Are Remote Labs Worth the Cost?

Insights From a Study of Student Perceptions of Remote Labs

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Abstract—**Remote online laboratories enable students to conduct scientific investigations using real experimental equipment. However, scaling up remote labs may require significant costs in purchasing and maintaining expensive equipment compared to scaling simulated labs. While these costs are a consequence of using physical equipment, we argue that there are unique educational advantages to remote labs. This paper presents the results of a preliminary study of student perceptions of a remote lab in comparison to an identical lab experience with simulated data. The findings reveal several intriguing themes that highlight the pedagogical value of remote laboratories. In addition, we provide recommendations for the design and pedagogy of online laboratory experiences based on our findings.**

Index Terms—**Education, Design, Remote Online Laboratories, Simulations**

I. INTRODUCTION

There continues to be significant debate regarding the relative value of remote, simulated, and hands on labs in science and engineering education [1,8]. However, efforts to scale up availability of large numbers of remote laboratories to serve tens or hundreds of thousands of users are still in their infancy and little empirical data exists on the actual costs of providing online laboratory access at scale. Critics correctly point out that scaling the experimental hardware required is inherently more costly than scaling up simulated lab experiences. The essential question is: Are remote labs worth the cost?

Answering this question in terms of financial costs is an area of active research and a focus of the newly formed Global Online Labs Consortium (GOLC). But beyond a strictly financial answer, we must also consider the question from the perspective of pedagogical value. Specifically, are there unique educational benefits for students in using a remote lab compared to a simulated lab? While we await more conclusive data on financial costs, we can begin to consider the *educational affordances* that remote labs provide and factor this into the value proposition for remote labs.

In this paper we describe the results of a preliminary study comparing students experiences using two online labs: a remote lab and a simulated lab presented through identical user interfaces. In comparing these two modalities, we explore the perceptions and understandings that students have about remote and simulated lab experiences and the educational affordances each provides. We conducted in-depth interviews after the use of each type of lab experience to probe students' perceptions as well as their understanding of both science content and process related to the lab. In uncovering their understandings and misconceptions we identified a number intriguing benefits of remote labs, including that conducting real experiments affords increased opportunities for inquiry, personal investment, trust, and ownership in their lab experience. These findings point to important considerations in evaluating the pedagogical value of remote labs. Additionally, based on our findings, we suggest guidelines for the design and deployment of remote lab experiences in educational settings.

II. AUTHENTIC SCIENTIFIC INQUIRY

From a cognitive and learning sciences perspective, perhaps the most compelling argument for remote labs is that they can support the development of more epistemologically-authentic student inquiry and scientific reasoning skills. Analyzing pre-college science education in the U.S., Chinn and Malhotra [2] found that "the cognitive processes needed to succeed at many school tasks are often qualitatively different from the cognitive processes needed to engage in real scientific research" and that "the epistemology of many school inquiry tasks is *antithetical* to the epistemology of authentic science" [2]. Schools lack the resources to reproduce authentic scientific inquiry tasks and instead replace them with *school inquiry tasks*, "simpler tasks that can be carried out within the limitations of space, time, money, and expertise that exist in the classroom" [2]. Remote labs hold the promise of overcoming many of these constraints, and–by providing students with the opportunity to engage in more authentic scientific inquiry tasks–result in the development of epistemologies that are better aligned with those of authentic science (i.e., a "sophisticated, constructivist epistemology" [3]).

But do remote labs actually support students in the kinds of authentic scientific inquiry skills that we hope to foster? What about simulated labs? These are the questions our study seeks to address.

III. OUR REMOTE LAB

We have developed a remote online laboratory called the Radioactivity iLab (RAL), which included curriculum and teacher materials for a 5-day investigation. The remote lab allows students to remotely control a Geiger counter to measure radiation being emitted from a sample of radioactive strontium-90.[1] The actual equipment is housed at the University of Queensland in Australia. The goal of the lab is to allow students to observe and experimentally derive the inverse square law. After conducting

[1] Visit http://ilabcentral.org/radioactivity to review the RAL curriculum materials for physics and adaptations to four other courses.

the RAL experiment, students use their data to mathematically describe the relationship between radiation intensity and distance.

The remote lab interface embeds instructional scaffolding to help students develop good experimental design and data analysis skills. Students engage in a structured inquiry process using an online "lab journal" (on the right side of Fig. 1) that provides instructions, readings, and metacognitive prompts [4, 5]. Experimental data, graphs, and responses to these prompts are saved as a PDF for students to submit to their teacher at the conclusion of the lab. At the lower left side of the interface are controls students use to design an experimental run, specifying the distances at which to measure radiation, the duration of each measurement, and the number of trials to run with these settings. On the upper left side of the screen are visualizations including an interactive Flash animation depicting how the device moves when controlled remotely and a live webcam view of the device as seen in Fig. 2. The student's experimental design variables are then sent to the remote device, the experiment is run, and results sent back to the student for analysis. Because this is real data, each student's results will differ depending on his or her experimental design (and from trial to trial).

In a separate large-scale efficacy study of the use of the RAL in high school science classes among 20 teachers and 949 students, across five states in the United States, and in both in-person and virtual classes, we found significant ($p < 0.0001$) pre/post learning gains in both science content (21% gain; 1.03 effect size) and scientific inquiry skills (8% gain; 0.37 effect size).

II. COMPARATIVE STUDY

We conducted a preliminary study to provide some baseline data and inform the design of subsequent, more detailed experiments. Subjects were randomly assigned to one of two conditions. One group experienced the remote lab, while the other group experienced a similar online lab using only simulated data. Both the remote and simulated lab conditions had the same web interface, except that the simulated lab condition did not include the webcam view of the equipment. In addition, the simulated lab returned data to the user immediately, while data in the remote condition took several minutes to obtain from the device, depending on the subject's experiment specifications. The simulated lab generated experimental data by using a mathematical model of the inverse square law and intro-

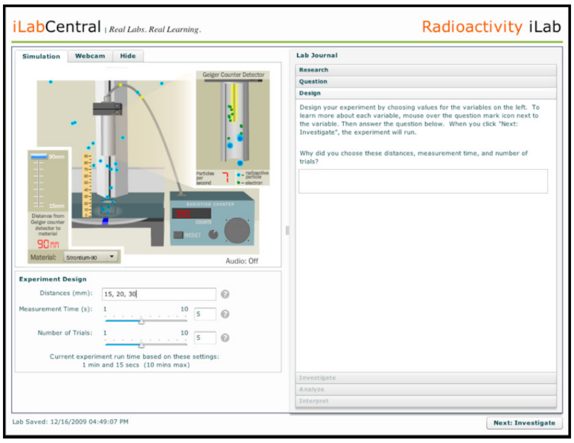

Figure 1. The design step of the Radioactivity iLab.

Figure 2. Live webcam view of Radioactivity iLab.

duced randomized error across all measurements to mimic sampling error seen in real data.[2] This randomized sampling error produced slightly different results for each experimental trial. All subjects were prompted to write reflective responses throughout the lab in the online lab journal that was part of the web interface, and then were asked structured interview questions upon completion of the experiment. In addition, to assess if the subject had any content or process learning gains from the lab experience, we administered identical tests before they conducted the online lab and immediately after completion of the lab.

Subjects were recruited from a pool of undergraduate students in an introductory psychology course at Northwestern University. We tested 11 undergraduate students and 1 post-graduate student. All subjects were tested at a laboratory at Northwestern University. 92% of the subjects had taken introductory high school physics, 25% had taken AP Physics, and 17% had taken college-level physics. Six students participated in each experimental condition. Prior to conducting the lab, students were informed about the type of lab they would be performing, either a remote or simulated lab.

Participants were briefed by a facilitator and then instructed to use the web interface to interact with either the remote or simulated lab. The facilitator was in the room with the participants and followed a script while interacting with participants. Participants' comments were audio recorded and transcribed. We analyzed participant comments and coded for common themes mentioned by participants.

III. KEY FINDINGS AND IMPLICATIONS

In this preliminary set of data, we analyzed and discovered five themes that emerged from interviews and lab journal responses: authentic affordances for inquiry, feelings of reality and presence, trust of data, perceptions of ownership and control, and preference.

A. *Authentic Affordances for Inquiry*

There appear to be more intrinsic cognitive affordances for inquiry provided by a remote lab than a simulated lab, particularly regarding student understanding of potential

[2]The simulation of the RAL was developed by Len Payne and his colleagues at University of Queensland in Australia.

bias or error in data. Subjects who experienced the remote lab directly addressed the presence of error in their data, whereas subjects who experienced the simulated lab did not. In response to a lab journal prompt asking about their initial observations of their data, 33% of subjects who conducted the remote lab referenced error. One subject wrote, *"The particle counts do decrease a lot at first, and less as the distances increase. In the farthest distances, there are some discrepancies to this but it is probably just a natural error.*"

In the simulation condition, although subjects were presented with experimental data exhibiting substantial variance, many subjects stated that simulated data does not produce errors. In addition, subjects expressed their belief that the simulated lab would return the same exact results for every experiment run despite the fact that their results demonstrated that these simulated models produced variability. One subject in the simulated lab condition said, "*It's not actual data so there's no variability and if you're just going to get the same results every time, even though in real life, I think, there should be some variability in your data.*" As a result of these misconceptions, subjects felt satisfied with their data analysis and did not feel compelled to question or validate their data with additional experimental runs.

In the remote lab condition, subjects' awareness of the error and variability in their data as well as in the experimental equipment naturally led them to question the reliability of their experiments. This trend in student responses suggests an interesting difference between the conditions. **Subjects in the remote lab condition more naturally questioned their results, demonstrating the authentic affordances for inquiry and understanding biases in data provided by a remote lab.** Subjects who experienced the simulated lab didn't seem to think about possible sources of error in their data. This finding is consistent with the results reported by Lindsay and Good [8]. From a learning design perspective, it is preferable to create learning situations that authentically generate appropriate student questions versus tasks that do not spark such curiosity. These results show that remote labs seem to more naturally evoke student inquiry into possible error or bias in experimental data than an identical simulated lab.

B. Feelings of Presence and Reality

Subjects in the remote lab condition perceived the lab as being real. For these subjects, **viewing the experiment on the live webcam made them feel like it was a real hands-on lab**. One subject said, *"I actually experienced it,*" in reference to her experience with the experiment. Another subject said, "*Just seeing the experiment being performed, I knew it was actually happening.*" A third subject said, "[The webcam] *gives a more tangible object when you actually see it happening in front of you, so it's like you're there.*" These findings directly address the concerns that a remote lab experience is somehow "less real" to students than a hands-on lab.

C. Trust of Data

Subjects in both conditions expressed the belief that data from a remote lab is more trustworthy or reliable than data derived from a simulated lab. When a subject was asked if he would trust his data more in a remote lab or a simulated lab, the subject said, *"I would be more inclined to trust the one that I can see moving up and down – the non-simulation – because when you see something, you know it's actually happening the way you want it to happen.*" Another subject said, "*I'd have to trust it more [in a remote lab], since it's real. Because I don't know where this data came from [in the simulated lab], but I know that that data [in the remote lab] came from the Geiger counter.*" A third subject said, "*It seems like it's [remote lab] more of a reliable source – whereas if you use the computer system then you have to rely on the people who programmed the computer system and hope that they knew what they were talking about when they did it.*" Subjects conceived of simulated labs as "black-box" artifacts whose outputs could be readily manipulated. These intuitions also caused them to assign greater validity to real labs because of the immediacy and ability to witness the procedures that lead to the generation of data.

D. Perceptions Ownership and Control

Subjects in the remote lab condition exhibited perceptions of ownership and control over their experiment – a sentiment that was not replicated in the simulated lab condition. One subject who did the remote lab said, "*When I did this experiment, I felt like I personally took part in it. But for [a simulated lab], I'd probably feel more detached in the experiment. It would kind of be like 'oh we did a fake lab today'.*" Again, we observed that subjects felt a greater sense of immediacy in the context of remote experiments than simulated experiments. Another subject said, "*With the [remote lab] you kind of felt like it was hands-on, because you were really controlling it. I guess you wouldn't feel a high level of control with [the simulated lab].*" The ability to manipulate objects, even indirectly and at a distance, suggests that the ability to personally control an experiment may heighten subjects' immersion and sense of ownership over the experimental process and resulting data.

When subjects who conducted the simulated lab were asked about how doing a remote lab would be different from their experience with the simulation, they said that they would take the remote lab more seriously, it would feel more important, there would be more responsibility associated with the lab, it would be more satisfying, and there would be more of a sense of purpose when doing the remote lab. One participant noted, "*I'd feel like I actually did the experiment and not just for learning, but I actually did it and acquired results*." Therefore across both conditions, subjects associated the remote lab with a more personal and meaningful experience compared to the simulated lab. **Knowing that an experiment is happening with real equipment under the student's control creates a personal investment and desire to ensure high quality data.** This is a critical benefit in crafting high-quality educational laboratory experiences for students because it fosters a heightened sense of ownership for the experimental data. These feelings of care and ownership appear to be important precedents to students' more critical analysis of the quality of their experimental results.

E. Student Preference

Four subjects in this study (three simulated lab and one remote lab) were asked explicitly about their preference in type of lab between remote and simulated. All four reported that they would choose a remote lab over a simulation. When asked which type of lab they would prefer, one subject said, "*Definitely the remote online lab because it's* *more like a real experiment.* ***I think science is always better when you experience it for yourself, like first-handedly.*** *Even though it isn't really first-handedly, it is more so than a simulation."* Since subjects only directly experienced one condition in the study, these preference results will need to be validated in a subsequent study that exposes subjects to both conditions. However, these results do indicate an apparent preference for an online lab experience where real experimental data is being obtained.

IV. DISCUSSION

The Radioactivity iLab used in this study is a relatively simple experiment. As discussed next, this simplicity is both beneficial and, at the same time, may limit extrapolation of the findings to other types of more complex remote laboratory experiences.

The Geiger counter moves in a single dimension away from the source emitter and the students use three parameters to design their experiment (i.e., measurement distances, time of measurement, number of replication trials) (Fig. 3). (Actually, selecting measurement distances constitutes two separate design decisions: the number of distances to use and the exact distance of each measurement.)

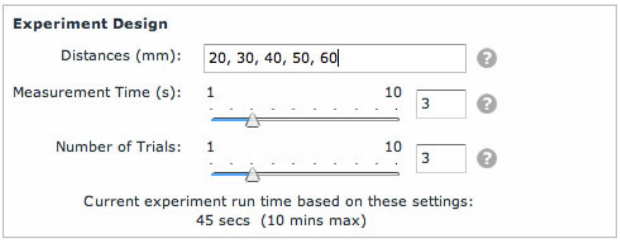

Figure 3. The RAL experiment design interface.

This simplicity is advantageous in that it allows us to study student reactions in both remote lab and simulated conditions without requiring extensive coaching and pre-lab preparation. It also makes it more straightforward for students to understand what they can manipulate in the design of the experiment and how the remote device operates. From an educational research standpoint, having only three parameters makes it easier to study how students' experimental design skills improve from trial to trial as they use the RAL in their courses.

Further, the data produced by the experiment is also relatively straightforward to view and interpret (see Fig. 4). Variability in results is (or should be!) quite easy to notice, and is very consistently obtained (getting identical results from trial to trial almost never occurs). This makes the RAL an ideal vehicle for exposing students to the important concepts of experimental design, sources of error and variability, data analysis, and interpretation.

The RAL is conducted in an asynchronous fashion. That is, students submit their experimental run, which gets queued up and executed by the lab device when it becomes available. Other remote labs are controlled synchronously, with students manipulating the remote device in real-time. This aspect of RAL is important to keep in mind in generalizing the results of this study. However, even given the absence of direct, synchronous control in RAL, we found students feeling high degrees of control and ownership. One would anticipate that synchronous remote lab interactions would only enhance the strength of these effects.

Distance (mm)	Trial 1 (particle	Trial 2 (particle	Trial 3 (particle counts)
20	189	197	188
30	107	86	103
40	65	77	67
50	52	59	34
60	30	32	37

Figure 4. The data returned from a RAL experimental run.

Another aspect of the RAL remote lab to consider is that the device does not require the student to calibrate it prior to an experimental run. Other remote labs, including for example, the MIT Neutron Beam Lab[3], and a new inductively coupled plasma (ICP) optical emission spectroscopy lab we are developing at Northwestern University, require calibration activities as part of the experimental process. Whether the additional care that must be taken to insure high quality data from remote labs that require calibration enhances or reduces students' feelings of ownership of the data and a desire to insure its quality, remains to be studied. Simulated labs typically do not require analogous instrument calibration steps to insure accurate data output (unless this is specifically part of the simulation design as in [8]), so one would anticipate this difference to play a more pronounced role in a comparison of remote and simulated labs where calibration is required.

V. RECOMMENDATIONS FOR DESIGN AND PEDAGOGY

The key findings described above suggest a number of implications for the design and pedagogy of remote and simulated labs. Both remote and simulated laboratory experiences play important pedagogical roles in science and engineering education. These results and guidelines are not intended to elevate one approach at the expense of the other. Rather, our view is that each type of online laboratory experience involves unique tradeoffs, and that designers and instructors deploying online laboratories would benefit from a deeper understanding of both the strengths and limitations inherent in each online laboratory modality. These insights can be used to better exploit advantages of an online laboratory as well as compensate for or avoid potential weaknesses (as also recommended by Lindsay and Good [8]).

A. Differential Scaffolding Burden

The misconceptions that subjects have about simulated data points out a clear need to explain all the factors that are involved in producing simulated data. Additional instructional scaffolding and explanation is needed in order to successfully teach students about scientific experimentation when using simulated data. Teachers, as well as curriculum materials, need to support students' understandings of simulated labs to characterize simulated data as a model of real data, which can include error. This need for scaffolding will necessitate extra instructional time as well as clear teacher materials that ensure that appropriate attention is paid to this issue.

B. Transparency of Data Collection

When designing the online experiment experience, transparency of how the lab experiment system operates—

[3] http://norbert.mit.edu/Reactor

whether real or simulated—is important in establishing credibility of the system. In the remote lab condition of our study, the webcam was critical in convincing students that the experiment specification that they designed was controlling the Geiger counter. Watching the webcam also enabled subjects to believe that they were the ones actually conducting the experiment despite the instrument being proximally controlled by a computer.

For simulated labs, the way in which the simulation actually generates and calculates data needs to be transparent to students so that they have an understanding of how their data is generated, instead of making assumptions that can hinder their understanding of their data and experiment. In other words, procedural transparency is important to validate the experiment in the eyes of student users.

C. *Highlighting Variability and Error*

In our remote lab interface, we scaffold the lab experience by asking students reflective questions at every step. Because of students' lack of awareness of error and variability in data returned by simulated labs, educators may need to prompt students to think about this when conducting a simulated experiment. Similarly, simulation developers may design the user experience to explicitly highlight the source of the simulated experimental data and lead students to more effectively question their results.

VI. FUTURE WORK

Future studies will further examine these and other emergent themes from our findings. These studies will include a scaled-up version of this study, an examination of what makes a remote lab feel real, and an exploration of additional visualizations to further scaffold the online laboratory learning experience for students.

A. *Scaled Study*

To conduct a more in-depth, quantitative analysis of the findings reported here, we are following up the present study with a larger sample of subjects and a more targeted examination of our key findings. This scaled-up study will follow the same experimental design as the current study with subjects split into two conditions of remote and simulated labs.

B. *Assessing the realism of remote labs*

Subjects in the remote lab condition expressed feelings of presence and reality, which contributed to their belief that they were experiencing a hands-on lab. However, not all the remote lab subjects were initially convinced that the lab was connected to a real device. One subject said, "*I don't think that my information was being sent to Australia and that there is a machine there interpreting my data.*" Future work in this area should examine the factors in which remote labs convey realism and immediacy so as to promote immersion and engagement. Our work already demonstrated that the use of even a low-resolution, high-latency webcam substantially promoted subjects' immersion and engagement.

C. *Additional Visualizations to Scaffold Experience*

In designing remote laboratories for education, simply providing access to real experimental equipment is not enough. Doing so requires a carefully designed learning experience, supported through a sequence of appropriate explanations, visualizations, and interactions [4, 6, 7]. Future research will also examine how visualizations provided to the student in the lab user interface affects the emergence of our key findings from this study. For example, in adding an animation of the Geiger counter and the invisible particle-emission phenomenon before students design their experiment, we anticipate a difference in learning outcomes between students that encounter the animation and students that do not. From this research, we also plan to develop a set of recommendations for the types of explanations, visualizations, and interfaces that are needed to best scaffold student understanding of scientific phenomena using a remote online lab.

VII. CONCLUSION

Despite the physical distance between users of remote online laboratories and the experimental devices, our findings suggest that the interaction with real equipment and real data in remote labs affords for more authentic inquiry, trustworthiness of data, a greater personal investment, a sense of presence and reality, and a stronger preference for remote labs than performing a similar experiment with simulated data. Subjects naturally associated remote labs with real error, and therefore acknowledge, analyze, and reason about the variability in their data. They instinctively trust data from remote labs because they perceive the experiment as being real, and take a greater sense of ownership and control in their experiment in a remote lab setting. In contrast, misconceptions of simulated labs can inhibit questioning of data and successive experimental runs to validate results.

This study showed that students using remote labs seemed to more intuitively understand and trust many of the basic aspects of experimentation that encourage thoughtful inquiry, data analysis and interpretation. Remote labs provide authentic affordances for understanding the role of error and variability in experimental data, giving students a platform for inquiring about scientific phenomena and, perhaps more importantly, about the scientific process. While simulations may provide a more cost-effective solution to conducting experiments online, our findings point to the need for additional pedagogical support and careful user experience design to successfully utilize simulations as tools for teaching scientific inquiry skills. In fully evaluating the relative costs and benefits of remote and simulated labs as educational tools, our findings indicate the need to factor into the calculation the many sources of "pedagogical value" provided by remote labs.

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REFERENCES

[1] J. Ma and J.V. Nickerson, "Hands-on, simulated, and remote laboratories: A comparative literature review," *ACM Computing Survey*, vol. 38, no. 3, pp. 7, September 2006. doi:10.1145/1132960.1132961

[2] C.A. Chinn and B.A. Malhotra, "Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks", *Science Education*, vol. 86, no. 2, pp. 175-218, February 2002.

[3] C.L. Smith, D. Maclin, C. Houghton, M.G. Hennessey, "Sixth-grade students' epistemologies of science: The impact of school science experiences on epistemological development", *Cognition and Instruction,* vol. 18, no. 3, pp. 349-442, September 2000. doi:10.1207/S1532690XCI1803_3

[4] B. Loh, B. J. Reiser, J. Radinsky, D. C. Edelson, LM Gomez, and S. Marshall, "Developing reflective inquiry practices: A case study of software, the teacher, and students", in *Designing For Science: Implications from Everyday, Classroom, and Professional Settings*, K. Crowley, C. Schunn, and T. Okada, Eds. Mahwah, NJ: Erlbaum, 2001, pp. 247-286.

[5] C. Quintana, B.J. Reiser, E.A. Davis, J. Krajcik, E. Fretz, R.G. Duncan, E. Kyza, D. Edelson, and E. Soloway, "A scaffolding design framework for software to support science inquiry", *Journal of Learning Sciences,* vol. 13, no. 3, pp. 337-386, July 2004. doi:10.1207/s15327809jls1303_4

[6] National Research Council, *America's Lab Report: Investigations in High School Science.* Washington, DC: The National Academies Press, 2006.

[7] K. Jona and J. Adsit, "Goals, guidelines, and standards for student scientific investigations", North American Council for Online Learning, June 2008. [Online]. Available: http://www.inacol.org/resources/docs/NACOL_ScienceStandards_web.pdf:

[8] E.D. Lindsay and M.C. Good, "Effects of Laboratory Access Modes Upon Learning Outcomes," *IEEE Transactions on Education,* vol. 48, no. 4, pp. 619-631, November 2005. doi:10.1109/TE.2005.852591

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