderson M, Selwyn N, and Aston R (2017) What works and why? Student perceptions of 'useful' digital technology in university teaching and learning. *Studies in Higher Education*. 42(8): 1567-1579. DOI: 10.1080/03075079.2015.1007946.
9. Vigeant M and Golightly A. (2022) Can video experiments be as effective as hands-on experiments for conceptual learning? *Chem. Eng. Ed*. 56(1):15-21. DOI: 10.18260/2-1-370.660-125205
10. Corter JE, Esche SK, Chassapis C, Ma J, Nickerson JV (2011) Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories. *Computers & Education*. 57(3): 2054-2067.
11. Corter JE, Nickerson JV, Esche SK, Chassapis C, Im Seongah, and Ma J (2007) Constructing reality: A study of remote, hands-on, and simulated laboratories. *ACM Transactions on Computer-Human Interaction*. 14(2):1-27.
12. Lindsay ED and Good MC (2005) Effects of Laboratory Access Modes Upon Learning Outcomes. *IEE Transactions on Education*. 48(4): 619-631.
13. Accettone S LW (2022) Student perceptions of remote chemistry laboratory delivery models. *J. Chem. Educ*. 99: 654-668.
14. Campbell J, Macey A, Chen W, Shah UV, and Brechtelsbauer C (2020) *J. Chem. Educ*. 97: 4001-4007.❑.