The remote laboratory VISIR – Introducing online laboratory equipment in electrical engineering classes

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***Abstract*— This innovative practice full paper is displaying research results on implementing a ready-to-use remote lab in the area of electronics called Virtual Instrument Systems In Reality (VISIR) in several electrical engineering classes at the University of Georgia (UGA) over three consecutive terms. The displayed research data has been generated during the spring, summer, and fall terms in 2019. This paper discusses existing research contexts and results concerning VISIR in general and the VISIR integration at UGA in particular. Furthermore, the students' feedback and educational research results from the focused three semesters will be displayed. It is evident, that the use of remote labs does exclude segments of reality and context during the experimental procedure. The question is instead, if and to what extent this is beneficial for the learning experience, e.g. by looking at collaboration and learning outcomes.**

Keywords—VISIR, online experimentation, remote labs

I. Introduction

Even though remote laboratories have been in engineering education for several years, such technologies are not yet widely used. In many cases, remote labs are custom-made technological developments at a single institution without offering a large reach beyond the home location. VISIR is different in this context, as several international institutions now use and share the same equipment. Hence, it is of special interest to gain relevant research results for VISIR's educational challenges and benefits. Considering that remote labs can solve location, time and capacity constraints in laboratory education, VISIR represents both an economical and a pedagogic solution. The introduced VISIR equipment was developed over a decade ago and it is used by several universities around the globe. Over the last 1.5 years, it has been implemented and investigated at the University of Georgia (UGA).

The VISIR workbench is equipped with a virtual interface enabling students to recognize the benchtop instruments including a breadboard that can be used on the student's computer screen. The equipment intends to reproduce tactile learning by emulating required operating functions, such as grabbing components and rotating instrument knobs. Consequently, the equipment has been replaced within VISIR by telemanipulators, i.e., a switching relay matrix, which the student can control by wiring on a virtual breadboard. Once the user has made all the wiring, chose the experimental settings, and sent this setup to the workbench, the desired circuit is created, the experiment is performed in fractions of a second, and, finally, the experiment's result is returned to the user. This allows many users to experiment simultaneously; therefore, VISIR can be used as an equivalent to a laboratory equipped with many traditional workbenches.

II. Online Laboratories Research

Recent innovations in online education and the need for laboratory exercises as part of competence development processes in STEM education have led to the development of remote (physically real existing equipment used over distance, VISIR is an example of this category), augmented reality (real existing labs with VR add-ons), and virtual labs (a software-based fully virtual laboratory, often based on simulation), which are subsumed under the term "online labs [1-9].

A. Benefits and challenges of online labs

Studies show that online laboratories are efficient tools engaging engineering students with hands-on learning experiences and practical tools, stimulating autonomous learning and offering practical experience of problem-solving, improving student motivation, and overcoming organizational shortcomings in higher education institutions [10-12]. Virtual labs, particularly, are coming into the focus, as they can overcome drawbacks classical labs have [8]. Benefits of virtual labs are especially seen in cost-efficiency for high quality laboratory work, flexibility in terms of varying the experience, multiple user access (not necessarily to the same environment at the same time but to parallel labs), damage resistance, user safety, accessibility of experimental setups, and making otherwise invisible parts of the experiment visible. Drawbacks of online labs, especially in the case of virtual labs, are defined by complex 3D-CAD modeling (which needs certain computer resources) and the disconnect between the real-world experience and the virtual simulation in terms of seriousness, responsibility and carefulness of the user [5, 13]. The crucial criterion for developing a virtual laboratory experience is the level of authenticity, defined by (i) the real-world equipment pieces, (ii) the system behavior, (iii) the overall visualization and look, and (iv) the social collaboration patterns [5].

B. The remote lab VISIR over time

Research on the development and usage of VISIR itself started in the years 2006 to 2008 with papers mainly focused on the technical development of such a remote lab technology [14-17]. However, early research focused on technical development rather than on its educational integration. The main motivation

This work is funded by the by the UGA Office of Research, Internal Grants & Awards

for developing VISIR was to extend student opportunities to perform and assess their own experiments, either in the physical classroom or in distance education courses [18, 19]. Early research and development work also focused on enhancing the sense of reality while using the equipment and finding ways to use VISIR as a collaborative remote lab for students from different countries [20, 21]. Over the years, VISIR has been adapted by other universities in different countries and, hence, the research scope has diversified slightly [22-28]. Nevertheless, the technical development and preliminary assessment of VISIR in the classroom remained at the core of a now global research community. In recent years, more explicit education research came up. For example, in [29] the author showed how VISIR can be used to enhance analytical skills among students and to contextualize math in engineering courses. Other research groups focused on how online labs compare to hands-on and virtual labs in the students' perception and performance [30]. The results in this regard are somewhat diverse, but it can be stated that the lab's representation and successful integration into the overall course curriculum is of focal importance.

In summary, it can be said that thorough comparative studies between different lab representations are seldom done. The research community in part is still lacking educational research that goes well beyond preliminary evaluation and results. In addition, many research activities employ primarily quantitative research tools. Hence, it is time to use well-grounded qualitative research tools in order to broaden the perspective, find new branches of research, and understand the faculty and student perspective on remote lab usage in greater detail.

III. REMOTE EXPERIMENTATION WITH VISIR IN CIRCUITS

The VISIR Open Lab Platform developed at the Department of Electrical Engineering of Blekinge Institute of Technology (BTH), Sweden, is an architecture for improving existing types of hands-on labs in the area of electronics and circuits. It features remote access with preserved content in order to supplement and increase the accessibility and capacity of standard lab equipment. A unique web-interface duplicates hands-on equipment and gives students a feeling of presence in the physical hands-on lab [20]. The VISIR system consists of four different parts: The web-interface, the equipment server, the measurement matrix, and the switching relay matrix.

A. Technical Infrastructure

The VISIR workbench is equipped with a web-interface enabling students to recognize the benchtop instruments. These include a virtual breadboard, a multimeter, and an oscilloscope that can be used on the student's computer screen (see Fig. 1).

The equipment's goal is to reproduce tactile learning by emulating the required operating functions, such as moving components and rotating instrument knobs. Hence, tactile learning has been replaced in VISIR by telemanipulation which the student can control virtually. To begin, the user creates a circuit in the web-interface and defines the settings of the instruments. This is accomplished by creating, wiring, and building components on the virtual breadboard. After pressing the 'Perform Experiment' button, the data is sent to the measurement and equipment servers. The measurement server acts as a gate-keeper that controls the commands passing from the web interface to the equipment server in order to prevent dangerous circuit designs and protect the instruments. It is programmed by 'max list' files, which contain the maximum component values and instrument adjustments for each experiment and describes the allowed circuits in the platform. The equipment server is connected to the relay switching matrix, and both are controlled by this server (which is coded in LabVIEW). It receives the commands from the measurement server over TCP/IP to the experiments on the real instruments in the switching matrix. A 'component list' file is coded into the equipment server to define the components physically installed on the matrix. After validation from both servers, the desired circuit is configured on the matrix and the experiment is performed in fractions of a second. The result is returned to the user and shown on the web interface.

Experiments in three different areas of circuits design can be performed by the system. Depending on the area, different equipment parts and components for circuits building are offered to the user. In the area of analog electronic experiments, the user is able to build circuits with resistors, capacitors, diodes, operational amplifiers or transistors, as well as check their behavior with the available instruments. Performing experiments with resistors include activities like connecting, measuring, and discovering how to combine resistors in a series

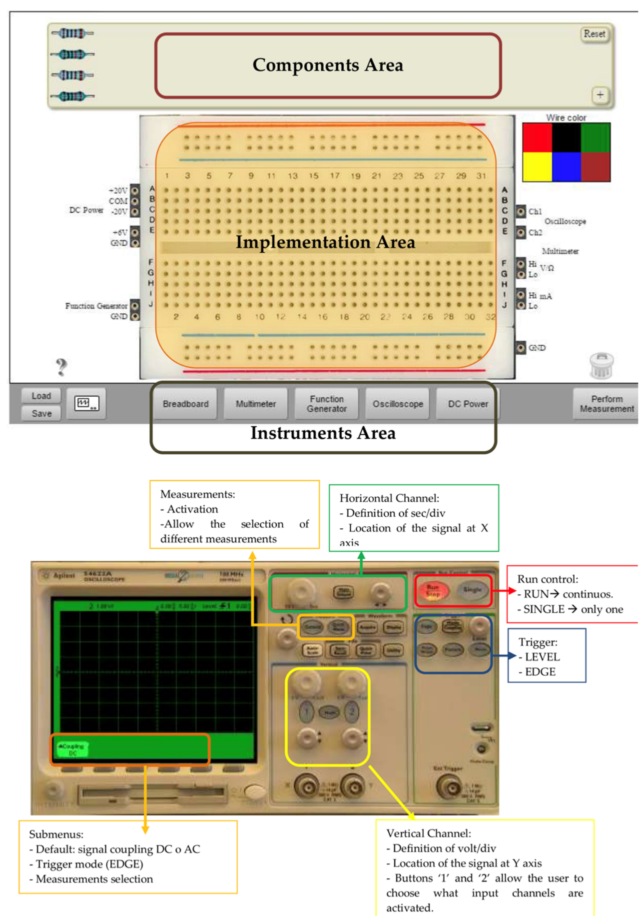

Fig. 1 Web-interface showing the breadboard and main areas for interaction (top) main functionalities of digital oscilloscope (bottom)

and/or parallel combination. Users can test all possible combinations built with two resistors of 1k Ohms and two resistors of 10k Ohms and measure the equivalent circuit using the digital multimeter. The third area covers performing experiments in context with Ohm's and Kirchhoff's laws. That includes building and measuring any circuit using two resistors of 1k Ohms and two resistors of 10k Ohms, supplying the circuit with the +20VDC source and using the multimeter for measuring the voltage across any circuit elements and the current flowing through any circuit elements.

B. Curricular Context at UGA

At UGA, VISIR has been introduced to two different courses that both use VISIR in conjunction with existing physical hardware. These courses are "Electrical Circuits" and "Introduction to Electrical Engineering". In particular, VISIR was deployed to help with topics that have been historically challenging at UGA. First, VISIR was used as a training tool for breadboarding skills. Students often confuse the rows and columns on a breadboard that are connected. The VISIR provides immediate feedback if the configuration is wired correctly. This one-on-one interaction allows for successful skill-building without the potential stigma of needing help, and it also provides an environment where the consequence of failing is not linked to destroying the hardware.

From a course design perspective, the introduction of VISIR to two UGA's electrical engineering courses has 3 main goals: students can (1) independently prepare themselves before class with the help of the remote equipment, (2) do the in-class experiment online instead of hands-on, and finally (3) recap concepts learned in class by autonomously performing additional experiments.

IV. Research Study Design

With our research activities, we want to get an in-depth view and understanding of how the students receive VISIR, how they see it to be beneficial for their learning process, and what challenges students to encounter while using VISIR. Hence our research question was:

- In the context of undergraduate electrical engineering education, what are the dominant determinants for the learning process using the VISIR remote lab?

This study was completed at the College of Engineering at the UGA. The VISIR system is physically sitting and operating in the Engineering Center building but can be used from any computer with an internet connection. For our research on VISIR, we combined quantitative and qualitative research approaches. Research data has been collected over three semesters (Spring, Summer, Fall 2019) using online surveys (in all three terms) and focus interviews with students at the end of each semester (only Fall term). We used the survey results to inform our focus interviews.

A. Methodology and Tools

The quantitative portion of our research activity consisted of an online survey with 32 closed questions and 4 free-response questions (see table I). This survey was sent out to all students in the two courses at the end of the respective terms. For the survey development and data analysis, the survey tool from Qualtrics was used. The online survey system randomized the order in which the items 1-32 were presented to the students.

For items 1-32, the students were asked to rate their personal level of agreement or disagreement to each item on a 5-point Likert-scale with 1 being strongly disagreed and 5 strongly agree. Items 10, 19, and 21 are phrased negatively, so a response with 1 or 2 can be regarded as positive in the study's sense. The items, based on several other survey tools for remote labs developed for and applied in other studies [24, 27, 31-33], were allocated to the following 6 categories: (1) Learning (7 items), (2) Acceptance (11 items), (3) Technology (4 items), (4) Usability (3 items), (5) Immersion (3 items), and (6) Guidance (4 items). Category 1 gauged how VISIR impacted students' ability to further learn theoretical concepts, apply theoretical concepts, and develop useful hands-on skills. Category 2 questioned VISIR's impact on student motivation to learn and complete labs, the similarities between VISIR and hands-on labs, and if students collaborated while using the program. Category 3 assessed the technological reliability of VISIR. Category 4 inquired into students' sense of reality while using VISIR as well as the program's ease of use. Category 5 explored the instructor and manual's success in explaining the labs and aiding students towards lab completion. Finally, category 6 sought whether or not the guidance provided to students during VISIR labs was sufficient.

The free-response questions gave students space to describe what they found interesting (item 33), where they found drawbacks (item 34), and what they would change concerning VISIR (item 35). The last item simply requested the name and email address from any student willing to complete an in-person interview to assess their experience with VISIR in a more detailed setting.

The second portion of our research consisted of semi-structured in-person interviews aimed at obtaining a detailed picture of how individual students performed using VISIR to complete their online labs. Five students from the Fall term 2019 circuits course were chosen based on their survey responses to participate in individual interviews. This group was made up of one mechanical, one biological, one electrical, and two computer systems engineering students. The questionnaire was separated into 3 main categories: (1) Engagement, (2) Learning, and (3) Motivation. The engagement section centered around student focus, feelings of reality, skill transferring, and emotion. The perceived learning portion focused on learning outcomes, skills transferability, user habits, and comparing remote and hands-on labs. Finally, the motivation section was based on the MUSIC model of motivation: empowerment, usefulness, success, interest, and caring [34-36]. For the MUSIC model, there are several questionnaires published and we used those to inform our questions. The questions themselves were posed as open as possible so that the students had enough flexibility to actually tell about their experience. Exemplar interview questions for each of the three categories are shown in table I.

TABLE I. EXEMPLAR QUESTIONS FROM THE SEMI-STRUCTURED STUDENT INTERVIEWS

Interview section	Exemplar questions
Engagement	• "[Tell me, between simulated and real,] How far did you have the feeling to actually do an experiment?", "Was it real?", "Was it only online?" • "While doing the experiment, tell me how your attention/ focus sticked with what was happening on the screen." • What was the most frustrating/disappointing/ fascinating/pleasing/enjoyable…?"
Learning	• "Tell me, what did you learn in terms of concepts?" • "Tell me, what did you learn in terms of hands-on skills?" • "How did you use the lab in terms of time of the day and frequency etc."
Motivation	• "Which components or mechanisms of VISIR promoted a feeling of control or lack thereof when using the program?" • "In how far did the VISIR lab give you properly useful knowledge to interact with circuits in real life?" • "In how far did using the VISIR platform affect your ability to succeed in completing circuits labs?"

Each interview opened with a broad question about the students' overall experience with VISIR, and then questions were asked from each of the 3 categories based on the interviewees' responses. The questionnaire was developed to best answer the posed research question and additionally informed by the survey results. However, we used the interview questions as a semi-structured interview guide for giving orientation during the conversation, but we were open for topics coming up during the interview and adapted the questions accordingly. In addition to these questions, hence, interviewers also paid special attention to new topics of interest and emotions that arose during the interviews. The interviews all lasted between 30 and 35 minutes and were audio recorded for transcripts to be later developed.

B. Participants and Research Context

The VISIR system, survey, and focus interviews were implemented in the beginner level undergraduate circuits class "Electrical Circuits" that is required for students of all engineering disciplines offered at UGA. This paper will display quantitative data from the VISIR research activities during the Spring, Summer, and Fall 2019 terms and qualitative data from additional research activities in the form of focus interviews performed during the Fall 2019 term.

Overall three sections in 2019, 448 experiments (154 in Spring, 140 in Summer, 154 in Fall) have been done by 94 different users (35 in Spring, 36 in Summer, 23 in Fall) in the course context, including students and instructors. The users perform experiments with the VISIR system in the following areas:

- Analog electronic experiments
- Experiment with resistors
- Experiment Ohm and Kirchhoff Laws

V. FINDINGS

In the following we will display the findings from the quantitative research and the qualitative research in two separate sections.

A. Survey results

While answering the survey was not required for students to earn credit, it was highly encouraged and garnered a high rate of participation of 84 responses from all three terms combined, which is close to 90% of the overall class participation. 80 students completed the full survey, making their answers useful for analyzing the data (n=80). The following table II shows the survey results for the closed questions of all three terms combined.

TABLE II. ONLINE SURVEY DIMENSIONS, ITEMS, AND RESULTS (N=80)

	#	Field	Mean	Std Dev.	Var.
learning	1	Using VISIR helped me understand better some issues in the subject.	3.58	1.03	1.07
	2	I tried the experiments several times when I found that the results were strange.	3.85	1.04	1.08
	3	I think I can solve many real electricity problems.	3.44	1.09	1.2
	4	I could use the scientific concepts to explain the results of the experiments.	3.9	0.83	0.69
	5	Using VISIR enhanced my ability to apply theoretical concepts to practice.	3.56	1.05	1.1
	6	Using VISIR strengthened my practical skills.	3.7	1.05	1.11
	7	Using VISIR strengthened my theoretical knowledge.	3.48	1.07	1.15
acceptance	8	I was able to use VISIR 24/7.	4.08	1.14	1.29
	9	*I would rather make traditional experiments than use a remote laboratory like VISIR. (reversed logic)*	3.79	0.97	0.94
	10	I shared the VISIR experiments with acquaintances who do not belong to the college.	1.99	1.24	1.54
	11	I have always shared the results with my fellows.	2.76	1.19	1.41
	12	I was less afraid of damaging the VISIR system than when I work with circuits in the traditional lab.	4.08	1.01	1.02
	13	I carried out experiments which were different from the ones I was allocated.	2.8	1.26	1.58
	14	I wish I had remote labs for other subjects.	3.49	1.28	1.65
	15	I can see similarities experimenting with remote labs as with traditional labs.	4	0.85	0.72
	16	Laboratories like VISIR serve as a complement to hands-on labs.	3.67	1.07	1.14
	17	While using VISIR, I was motivated to continue carrying out the experiment.	3.44	1.13	1.27
	18	I used VISIR more often than I needed to on the basis of the assignment out of curiosity.	2.63	1.23	1.51
technology	19	*I have had many difficulties with the server and VISIR. (reversed logic)*	3.2	1.24	1.53
	20	The response time of the system was adequate.	3.98	0.89	0.8
	21	I *found it difficult to find time to carry out the experiments allocated. (reversed logic)*	2.89	1.13	1.27
	22	VISIR worked without any problems.	2.95	1.22	1.5
usability	23	I think I can handle VISIR well.	3.39	0.98	0.96
	24	I found that VISIR and its devices were easy to use.	3.13	1.1	1.21
	25	Moving between the breadboard page and other equipment and instrumentations pages did not hinder my attention	3.49	1.18	1.4

immmersion	26	I felt that VISIR is real and not virtual	3.1	1.1	1.22
	27	The equipment and instrumentations in VISIR are identical to their real equivalence.	3.41	1.02	1.04
	28	Although I was far from the VISIR (the real system is situated in Driftmier), I felt myself to be in control of it.	3.51	1.11	1.22
guidance	29	The instructions for the experiments were always clear.	3.19	1.26	1.58
	30	I consulted the VISIR manual to learn more about the systems.	3.24	1.27	1.61
	31	I didn't need the assistance of the experiment tutor in most of the activities.	3.26	1.17	1.37
	32	The objectives of the experiment(s) were clear to me at all times.	3.38	1.09	1.18
	33	What have you found most interesting when using VISIR?			
	34	What drawbacks have you found when using VISIR?			
	35	If you could change anything about VISIR and its usage in course contexts, what would that be?			

Even though the standard deviation and the variance are rather high for each of the items, it is still possible to derive insights and tendencies from these results. For the learning category, the most supportive items are #2 and #4. They are not only the highest rated ones, but they also show that VISIR made the students both redo experiments in case of unexpected results and connect their activity with the underlying theory.

For the acceptance category, we want to highlight items #8, #12, and #15. Being able to use the equipment 24/7 is definitely a benefit, and this is supported by the students' responses. Referring back to the VISIR usage dashboard explained earlier, it is safe to say that students appreciate this flexibility and take advantage of it, too. However, students see technology like VISIR as a supplement to the hands-on lab rather than a sufficient lab activity. Likely this could be related to the fact that ability of the VISIR does not cover the ability to provide experiments for all of the materials presented in the electrical circuits course This insight can inform more research on how to combine hands-on and online experimentation in the curriculum to benefit from both hands-on skill development and online flexibility. #12 asked about the fear of damaging lab equipment in real labs but not in the online lab, and we will come back to this point during the interview analysis. Nevertheless, it can be stated here that free experimentation without the risk of breaking equipment does have an impact on how students see this remote lab and the underlying benefits.

The technology category shows that the technical equipment showed some issues and needs to be improved. Except for the item about the response time, all other items show a slightly negative result. We will touch on this during the discussion of the open-ended question again.

The items concerning immersion and usability show a slightly positive result. Even though the technology did show some technical flaws during use, usability is still seen positively. In particular, changing between the different screens in the web-interface seems to be smooth enough. Looking at the immersion category, two aspects stand out. Firstly, the sense of reality seems to be rather low as it is rated as average. Using some kind of webcam could help the user to feel more connected to the physical equipment. However, the sense of feeling of control over the equipment seems to be higher based on the students' ratings, which can be seen positively.

Finally, the guidance category shows an average result as well. This category needs to be seen in context with the course instruction. It is safe to assume that as the lecturer introduces more remote labs to class and more students are guided through the individual activities, e.g. while using VISIR during a face-to-face lab session, the higher the results for the guidance category may become. On the contrary, if an instructor assigns VISIR mostly for self-guided lab work, the students may experience this lack of guidance and rate this category lower. However, we used this result to begin a more detailed discussion with the lecturers on how they implement VISIR in their classes and find a balance between thorough guidance and flexible self-guided activities.

Next, we want to only shortly touch on the open-ended questions as they need to be seen as a course and technology evaluation rather than a research activity. Yet, some of the students' answers still included valuable feedback which also informed our interview study. Item 33, for example, showed that aspects like the level of reality, damage, safe design, and user friendliness are of focal interest for the students:

- *"I find it interesting how similar the virtual lab looks to the actual devices as if it were a real lab."*
- *"Being able to test theories/ideas using VISIR then applying it to the actual equipment was a great way to practice"*
- *"How it is almost identical to the real life substitute. I like that I can try different circuits without worrying about damaging any of the lab equipment."*

On the contrary, the students definitely found some usability drawbacks while using VISIR, mostly on the technical side. Some of them even contradict the results on item 33. For example, answers indicate that having a second layer of technology in the lab leads to more diverse options for failure and makes it more difficult to troubleshoot. The students expressed the following in their answers for item 34:

- *"Almost impossible to troubleshoot. It adds another node of failure. Now I have to worry that the error could be due to a fault or bug in VISIR."*
- *"The version of the oscilloscope we have in the classroom is different at the one the VISIR uses, the first couple of times I used VISIR I had issues putting the new information. I think not seeing clearly how the breadboard is connected to the multimeter and oscilloscope confused me a little."*
- *"It can be unresponsive at times, and the multiple menus are a little off-putting and can be confusing when working with many elements."*

When directly asked for any potential of improvement, the students answered the following (item 35):

- *"If there was some way VISIR, could tell you you did something wrong whether on the breadboard or function generator. It didn't have to answer but gave some form of hint."*
- *"It would be nice to see if certain buttons are pressed, like on the function generator and oscilloscope. Sometimes it's*

hard to tell what I'm changing since the buttons don't display their state."

- *"Making the VISIR labs more complex, possibly more complex than you would make the in-class ones, but the VISIR would make doing them a bit easier."*

Summing up the quantitative portion of the findings, it can be said that the results are positive and supportive, even though there is definitely potential for technical improvements in the system. The results and the feedback from the students showed that VISIR can be used as an online experimentation learning tool in circuits and that students see this as a benefit. Nevertheless, more research is needed here, not only about VISIR but also to develop a tested and validated tool. Even though the survey questionnaire has been applied in this or similar forms to other studies, the derivable findings are still somewhat limited. There is a desperate need for a more thoroughly developed tool. The lack of such a tool needs to be seen as a shortcoming for the described study as well. This was part of the reason why we complemented these results with an interview study. These results will be explained in the following.

B. Interview Results

Once coding up from the qualitative data began, the most prominent findings categories became collaboration and learning outcomes. While qualitative data was still collected for engagement and motivation, the transcripts revealed more useful data on these main 2 categories. Other developed parent nodes included technical function and troubleshooting. For the purposes of this paper, we will focus on the above-mentioned most prominent categories.

1) Collaboration

Collaboration was coded into positive and negative instances within VISIR labs. Positive instances occurred when students' collaboration helped them complete a lab or achieve a learning outcome. Negative instances occurred when students' collaboration prevented them from completing a lab or achieving a learning outcome.

a) Negative Hands-On Collaboration

- *Student 1: "Most of the time when I am working in groups, I've noticed that only one person is actually doing anything to begin with."*
- *Student 2: "sometimes it did feel a little bit awkward, because my lab partner would be sitting there while we were trying to figure out if I was plugging it in right"*

b) Positive Hands-on Collaboration

- *Student 2: "It's a little bit easier to build a circuit together in real life, or to feel like there's more teamwork involved, because it's like, 'I'll start setting up the wires while my partner goes to get the resistors.'"*
- *Student 3: "I'm an independent worker but for these labs or these types of labs, it really helps to have more than one person. Because you can have one putting things together and the other one hooking up the cables and then someone else is typing what you're doing. So just dividing but still doing everything together helps things go along a lot smoother."*
- *Student 4: "Yeah, I think group work is a lot more beneficial in circuits, rubber ducking and stuff. If you can't figure something out, maybe your partner can."*

c) Negative VISIR Collaboration

- *Student 1: "I think it would've been one person dragging and dropping and the other person watching and trying to figure out what's going on."*
- *Student 2: "…if we were in separate places, I feel that would be where things would start to go wrong… just because stuff like that is easier when you can physically talk with each other."*

d) Positive VISIR Collaboration

- *Student 1: "It would probably have to have also some form of communication built into it to be able to talk to the other person… that could actually push collaboration to be more cohesive than in-person working together because a lot of the issues is generally that there's only so much space to be in front of to actually work on it. If both people are able to access the breadboard and the tools equally easily without being in someone's way, that could actually end up helping for a collaborative environment."*
- *Student 3: "With the VISIR, we actually did the three-way FaceTime… we could all try different methods of doing a certain example problem. We could all have something different at the same time, so it's like three different breadboards. Instead of like in class you'd have one breadboard…"*

It's important first to recognize that these responses can be used to fit two different conclusions. Students 2 and 3 initially offer clear support for hands-on labs because their positive experiences with teamwork were predicated on the division of labor. They are holding efficiency as paramount over collective learning outcomes within the group. Further responses from students 1 and 2 show a deeper skepticism of how VISIR could replace in-person interactions while maintaining sufficient empathetic connections that make teamwork successful. If these are the primary statements extracted from the interviews, VISIR may not be a viable option for remote collaboration.

Student 1, on the other hand, views division of labor as a hindrance to collaboration. From his perspective, lab partners performing separate tasks cuts the group's learning outcomes short because the student gathering supplies isn't present enough to learn how to breadboard too. One student must physically leave the learning atmosphere to complete an administrative task, rather than absorb information about how the system works. Student 1 also says that collaboration would not be enhanced with a remote system because the construct of 'one person does one task at a time' remains the same. While this perspective does not confirm VISIR's potential, it does open the strain of doubts concerning hands-on labs' viability in promoting collaboration.

Student 3, without any prompting, demonstrated the very vision of remote collaboration by connecting with his lab partners via FaceTime and completing the lab by comparing results from their perspective virtual breadboards. Student 1 offers support of the same scenario after hearing its description during the interview. Not only does student 3's experience confirm the possibility of collaboration from a remote setting, but it also presents a solution to spatial shortcomings within hands-on labs. Each member of the lab group was able to view and work on their own breadboard without leaving to gather components. This instance supports the antithesis of the first conclusion. As educators, we must first define expectations for the collaboration outcome before drawing analysis from the data.

Collaboration can be defined as working with someone to complete a task. If our perspective is viewing the whole lab as the task, then a hands-on setting provides the space to collaborate. Lab partners are working together to complete the assignment. For example, one student may place the components on the breadboard while another student records reading from the multimeter. However, if our perspective is viewing actions within the lab as the task, then hands-on labs appear to fail at providing the space for students to collaborate. With VISIR, students may format their interactions to work simultaneously on separate computers to complete a single task. Even if one student is following the same instructions they would have received while watching a hands-on lab, they would still be able to place components on the breadboard themselves. This action promotes improved participation and transferable hands-on skills.

2) Learning Outcomes

Learning outcomes contained prominent codes for a fear of breaking equipment and acquired hands-on skills. The first category was an unexpected result that led to valuable insights. Students within this introductory level circuits course are often younger and less experienced than the rest of the college, and they may carry a consequential hesitancy into the classroom. If the fear of breaking equipment can be mitigated, students may feel more freedom in pursuing an understanding of new equipment and systems. The second category is arguably one of the most important outcomes for VISIR implementation. The skills learned during a remote lab must be transferable to the physical, hands-on world. The responses offer both useful criticism and encouragement for how VISIR was utilized in this course.

a) Fear of Breaking Equipment

- *Student 1: "I didn't have the fear of ruining equipment because I knew that it wouldn't let me do anything incorrectly."*
- *Student 2: "I was less worried about breaking stuff in the virtual one, because if I was going to break something it just wouldn't let me do it… sometimes if we were working with diodes, especially an LED, we were worried that we would accidentally set it up wrong. We'd short out the LED and break it. But in the virtual one, it's not like we can break an LED, because it just won't let it go through."*
- *Student 5: "I'm that kind of person that I always break something. So in class, I was always scared of doing something wrong and damaging the machine. So with [VISIR], I feel more confident of not messing anything up because basically if I did something wrong, it wouldn't do anything… I don't have a lot of experience putting things together, so I feel like that's why I'm scared of breaking things or messing them up… if it worked in the virtual lab, it's going to work in real life."*

The fear of breaking equipment was not a response we expected to receive during the interviews, so the topic was not directly included in any sample question prepared beforehand. Instead, all three students described this fear without solicitation. This anxiety surfaced as crucial to our qualitative research because it marks an emotional and physical turning point for students triggered by VISIR. Students 1, 2, and 5 experienced hesitancy within hands-on labs because they lacked experience in putting circuits together. VISIR, however, provided an environment where the students could test theories, schematics, and components without the hindrance of breaking equipment. Student 5 specifically recounts how copying her lab partners breadboarding on VISIR during a hands-on lab gave her the necessary confidence to complete the breadboarding herself. VISIR's remote environment served to mitigate these students' fears and enable them to act confidently in the physical world. In addition, it is important to recognize that new students are indeed much more likely to break lab equipment than those conducting a senior design project. If VISIR is made more widely available to introductory circuits classes, this could be an avenue towards further cost savings.

b) Hands-On Skills: Negative Transferability

- *Student 1: "I noticed what should have been hands-on similarities. It's just that the VISIR tools were very different from what we actually have on campus here... A lot of test bench equipment has a very steep learning curve… but because different companies do things so differently, you have to relearn it every time. Because the [VISIR] software wasn't the same as what we actually have on campus to work with, we had to relearn a lot of test equipment to be able to use the [VISIR] lab."*
- *Student 2: "When you're at home, and you don't have a TA or a teacher, it can be sometimes really difficult to figure out what you're doing wrong… It was definitely easier to learn the basics in real life because you are able to get a feeling of what goes where and why."*
- *Student 4: "I learned more in the physical lab because there are more modifications we can make to the circuit. We have more components that we can use and different ways to measure things. Because we have more tools to access in our lab, it's easier to design labs based on that."*
- *Student 5: "I think one of the outcomes by using the physical stuff in the lab was it was easier for me to use a oscilloscope in class than using it in the virtual lab."*

c) Hands-On Skills: Positive Transferability

- *Student 1: "So a lot of what we did through VISIR was the electronics basics that we had covered in previous classes… It was more of learning to adapt to using new tools than it was actually learning the material… it wasn't strictly difficult to learn the [VISIR] equipment. It was a learning opportunity to see if you're in an environment that has a different set of tools, you need to be able to adapt quickly to use the tools available in that setting"*
- *Student 3: "When working with the op-amp in [VISIR], because of the repetition with all the different inputs, [VISIR] helped me just because you were able to do it over and over again. If you were doing it in the classroom and hands-on lab, it would take a lot longer. That repetition helped me understand where everything goes… because after that, we*

actually had a hands-on lab using the op-amp... we were able to get set up a lot quicker than if we hadn't been exposed to that [in VISIR]. I also think that if you were trying to get someone comfortable with just using a breadboard, someone just starting out in circuits doesn't know what it even is. If you had them play around for like 10 or 20 minutes with [VISIR], I think they could definitely be like 100% comfortable using a breadboard.

- *Student 4: "It was pretty easy to go from VISIR to the physical breadboard… The output is pretty identical, give or take, to the physical implementation."*

In order for VISIR's implementation to be marked with success, there must be evidence of learned hands-on skills as students move from using VISIR to hands-on labs. The above responses have been coded into negative and positive transferability to separate instances where students absorbed useful hands-on skills and when they felt VISIR fell short of this outcome. Student 1 identifies learning VISIR's lab setup as negative because its degree of similarity with their hands-on setup was too small. If VISIR was to be successful in transferring hands-on skills, he would have learned more about his hands-on setup during the remote lab. Students 2, 4, and 5 all carry a similar tone in describing how the hands-on labs had more resources from which to learn. In other words, these students' perception implies that the scope of VISIR's learning environment was too narrow. They felt more control over the hands-on the breadboard and test equipment.

In contrast, a circuits class's curriculum may become more robust as students gain exposure to multiple types of test equipment. Pushing students to specialize at an early stage has few positive benefits, especially at this introductory level. As the real world is a rapidly changing setting, requiring students to learn new equipment will enforce valuable hands-on skills. Student 1 later supports this claim by describing how he learned adaptation skills by using both the hands-on and VISIR systems. An increased ability to adapt will simultaneously cultivate creativity and problem solving skills, both of which are crucial strengths in a hands-on environment. Student 3 recounts how the opportunity for repetition within VISIR enabled him to complete a hands-on op-amp lab more efficiently and independently. This perspective points towards VISIR's employment as a training device rather than a substitute for hands-on labs. Student 4 provides further corroboration by observing how the output results were sufficiently similar between both modes. If the outputs are similar, educators and students can be more confident that the skills they learn using VISIR will transfer to physical labs.

VI. Discussion and Future Research

Our quantitative research data indicates positive, encouraging results towards our implementation of VISIR. Students repeated experiments following unexpected results, giving them increased exposure to both breadboarding components and the application of underlying theory. Students took consistent advantage of VISIR's 24/7 availability by completing labs outside their designated class times and away from the physical lab setup. We understand students' perception of VISIR's best use to be a supplement rather than a replacement for hands-on labs. While this may carry negative connotations for VISIR's viability within the core of engineering education, it makes point towards a very real and valuable use for the program: training on new equipment. The survey responses indicate a smooth transition from remote to physical lab equipment, while student immersion could be improved by video communication with lab partners or a lab assistant. The technology category received average ratings for connectivity with the server and VISIR, difficulty completing VISIR labs in a timely manner, and general problems while using the program. While the quantitative nature of these results does not point towards a direct solution, it can be assumed that software upgrades and IT support deserve attention in future use.

The qualitative data from our interviews offers deeper insights into these topics and more. Collaboration rose from the transcripts as a crucial topic of interest, and while student responses can be viewed as positive, there is ample room to improve. Some students perceived hands-on labs as the perfect atmosphere for collaboration because they could apply division of labor to complete labs efficiently while letting experienced students lead the technical tasks. However, this arrangement does limit inexperienced students from getting sufficient exposure to employing technical hands-on skills. VISIR presents an opportunity for students to work separately on the same task so each lab partner completes each step individually. This collaborative arrangement would be best facilitated by using webcams to connect students taking advantage of VISIR's remote availability. Students with a fear of breaking equipment were definitively able to mitigate their hesitations by first using VISIR. This again points towards the program's viable use as a supplemental training system. Students gave mixed responses towards VISIR's transferability of hands-on skills. Some students felt strongly that a physical setting was the most beneficial environment to learn tactile skills and understand real components. However, other students recognized how the advantages of adapting to a new system mirrors requirements of the real world, and, hence, VISIR developed valuable real-world skills. These qualitative results have considerable correspondence with our quantitative results, indicating reliability within the deeper insights provided by the in-person interviews.

Based on this discussion, future research should focus on collaboration, feelings of control, and feelings of reality. As seen from the data, collaboration could be improved by increased communication between lab partners from remote locations. One interviewee did employ this arrangement and gave positive feedback for its viability. Feelings of control could be improved by enabling VISIR to provide more specific error messages as to why a system garners an unexpected result. An alternative and/or simultaneous solution would be providing ready guidance in the form of a lab assistant or instructor who has screen sharing abilities with the student. Feelings of reality could benefit from VISIR's system more closely resembling the appearance of their familiar hands-on setup. In addition, increasing tactile responses within the software could improve their sense of reality. Students' suggestions for this improvement include more rotating dials, pressable push-buttons, and audible feedback.

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