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Enhancing distance learning of science—Impacts of remote labs 2.0 on students' behavioural and cognitive engagement

Shannon H. Sung[1] | **Chenglu Li**[2] | **Xudong Huang**[1] | **Charles Xie**[1]

[1]Institute for Future Intelligence, Natick, Massachusetts, USA

[2]School of Teaching and Learning, University of Florida, Gainesville, Florida, USA

Correspondence
Shannon H. Sung, Institute for Future Intelligence, Natick, MA 01760, USA.
Email: shannon@intofuture.org

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Abstract

Background: With the increasing popularity of distance education, how to engage students in online inquiry-based laboratories remains challenging for science teachers. Current remote labs mostly adopt a centralized model with limited flexibility left for teachers' just-in-time instruction based on students' real-time science practices.

Objectives: The goal of this research is to investigate the impact of a non-centralized remote lab on students' cognitive and behavioural engagement.

Methods: A mixed-methods design was adopted. Participants were the high school students enrolled in two virtual chemistry classes. Remote labs 2.0, branded as Telelab, supports a non-centralized model of remote inquiry that can enact more interactive hands-on labs anywhere, anytime. Teleinquiry Instructional Model was used to guide the curriculum design. Students' clickstreams logs and instruction timestamps were analysed and visualized. Multiple regression analysis was used to determine whether engagement levels influence their conceptual learning. Behavioural engagement patterns were corroborated with survey responses.

Results and Conclusions: We found approximate synchronizations between student–teacher–lab interactions in the heatmap. The guided inquiry enabled by Telelab facilitates real-time communications between instructors and students. Students' conceptual learning is found to be impacted by varying engagement levels. Students' behavioural engagement patterns can be visualized and fed to instructors to inform learning progress and enact just-in-time instruction.

Implications: Telelab offers a model of remote labs 2.0 that can be easily customized to live stream hands-on teleinquiry. It enhances engagement and gives participants a sense of telepresence. Providing a customizable teleinquiry curriculum for practitioners may better prepare them to teach inquiry-based laboratories online.

KEYWORDS
design-based research, engagement, inquiry-based learning, mixed-methods, remote labs 2.0, student-teacher-lab interaction, telepresence, virtual/3D environments

1 | INTRODUCTION

As science educators face mounting pressure to resume hands-on labs halted by the COVID-19 pandemic, remote labs offer a promising avenue to mitigate risks of contracting disease yet offering them a sense of telepresence (Childers & Jones, 2017; Colwell et al., 2002). Following the trend of distance learning, our team developed a scalable remote lab, branded as Telelab, that could foster inquiry-based labs regardless of physical and instrumental constraints. We formulated a guided inquiry lab model, coined as teleinquiry throughout the rest of this paper, to promote scientific practices and facilitate synchronous interactions between instructors and students in a computer-supported learning environment (Hossain et al., 2018; Xenofontos et al., 2020). We would like to investigate the behavioural engagement patterns between teachers and students during the teleinquiry sessions and determine the impacts of engagement on conceptual learning.

1.1 | Engagement in inquiry-based laboratory

Engaging students in learning is challenging for teachers in online education (Carey, 2020; Dixson, 2012). As physical labs are often used in science education to intrigue and captivate students, we assumed that Telelab, which represents good approximations to physical labs, can achieve similar effects to a certain degree. Considering that Telelab is still undergoing early stages of development, as a first step, we would like to study how innovative technology could facilitate inquiry-based instruction in distance learning. In other words, research as to how teleinquiry can improve students' engagement in the remote labs and how their behaviour impacts the acquisition of science concepts and practices are needed (Childers & Jones, 2015; Lowe et al., 2013; Post et al., 2019; Villanueva & Zimmermann, 2020). This demand becomes more pressing as distance education grows, especially when schools are shut down due to disasters.

2 | BACKGROUND

2.1 | Reality check for inquiry-based laboratory

The inquiry-based laboratory has been a controversial topic supporting student-centred pedagogy (Beck et al., 2014; Zacharia et al., 2015). Practitioners and students shared mixed feelings toward this type of open ended-learning. The merits of inquiry-based learning are that the activities are more authentic, engaging, and the inquiry processes leverage their self-efficacy (Branan & Morgan, 2010; Fisher, 2016), learning gain (Silva & Galembeck, 2017), and enhance their scientific practices (Cunningham et al., 2006). Some drawbacks of inquiry-based labs were equally prevailing. For instance, educators expressed concerns about their insufficient pedagogical knowledge, impeding effective learning (Zacharia et al., 2015). Others criticized that the inquiry-aligned curricula are too cumbersome to foster targeted understanding systematically (Eastwell & MacKenzie, 2009). Indeed, inquiry-based labs require an intentional instructional design to scaffold learning processes and keep learners cognitively engaged (Sedwick et al., 2018; Shea & Bidjerano, 2009). Labs that adopt guided inquiry may enculturate the classroom ecology of shared duty on lab-design ideation before moving to the next steps of the investigations (Farley et al., 2021; Sedwick et al., 2018). Since conducting experiments in physical labs is disrupted during the pandemic, it is urgent to search for an avenue that could foster the teacher–student interactions mentioned above and support scientific experimentation in online settings. Virtual labs are one of the most popular and convenient approaches to supplement, even supplant, physical labs (Darrah et al., 2014; de Jong et al., 2013; Yaron et al., 2010; Zacharia & Olympiou, 2011). Even though dynamic simulation and visualizations are commonly adopted in science learning, the American Chemical Society's policy position suggests that computer simulations can be a supplement but *not a substitute in the* laboratory (2017). In other words, virtual labs or simulation-based labs that lack physical components would deprive students of the opportunities to engage in an authentic experience with the material world. Another alternative to cultivate first-hand practices in science is through remote labs, which allow students to interact with actual experiments through the Web.

2.2 | Remote labs broaden participation in science

The remote labs concept emerged from a proposal by Aburdene et al. (1991) at the beginning of the Internet era. Remote labs retain many characteristics of physical labs in the promotion of science-as-practices, such as authenticity, complexity, uncertainty, errors, and psychology of presence (Azad et al., 2003; Colwell et al., 2002; Heradio, de la Torre, Galan, et al., 2016; Ma & Nickerson, 2006; Post et al., 2019). Colwell et al. (2002) described how they successfully extended access to students who could not attend conventional labs in physical science and engineering classes, mainly due to a range of disabilities. Heradio, de la Torre, Galan, et al. (2016) reviewed publications about the eligibility of adopting virtual and remote labs in teaching automatic control education. They concluded that online labs have substantial potential in improving and broadening participation in control education. Ma and Nickerson (2006) reviewed the literature on three laboratory modes: hands-on, simulated, and remote. They concluded that regardless of the pros and cons of each mode, the psychology of presence is as critical as the technology itself. In almost two decades of exploratory research, remote labs have provided students access to dangerous measurements (e.g., detecting radioactivity, Sauter et al., 2013) and expensive apparatuses (e.g., electron scanning microscopes, Childers & Jones, 2015, 2017; Jones et al., 2003). Biological instruments such as biotic processing units (Hossain et al., 2016; Hossain et al., 2018; Washington et al., 2019) and engineering shops that have special equipment (Cooper & Ferreira, 2009; Heradio, de la Torre, & Dormido, 2016; Lowe et al., 2013; Martin et al., 2019) are also popular forms of web labs. Doubts about the effectiveness of remote labs could be mitigated as studies showed that the differences in learning outcomes between remote and local labs (Roschelle et al., 2017). Remote labs may help broaden participation in science with comparable affordances and promote equity in education by giving anyone—including those in underserved communities and those with physical disabilities—access to scarce laboratory resources.

2.3 | Toward a non-centralized and scalable model of remote labs 2.0

Despite their remarkable successes, most reported remote labs are based on a somehow centralized model in which the experiments are, for the most part, designed and operated by an expert provider at a well-equipped facility. Students and teachers then work with such remote experiments through computer interfaces that control a set of parameters allowed by the expert designers. While this ensures the efficiency, reliability, and reproducibility of the experiments, it limits students' and teachers' abilities to choose their own topics, subjects, and methods (Roschelle et al., 2017). For remote labs to become a cyberinfrastructure that supports online experimentation on a large scale, they must first meet teachers' needs to address diverse content and customize laboratory setup. A non-centralized (as opposed to the conventional remote labs that are mostly centralized), scalable, social, and secure model of remote labs—remote labs 2.0—that can accommodate multiple remote experiments is demanded (Xie et al., 2022). The teachers can conveniently live-stream lab sessions on any topics of their interest at a place of their own choice. The bottom-up design gives teachers and students autonomy to conduct experiments distinctive from most traditional remote labs that usually offer top-down service for users to merely work with the pre-defined parameters set by remote lab experts. Like the concept of breakout rooms in virtual meetings that anyone can initiate and invite others to join, such an open cyberinfrastructure will engender many educational innovations. For example, teachers co-design experiments with students, stream live data captured by sensors and cameras to students' devices for real-time analysis, discuss the results as they emerge, and then lead students to iterate through a circle of inquiry. The prototype of remote labs 2.0 that promotes shared-lab resources and the teleinquiry above is called Telelab (see more information in Section 5).

3 | THEORETICAL FRAMEWORK

Remote labs support some of the critical practices in science experimentation, such as observation and analysis. Currently, the key research direction for remote experiments is to explore ways to increase students' epistemic agency (Ko & Krist, 2019; Miller et al., 2018) and sense of presence (Childers & Jones, 2015) in remote experiments to reproduce as many educational effects of their local counterparts as possible. For example, Childers and Jones (2015) found that simply allowing students to choose their subjects of observation could enhance their perception of ownership and realism. Our goal is to provide a remote laboratory platform that can augment student's hands-on minds-on experience and increase science experimentation competency on the Web.

Along this line of thinking, we envision an open cyberinfrastructure with which teachers can explore teleinquiry to support remote experimentation with a broad range of possibilities and flexibilities. In contrast to relying on a central provider, with their own remote labs powered by a common platform, teachers only need to attend to the requests from their students. Being the owners of remote labs, they also have the freedom to explore various subject matter and enact guided inquiry labs that may be most appropriate for their students (Clarà, 2019; Lakkala et al., 2005). Students can jointly explore a more expansive problem space in online settings under their teacher's guidance, which benefits the coaching of experiment design skills (Ma & Nickerson, 2006). Figure 1 shows a simplified illustration highlighting the synchrony portion of this instructional model, referred to as *Teleinquiry Instructional Model* (TIM) in this study. From a practical point of view, TIM is similar in many ways to how teachers use demonstration experiments to engage students in the classroom (except we streamed real-time data to the students through the Internet). In this preliminary study, we would like to investigate the impact of applying TIM in facilitating students' behavioural and cognitive engagement during the science teleinquiry processes. We primarily focus on the student–teacher–lab interactions to study the relationship between behaviour patterns and conceptual learning. The exploratory research on TIM is crucial because there is no unanimous protocol to determine students' effortful engagement during inquiry-based, synchronous remote laboratories.

4 | ENACTING TIM VIA TELELAB

Telelab is a sophisticated cyber-physical system that connects experimental objects in labs with students and teachers through the Internet of Things (Jiang et al., 2021, Sung et al., 2021, Xie et al., 2021). It is developed to support secure data sharing, remote control, telepresence, and collaborative learning in real-time. We adopted the thermal imaging technology and Infrared Explorer app (Xie 2011, 2012, 2019; Xie & Hazzard, 2011; Xie et al., 2022; Jiang et al., 2021) to investigate how the curriculum could be developed to support synchronous science experimentations via Teleinquiry Instruction Model—consisting of three interaction cycles among students, teacher, and Telelab—introduced below.

Teacher-lab live-stream cycle. The instructor and the lab assistant collaborated to prepare and perform the lab activity via Telelab. When equipped with a thermal imaging system, a vivid visualization of what is happening energetically can be transmitted to students' devices (Figure 2), enabling students to explore the questions that would otherwise be too difficult to tackle without the instrument.

The instructor or lab host live-streams the teleinquiry activity on the Telelab platform and feeds the data to facilitate the student–lab interaction cycle, where the guiding questions can be tackled (see the purple dash-dot lines in Figure 1). The teacher or lab host sets up sensors to gather time-varying data (the thermal energy released or absorbed in an experiment can be turned into colourful indicators under a thermal camera, see Figure 2).

Student–teacher interaction cycle. Students submit their requests to the instructor. The lab host then uses their proposals for conducting remote experiments where students can test their hypotheses (see red line pointing from student to teacher in Figure 1). The proposed experiments are then realized by the teacher and a lab assistant

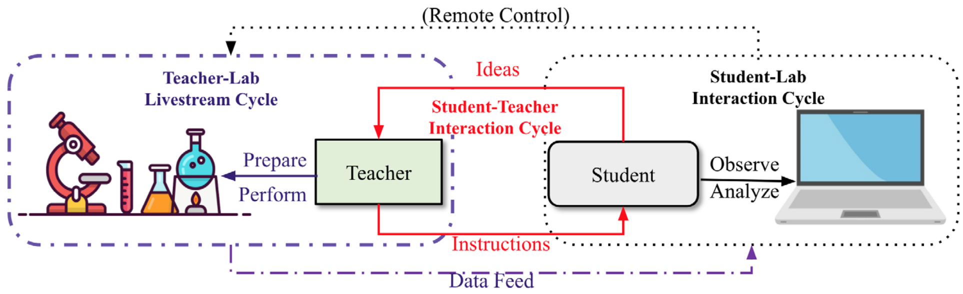


FIGURE 1 The Teleinquiry instructional model (TIM) comprises three cycles: Teacher-lab live-stream (purple dash-dot lines), student-teacher interaction (red lines), and student-lab interaction (black dot lines). Remote control element was enclosed in the parenthesis because the Telebot component is still under development. Due to limited space and clarity, we use only one student-rectangle to represent an individual student in the above diagram and omit student–student interactions [Colour figure can be viewed at wileyonlinelibrary.com]

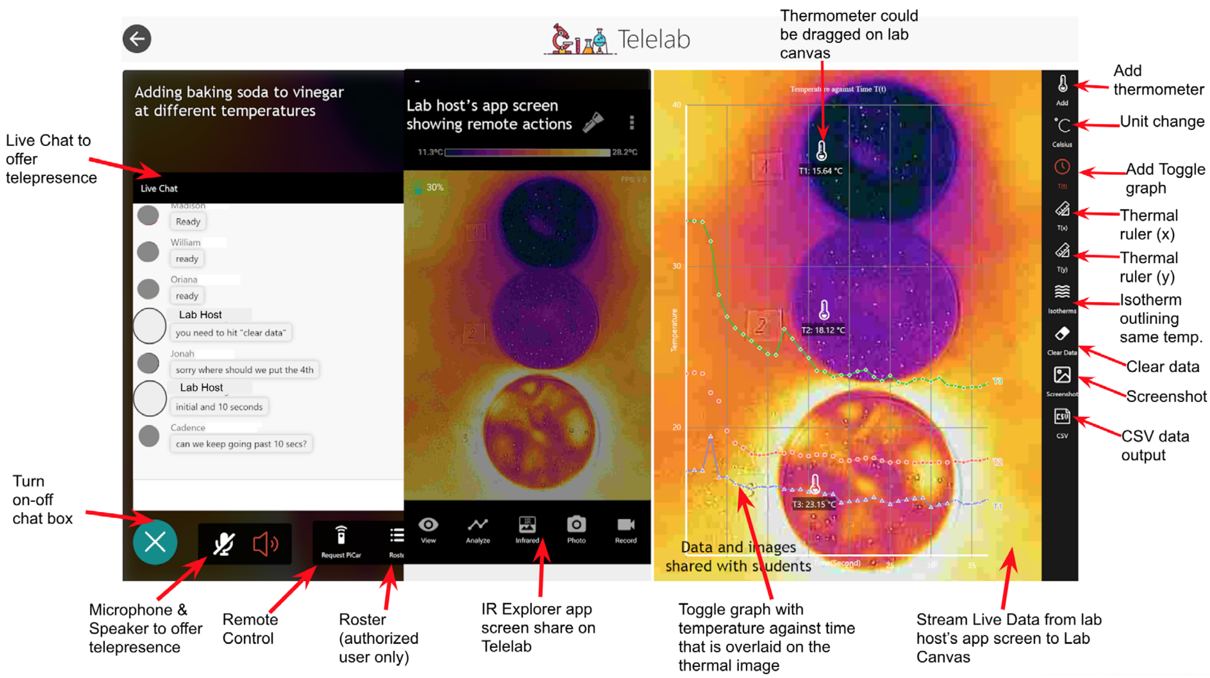


FIGURE 2 The annotated features of the vivid visualization on Telelab equipped with thermal imaging technology. The lab host live-streamed the acid–base reaction lab from the IR Explorer app screen, showing remote chemical reactions (middle screen). The host's sensor data and images are shared with students on the lab canvas (right screen), where students could add, move, and remove thermometers as they wish to test their hypotheses. Live chat among the teacher/lab assistant and the students could occur in the chatbox (left screen) to facilitate the student–teacher interaction cycle [Colour figure can be viewed at wileyonlinelibrary.com]

in Telelab and the data are instantaneously shared with the students in a live session that they joined through the Internet.

Student–lab interaction cycle. Local supporting apps, such as IR explorer, stream all sensor data, including thermal imaging to students' devices through the Telelab platform (see purple dash-dot line pointing from Teacher-Led Live-stream Cycle to Student-Lab Interaction Cycle in Figure 1). Students observe, analyse, and discuss the initial results and then make requests to speed up, slow down, or reverse the reaction that offers the entrance to the student–teacher interaction cycle (see the red line pointing from student to teacher in Figure 1). During the live-stream session, students observe the thermal images generated in the experiment (see black dot lines in Figure 1) and analyse the temperature data distributed to them in real-time with a user interface in their Web browsers. The experiments can also be recorded and published by the teacher in the online library of Telelab so that students can revisit them later if needed. The remote labs 2.0 model presents the key features of the envisioned remote teleinquiry labs distinctive from the previous generations.

4.1 | Research questions

Considering the novelty of the non-centralized remote labs, our central focus is to research the behavioural and cognitive engagement using the teleinquiry instructional model in this preliminary study. We would like to address the following research questions (RQs):

RQ1: If and to what extends do the teleinquiry instruction cycles facilitate students' scientific teleinquiry processes in a scalable remote laboratory? Two hypotheses (H1 and H2) for RQ1 are formulated:

H1. The guided teleinquiry pedagogy facilitates student–teacher interactions.

H2. The remote labs 2.0 model facilitates student's scientific teleinquiry.

RQ2: How does engagement levels during teleinquiry activities impact student's learning gains? One hypothesis (H3) for RQ2 is developed:

H3. Students' engagement levels can predict their learning gains.

5 | METHODS

5.1 | Context and participants

The four-phases teleinquiry curriculum for chemical reaction laboratory was developed following the Teleinquiry Instructional Model (see Table 1). The student–teacher–lab interactions and the modes of learning activities for each phase are also described in Table 1 (see Supporting Information Appendix). Among the 59 students who enrolled in a virtual summer school, 37 consented to participate in the teleinquiry activity. Thirty-three participants attended at least one live-stream session, and 23 of them also completed both pre- and post-tests. One of the goals of this study is to examine whether students' engagement levels during teleinquiry could help with science learning. Therefore, this study only focuses on the 23 participants who have pre- and post-test scores. Among the 23 participants, 13 were female and 10 were male, with English being the primary language at home ($n_{English} = 21$). The participants are from diverse ethnicities ($n_{White/Caucasian} = 15$, $n_{Asian/Pacific\ Islander} = 3$, $n_{Black/African\ American} = 2$, $n_{Hispanic} = 1$, $n_{MiddleEast} = 2$).

5.2 | Data and data analysis

Student engagement is strongly correlated with their performances in traditional classrooms and online learning environments (Martin & Bolliger, 2018; Pardo et al., 2016; Vytasek et al., 2020). In online learning contexts, numerous researchers have suggested that students' interactions with the learning platform can be important indicators for their engagement level (Lu et al., 2017; Mubarak et al., 2021). In these studies, students' interactions are often captured with log data recorded by the learning system. The advancement in technologies has enabled researchers to examine students' behaviours and performances with learner-generated log data within educational

TABLE 1 The four-phase teleinquiry instructional design based on Telelab

Phase	Mode	Student–teacher–Telelab interaction
Pre-Lab: Familiarize students with Telelab interface	Asynchronous	1. Teacher introduces how to use Telelab in a video tutorial 2. Students log into Telelab to observe the reaction and collect data on a pre-recorded experiment about adding washing soda to water
Live stream #1: The baking soda and vinegar reaction	Synchronous	1. Teacher carries out and streams the experiment to students' devices in real time 2. Teacher prompts students to predict the results and collect data to support their prediction 3. Students ask questions and discuss the results with the teacher and peers via online chat
Science practices: analyse, plan for investigation, communicate	Asynchronous	1. Students work on the lab report for Livestream #1 based on the screenshots taken from Telelab 2. Students reflect on their experiences from Livestream #1, brainstorm what experiments they would like the teacher to conduct, and post their ideas on the discussion board via the internal learning management system 3. Teacher reviews students' ideas and selects experiment(s) that help address learning objectives
Live stream #2: Factors that impact reaction rate	Synchronous	1. The teacher carries out and streams an experiment that is slightly modified from students' proposals in real time 2. Teacher prompts students to predict the results and collect data to support their prediction 3. Students ask questions and discuss the results with the teacher and peers via online chat 4. Students finish the lab report for Livestream #2 based on the screenshots and graphs collected from Telelab

contexts through various methods (Peña-Ayala, 2018). For example, researchers (Jo et al., 2017) used students' frequency and duration of a learning platform usage to construct variables that provide information on students' interaction patterns and examined how these variables associated students' performances. Other than computing numeric metrics, studies have shown that visualizing students' temporal interaction logs can also effectively reveal students' engagement (Chen, 2014; Dobashi et al., 2019; Ginda et al., 2019). For example, Dobashi

TABLE 2 Student-lab interactions via Telelab in live-streaming mode

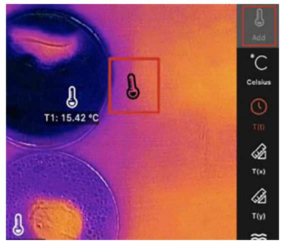
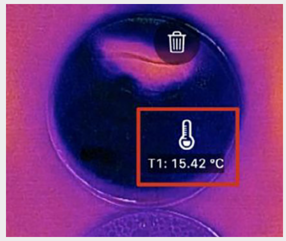
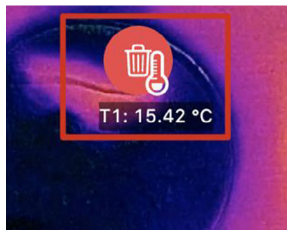
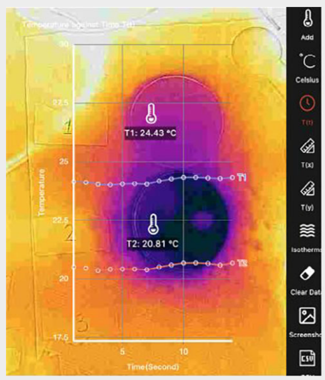
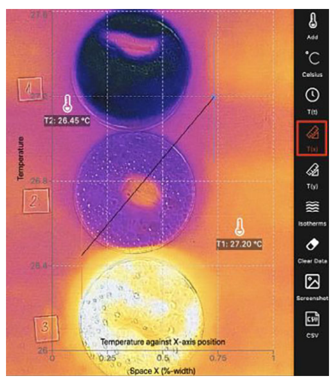
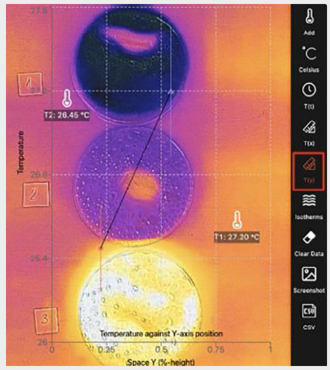
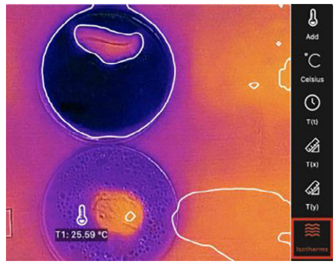
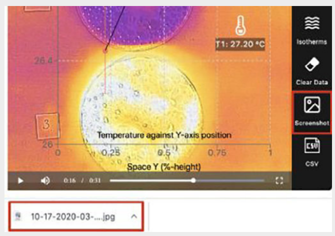
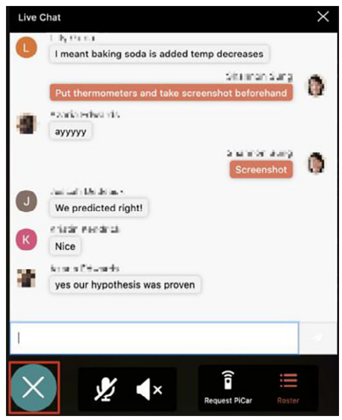
Action		Description	Screenshot
Create a thermometer		Add a thermometer to the Telelab canvas	
Move a thermometer		Move an existing thermometer on the Telelab canvas	
Remove a thermometer		Remove an existing thermometer on the Telelab canvas	
Toggle graphs	*T*(*t*)	Turn on/off the plot that visualizes thermometers' values change over time	
	T(*x*)	Turn on/off the plot that visualizes thermometers' values, standard deviations, and horizontal distance	

TABLE 2 (Continued)

Action	Description	Screenshot
T(*y*)	Turn on/off the plot that visualizes thermometers' values, standard deviations, and vertical distance	
Isotherm	Turn on/off the temperature isotherm that highlights regions with similar values	
Take a screenshot	Save and download a screenshot of the Telelab canvas, with thermometers and graphs retained	
Chat	Send messages with Telelab or ZOOM	

et al. (2019) used a heatmap to visualize students' access to course materials over weeks and then used the heatmap to identify disengaged students through engagement patterns. We modified from the heatmap example to visualize the student–teacher–lab interaction patterns.

Given its effectiveness and appropriateness for studies at a small scale in this study, temporal visualizations of students' interactions with Telelab were adopted to help dissect students' engagement both at collective and individual levels. Moreover, engagement metrics were calculated for a multiple regression analysis to understand the relationship between students' different engagement levels and performance. Telelab records every mouse click and keystroke made by students with detailed information. For example, when a student creates a thermometer, the system not only logs such an action but also retains information such as the coordinate of the newly created thermometer, so we can take advantage of this capacity to determine the displacement of the virtual thermometers from the backend logs. This study used 9164 entries of log data from the 23 students who attended the live sessions in Phase 4 who also completed the pre- and post-tests. Table 2 illustrates each type of interaction in the live-stream lab sessions. The following sections explain the details on how we process the log data for analysis.

H1: *The guided teleinquiry pedagogy facilitates student–teacher interactions*. We tested this hypothesis using a mixed-methods approach (Johnson & Christensen, 2019) based on multiple data sources. For example, similar to using data analytics to measure student engagement in learning management systems and other digital learning environments (Vytasek et al., 2020), students' activity logs collected in the backend were analysed to provide quantitative indicators of engagement. Specifically, during student–teacher and student–lab interaction cycles, a student was likely not engaged if no interaction data was ever logged in her/his account when the teacher prompted them to respond to questions or collect data on Telelab. The backend log data could offer hints as to whether a student was persistent during teleinquiry or had given up the quest if her/his trace of digital footprints was discontinued. Specifically, we addressed H1 by tackling how the instructions impacted students' interaction with the Telelab features, such as creating, moving, or removing thermometers, online chatting, and taking screenshots or toggle graphs.

We selected Phase 4 (i.e., the second live-streaming class listed in Table 1) to test H1 because the lab was designated to test student's experimentation ideas proposed in the previous phase. We first transcribed the live conference video, then we coded and highlighted the timestamps of teacher actions as follows: prompt students to type (PT), prompt to use Telelab features (PF), and respond to questions (R/Q), which were used to construct the *instruction* stamps on the *x*-axis of the student–teacher–lab interaction heatmap. More specifically, each students' lab-interaction log data (see Table 2 for the definition of each interaction) was chucked into subsets in units of 60 s after the onset of each instruction stamp. We then transformed the data to quantify and compare engagement levels.

H2: *The remote labs 2.0 model facilitates student's scientific teleinquiry*. To understand how students interacted with Telelab features from a collective perspective over the entire time-series of both live-stream sessions, we aggregated all students' log data by minute to get frequencies of lab interactions. We visualized the collective investigation and data collection behaviour to substantiate teleinquiry. Also, an end-of-course/post-lab survey and a short post-lab reflection survey were filled out by the participants and instructor, respectively, to evaluate the effectiveness of the teacher–lab live-stream cycle design development team could use for modifying and designing future teleinquiry curriculum.

In addition to the whole-class data analytics, we also identified a student who completed all tasks with flying colour and held a positive attitude toward the teleinquiry lab as the subject for our case study. We adopted three methods to visualize an exemplary active teleinquiry during the live-stream lab session(s). The analysis helps researchers better understand the teleinquiry learning processes demonstrated by an individual student when interacting with Telelab. First, similar to the collective visualization, we aggregated a representative student's log data by minute and plotted a line graph depicting the student's usage frequency of each feature against time during the two live sessions during Live-streaming #2. Second, to add a sequential dimension to the analysis, we sorted the student's log data by timestamp and used a sequence plot to show the student's time-series interactions with Telelab.

Finally, we assessed how well a student could follow instructional signals during teleinquiry using one example—computing the distance between locations where the student was instructed to place the thermometers instead of the actual positions the thermometers were placed during the lab. Students' thermometer-movement behaviour within 45 s before and after the substance was added to each petri dish can be visualized and compared between two instructional signals. The purpose of this analysis is to demonstrate how a pre-defined computational algorithm could be easily customized to satisfy instructional needs. It has the potential to support lab instructors in formatively assessing whether students actually follow along during teleinquiry.

H3: *Students' engagement levels can predict their learning gains*. Laboratory experiences are prominent in accomplishing three-dimensional learning objectives suggested in the Next Generation Science Standards (NGSS Lead States, 2013). Examining whether engagement levels during teleinquiry sessions can support students to attain learning gains can support future curriculum and software development. Therefore, we built a multiple regression model to examine the relationship between students' occurrences of different engagement levels and their learning gains. This hypothesis was probed using pre- and post-test of science concepts pertaining to the energy involved in the baking soda and vinegar reaction. Considering that this virtual chemistry class was a remedial course for high school students to recover credits, the assessment items were based on factual knowledge and on eliciting scientific practices. A sample question reads:

> If we added more baking soda to the vinegar, what would happen to the thermal energy of the solution? The energy change would______ the previous reaction with less baking soda. Explain your response.

With the assistance of Telelab features, such as colour heat map, thermometer reading, and automatically populated graphics (Jiang et al., 2021; Sung et al., 2021), we expect that students can explain that different factors, such as temperature, can impact chemical reaction rate (NGSS Lead States, 2013).

The learning gains were calculated as the differences between the post- and pre-test scores. Students' occurrences of different engagement levels were computed based on the result of instruction heatmap visualization generated from H1. For example, level 5 engagement means a student's interaction frequency was above the 75th percentile among peers at five different instruction stamps. Pre- and post-test scores were transformed to percentages of correct answers to ease of interpretation. Students' pre-test scores are the only independent variable (X_1), and their learning gains are the dependent variable (Y) in the base regression model (see Equation 1). Then, students' occurrences of different engagement levels and their pre-test scores were used as independent variables for the final model to find the additional variances explained by engagement levels (X_2 represents high levels of engagement, X_3 represents low levels of engagement) compared with the base model. To better understand how the levels of engagement interact with each other, we included

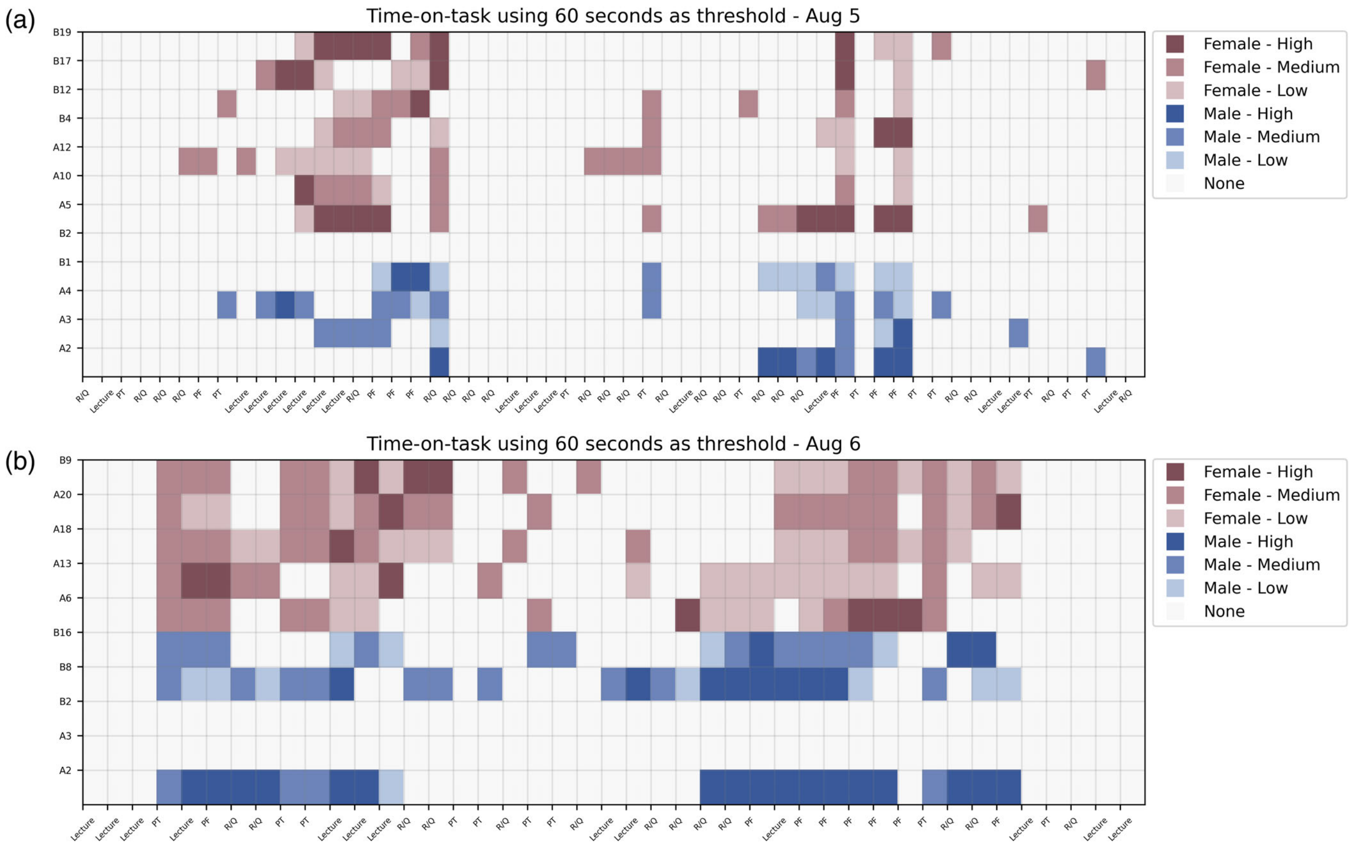


FIGURE 3 Student–lab and student–teacher interaction heatmap for two live-stream sessions. The darkest maroon grid indicates the highest student-feature-interaction frequencies, while the white grid represents no relevant feature usage logs detected during that minute. The instruction stamps include: Lecture, prompt to type (PT), prompt to interact with feature (PF), responding to questions (RQ). Student code could be found on the *y*-axis (Figure 3(a)). The interaction heatmap of 12 students who joined the first live-stream session (Figure 3(b)). The interaction heatmap of 10 students who joined the second live-stream session [Colour figure can be viewed at wileyonlinelibrary.com]

interaction terms in the analysis (i.e., X_2X_3). Multicollinearity was checked with variance inflation factors (VIF) which are commonly used in regression analysis (Alin, 2010), and the occurrence of medium engagement level was dropped to eliminate multicollinearity (see Equation 2). The regression models were defined as followed:

$$Y_i = \beta_0 + \beta_1 X_{1i} + e_i, i = 1, 2, \ldots, n \quad (1)$$

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{2i} X_{3i} + e_i, i = 1, 2, \ldots, n \quad (2)$$

where *i* is the observation number, and *e* is the error term.

6 | RESULTS

H1: The guided teleinquiry pedagogy facilitates student–teacher interactions. Figure 3 illustrates the impact of teacher instruction on the student–lab interactions for the two guided teleinquiry sessions from the second live-streaming class. Each bar on the *y*-axis was constructed based on each student's log data based on the feature-interaction frequencies against each instruction stamp marked on the *x*-axis. Every grid represented the aggregated Telelab feature-usage levels for 60 s after the onset of each instruction stamp and was transformed and colour-coded with their engagement levels. Frequencies encoded in each grid as low (below the 25th percentile), medium (between the 25th and 75th percentiles), and high (above the 75th percentile) were derived by comparing peers' interactions in the same column of the instruction stamp. On both interaction heatmaps, there were approximately two clusters. For the first live-stream session, the first cluster appeared after the sixth instruction stamp of lecturing. The absence of student-lab interaction is expected as the classes started in a conference room, and the students were sent to Telelab after the didactic lecture. The second cluster began to form near the end of the session after the instructor prompted students to use Telelab features (PF) for the second experimental trial. Similar patterns were observed during the second session. Both clusters showed that female students tend to show higher and more continuous interactions in Telelab when responding to instructions. However, the engagement levels of male students increased when instructors prompted them to use features.

The teacher reflection survey indicated that this chemistry teacher felt neutral about his confidence level using remote labs to investigate energy change during a chemical reaction (three out of five-point scale). He did, however, speak highly of the engagement

FIGURE 4 Collective feature-interaction frequencies against time during the second live-stream teleinquiry from the first class (a) and the second class (b) [Colour figure can be viewed at wileyonlinelibrary.com]

level of the live-stream lab as compared to the virtual simulation labs (9 out of 10-point scale). He enjoyed using Telelab because 'Telelab gave students a chance to collect their own data and have some license to customize their data-taking by placing different thermometers'. He also reacted positively to some features by stating, '… screenshots are very user-friendly. I like that they go right into the downloads folder with the timestamp as the file name. They can then pull them up easily as evidence for their findings'. When prompted to reflect on the effectiveness of Telelab on experimentation, he liked the fact that the setting encourages '… proper experimental design, such as isolating just one independent variable and controlling all others'. He also provided constructive feedback about the teleinquiry instruction '… this [preparing lessons and worksheets] took a lot of my time. As a summer teacher I had the time, but during the school year I would need these ready to go'.

H2: The remote labs 2.0 model facilitates student's scientific teleinquiry. We depicted time-series line graphs showcasing the collective student–lab interaction patterns against time for both live-stream sessions (Figure 4(a),(b)). There are apparent spikes for 'move thermometer' and 'screenshots' in both sessions when instructors prompted the students to interact with Telelab features.

In Figure 5, we showcased a series of behavioural engagement patterns. We selected a representative student who used all Telelab features and frequently responded to the action prompts during the live-stream teleinquiry session (student A4). In the left IR image of Figure 5 (5.1), the student took a screenshot after adding the thermometers on the Telelab canvas. The image also recorded the initial temperature reading, thermal heatmap, and a $T(t)$ graph. The right IR image on Figure 5 (5.1) was taken 15 s after the onset of the

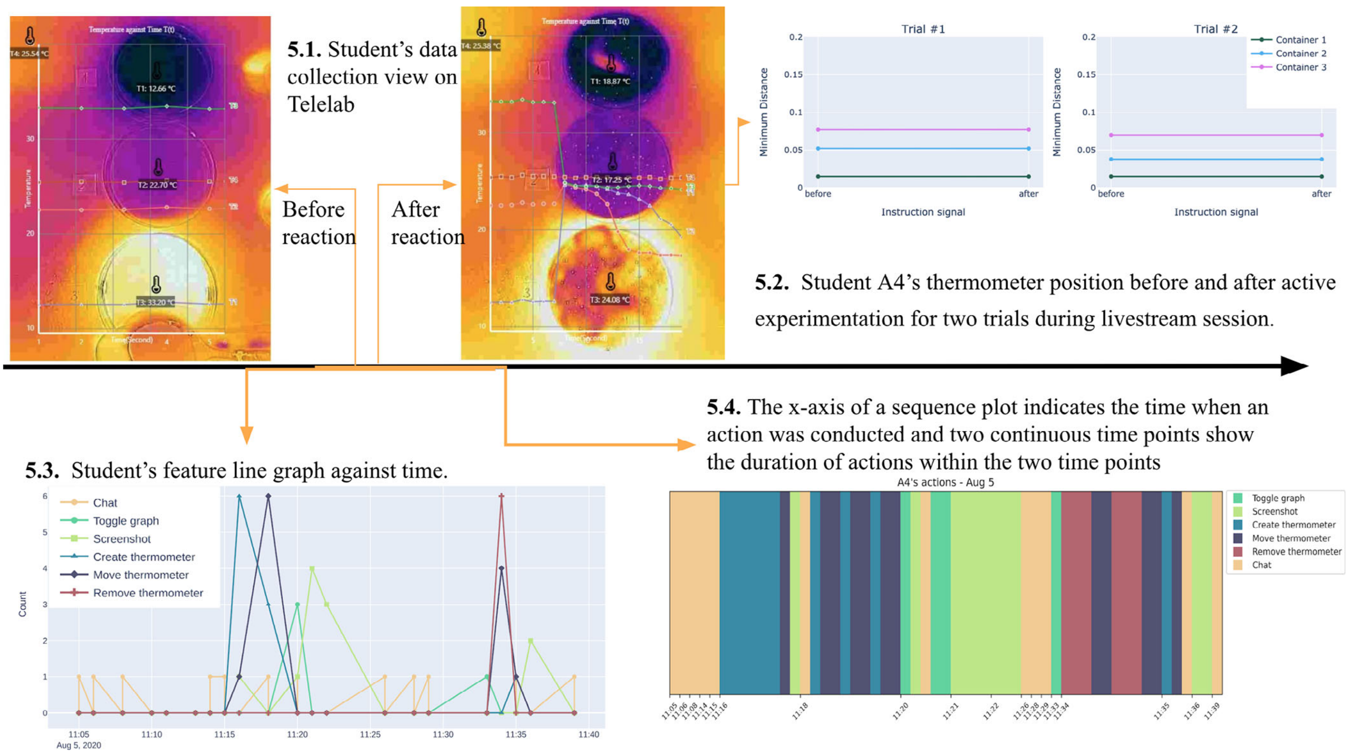


FIGURE 5 Behavioural engagement patterns of student A4 on live-stream teleinquiry session. (5.1) demonstrates student's data collection view on Telelab canvas; (5.2) shows thermometer position graph that is transformed based on the difference between pre-defined location and the location where student places the thermometer; (5.3) depicts student's Telelab feature line graph against time; (5.4) is the sequence plot highlighting the temporal behaviour patterns [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Regression results for pre-test, occurrences of three engagement levels, and learning gains

		B	t	Significance
Pre-test	Base model	0.45	1.763	0.098
	Full model	0.57*	4.024	0.002
engagement_low		−6.27*	−5.430	0.000
engagement_high		−0.46	−0.457	0.656
engagement_low:engagement_high		0.69*	2.579	0.024

*Indicates significance. $R^2\left(\text{adj}.R^2\right)_{\text{base}} = 0.116$, $R^2\left(\text{adj}.R^2\right)_{\text{full}} = 0.741$.

chemical reaction. We could use this imagery to triangulate the accuracy of the thermometer locations before and after the reaction. Figure 5 (5.2) indicates that the positions of three thermometers on Figure 5 (5.1) were stable before and after the reaction. The analysis presented in Figure 5 (5.2) is accomplished by identifying the precise timing just before chemical reactions were about to take place. The *y*-axis of this visualization is the minimum distance among all thermometers placed by a student relative to a petri dish's centre point. The *x*-axis shows the discrete steps before and after a signal point.

The minimal distance discrepancy between the actual and ideal locations also implies that A4 follows this particular instructional signal well. Figures 5 (5.3–5.4) demonstrated that the student used the chat feature throughout the session, and the overall engagement patterns were very rich, indicating a high level of behavioural engagement.

The post-lab survey from Student A4 revealed positive attitudes toward the teleinquiry activities. For example, when asked what features of the remote lab engaged them most, Student A4 responded: 'I liked the fact that we could ask questions and have discussions live. Also, I liked the fact that a teacher was there explaining what was going on instead of just a sheet of paper explaining'. This response reinforces the merit of the remote labs 2.0 in promoting social cognitive learning (Bandura, 1986). As for the question prompting them to reflect on how they used Telelab to gather evidence, the student stated: 'I used the remote lab to be able to take live evidence and screenshots so I could remember the data points better. Also, we could compare our findings with other students to see how each of ours compared and if what we found was just an outlier. Also, because we had an IR camera which not a lot of us have, we were able to use thermometers in order to see the true temperature changes between the three petri dishes and therefore see if the reaction rate of warmer vinegar really was higher'. The response reassured that remote labs 2.0 opened up equal access to lab instruments which helped him proceed with the scientific teleinquiry. Similar comment was found in his end-of-course survey in the eight-week summer course: 'The lab component was not extremely helpful to me … but that was expected because at home there isn't as much access to equipment. However, all of the equipment did function well and I especially liked the baking soda vinegar reaction because I think I learned a lot with the IR camera'. Student A4 shared two things he liked best about this course and provided suggestions on how it could be even better by stating: 'I liked the IR camera lab because we didn't have to gather materials but we still got to learn a lot. Also, we did it with other people… so it was more engaging and easier to gain live feedback. I would like if we could talk about what things may have caused the reaction more and also what factors could have impacted it a little more'.

H3: *Students' engagement levels can predict their learning gains*. Table 3 shows the results of regression analysis. Students' pre-test scores can explain 11.6% variances in learning gains. An additional 62.5% variances in learning gains can be explained by students' occurrences of high and low engagement and their interactions. The results showed that students' occurrences of low engagement ($t = -5.430$, $p < 0.001$) and the interaction term between the occurrences of low and high engagement ($t = 2.579$, $p = 0.024$) are strong predictors for students' learning gains. The significant coefficient value for students' occurrences of low engagement ($\beta = -6.27$) indicates that holding other variables constant, one unit increase of students' occurrences of low engagement will decrease the learning gains by 6.27%. Meanwhile, the coefficient of 0.69 of the interaction-term between students' occurrences of low and high engagement indicates that the effects of students' occurrences of low engagement on learning gains are affected by their occurrences of high engagement. For students with the same occurrences of low engagement, those who have more occurrences of high engagement will have higher learning gains.

7 | DISCUSSIONS

This study speaks specifically to the impact of remote labs 2.0 on inquiry-based lab instruction and student learning outcomes during mandated distance learning. As suggested in the literature (Childers & Jones, 2017), a key challenge in developing remote labs is to give students the feeling of being there through telepresence. The effectiveness of this live-stream lab activity in enhancing telepresence could be summarized in one participant's end-of-course survey: 'I thought it was really cool that although we are all so far apart in distance, we were all able to participate in the live experiment together in real-time'. This response was not a standalone reflection of only a few participants but a shared experience among more than half students. They self-reported that they enjoyed the augmented interaction with other peers/instructor and with data offered by Telelab.

The student–teacher–lab interaction heatmap shows highly synchronous interactions between the intensity of student's feature usage and the instructional signals. The results confirm the first hypothesis that the guided teleinquiry on a non-centralized remote lab can facilitate student–teacher interaction. It implies that the three cycles described in the Teleinquiry Instruction Model can enhance behavioural engagement individually and collectively (Figure 4). The enhanced student–teacher interactions help address the common concerns that students felt clueless during the inquiry-based lab. By adopting standalone and customizable lab activities that allow teachers to flexibly explore the phenomena at the paces that fit their own students. This also highlights another unique affordance of the Teleinquiry Instructional Model, in which students' ideas can be carried out remotely by teachers or lab hosts and then analyse the data sent back to them to complete the claim-evidence-reasoning cycle. Compared with previous generations of remote labs that are more fixated on the experimental subject and design, remote labs 2.0 will preserve a higher degree of open-endedness of authentic science investigations, increase student agency, and foster student–teacher interactions. In other words, the instructional model may provide a promising avenue to incorporate student's experimental design (Farley et al., 2021) that is grounded in the shared responsibility of instructors and students (Sedwick et al., 2018). By so doing, one's self-efficacy in scientific inquiry and practices can also be cultivated.

Despite the strong recommendation on promoting student–teacher interactions during distance learning, we recognized that for students to receive timely feedback, teachers should acquire more understanding of the students' learning patterns during teleinquiry, which could also be very time-consuming. The teacher also shared similar complaints in the post-lab survey responses. Regardless of praising the power of Telelab in facilitating scientific practices, he expressed his concerns about the amount of preparation time required to enact the lesson. Suppose the teachers feel that the teleinquiry instruction model requires disproportional preparation time and unpredictable learning processes. In that case, they might not buy in the idea of adopting such inquiry-based labs on their own (Chang et al., 2008). One way to mitigate the reported instruction load is to create a teacher dashboard that projects student behaviour during the student–lab interaction cycle as students interact with Telelab features. For example, Figure 5 (5.2) was a graph transformed from Figure 5 (5.1) to detect how far away Student A4 placed his thermometers from the ideal locations (i.e., one thermometer at the centre of each petri dish) pre-identified by the instructor. By seeing the stable thermometer positions on the dashboard, the instructors may conclude that Student A4 places the thermometers very close to the location where they are expected to be. The synchronous student–lab interaction patterns during an ongoing live lab would help teachers and researchers monitor students' behavioural engagement without interfering with the natural instructional flow (Shute et al., 2016). Doing so reduces the time for instructors to correct students' mistakes after the live session and miss the prime time to enact just-in-time instructions.

In response to the second hypothesis, generally speaking, we found that remote labs 2.0 can support students' scientific teleinquiry. In addition to the rich collective teleinquiry patterns shown in

Figure 4, an individual student's teleinquiry showcased in Figure 5 also confirmed that the student intensely interacted with Telelab features to collect data to construct his reasoning. The behavioural engagement results indicate that these activities effectively leveraged scientific teleinquiry and practices in online learning environments. Enacting a teleinquiry curriculum using the remote labs 2.0 platform (see Table 1) promises to facilitate scientific practices. Such practices include but not limited to planning and carrying out investigations (e.g., identifying variables to be studied), analysing and interpreting data (e.g., colour heat map, add and move thermometers and populate data in toggle graph), communicating information (e.g., chat on Telechat and conference call). Specifically, based on the case study of Student A4, who felt that IR technology enabled him to provide his rationales to respond to the hypotheses using the Telelab data. He also felt confident (7 out of 10) using Telelab to collect evidence and extract interpretation and inferences based on the collected data.

Student A4's self-reported engagement level in the post-survey and end-of-course survey triangulated with the learning processes depicted in the visual aids. His conceptual understanding also improved from pre- to post-test (60%–75%), which is not impressive. Still, the improvement is indeed an encouraging finding, given that the instructor spent much less time lecturing during the guided teleinquiry. The learning gain, however, is not intended to be compared with other modes of inquiry-based learning. It is presented to affirm the interested educators that such a method did not necessarily hinder conceptual knowledge acquisition.

Another contribution of this study is that we showcased how we operationally defined and measured engagement behaviour and measuring engagement in science, which has often been a daunting task for educators (Sinatra et al., 2015; Vytasek et al., 2020). We performed innovative analysis methods by adopting a mixed-methods approach using data such as the student–teacher–lab interaction heatmap by combining video analysis with backend data logs. We used the mentioned data to construct an interaction heatmap to indicate a rich engagement pattern. Besides sending time-series data to students, Telelab also uses Infrared cameras and IR Explorer apps to stream live views to closely observe the experiments, act on teachers' instruction, and listen to the live questions and answers all mimic the interactions in a 'brick-and-mortar' school. Augmenting social cognitive learning helps establish a sense of participation in distance learning settings. Even though we did not include a control group in this study, student's behavioural and cognitive engagement patterns on this prototype remote lab resonated with Sauter and her colleagues' finding where students felt most engaged with the task when they participated in live sessions (Sauter et al., 2013).

The regression result indicates a strong correlation between low engagement levels and low learning gain. The finding implied that the less engaged a student is on Telelab, the less likely s/he would attain a good learning gain. The strong correlation between low engagement levels and low learning gain has instructional implications. We recommend lab instructors scaffold teleinquiry by enhancing student–lab and student–teacher interactions. The result also suggests that students' engagement patterns and experimentation sequences identified during innovative teleinquiry might be valuable for teachers to monitor students' learning processes closely. Student's acceptance and engagement when using innovative technology during remote labs would be reassuring for teachers who are uncertain about the feasibility of adopting multimedia and might be more likely to try out teleinquiry. In the meantime, the data analytics presented in this paper offer a promising approach for lab instructors to customize the inquiry-based laboratory to fit students' needs with the tested curriculum during distance learning. It is also worth noting that the computational algorithms applied in studying user experience in Figure 5 (5.2) could be easily modified to address teacher's demands.

The teleinquiry activities model after the 'lab-on-the-chip' innovation in health sciences (Dittrich & Manz, 2006) transcends the limitations of physical presence and resources. The platform promotes the telepresence of both teachers and students during the real-time hands-on inquiry. In the era of a highly connected social network, where every voice counts (Chen et al., 2018), Telelab offers a promising and scalable platform for teachers who wish to share responsibility with their students during the scientific inquiry. It also enables anyone to access and engage in scientific experimentation from anywhere at any time.

8 | LIMITATIONS AND FUTURE STUDIES

Among the 37 students who consented to participate in this study, only 23 attended the live-stream sessions and also completed the pre- and post-survey. However, we did provide equal opportunities for those who had conflicting schedules with the pre-recorded lecture and pre-recorded Telelab experiments. Studies comparing students' behavioural and cognitive engagement during different Telelab modes would be interesting to evaluate the effects of live versus recorded experiments. More intensive design-based research (Barab & Squire, 2004; Sandoval & Bell, 2004) on behavioural engagement, such as adopting eye-tracking apps, could be conducted to profile specific student–teacher–lab interactions and to study students' scientific teleinquiry processes.

Even though students' ideas were considered before the teacher-led live-stream lab cycle, instructors or lab hosts still operated the teleinquiry lab. Students could not remotely control the lab freely to realize their experimentation ideas, thus increasing their sense of presence during teleinquiry. One way to reinforce even more robust telepresence is to allow students to remotely control the IR camera connected to a Telebot and observe an experiment from different distances and angles, just like what they would do if they were in the lab.

The development of a teleinquiry curriculum might be a foreign or even intimidating idea for many science educators who are already bombarded with virtual learning responsibilities. The scalability of Telelab would be a common platform to support science teachers and students to cloud-sourcing for more experimentation ideas that could leverage and streamline the teleinquiry instruction to the next level.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

The study is approved by Solutions IRB.

ORCID

Shannon H. Sung https://orcid.org/0000-0001-5704-2920
Chenglu Li https://orcid.org/0000-0002-1782-0457
Charles Xie https://orcid.org/0000-0002-1178-8361

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SUPPORTING INFORMATION

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