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ARTICLE
Developing and Implementing Low-Cost Remote Laboratories for Undergraduate Biology and Neuroscience Courses

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The global pandemic caused by the novel coronavirus (SARS-COV-2) has forced many universities to abruptly change the delivery of courses from in-person to online. This change to remote learning requires creating new ways to deliver lectures, exams, and discussion groups through online meeting platforms. An often-overlooked challenge is performing lab courses that require access to specialized equipment and resources typically found in the undergraduate laboratory classrooms. Here we discuss some strategies for developing and implementing a full semester neuroscience laboratory course that allows students to fully participate in laboratory exercises at home or in their dorm rooms. Performing lab exercises remotely and independently was shown to significantly improve participant's self-efficacy and confidence that they can learn complex neuroscience material, when compared to participants who passively watch experiments online. We review best practices to ensure that lessons can be successfully demonstrated by the instructor and carried out by all students. Finally, we discuss the need to provide a level playing field such that all students may succeed, regardless of their current technology resources at home.

Key words: distance learning; remote labs; neuroscience labs; remote teaching; anatomy & physiology (A&P)

INTRODUCTION

COVID-19, the disease caused by person-to-person spread of the novel coronavirus (SARS-COV-2; Harapan, 2020) has forced campuses to enact disruptive policies on social distancing (Ramos, 2020). These changes have forced many high schools, colleges and universities to switch from in-person lectures to safer tele-remote classrooms over online meeting software. This challenge to move to virtual classrooms is amplified in laboratory courses requiring research performed with specialized equipment (Gage, 2019). Instead of using the well-equipped teaching laboratories located on university campuses, instructors must find a way to deliver compelling lab exercises that can be performed remotely. One way to implement a remote lab course is to post videos of instructors doing the experiments, so that the students can see the methodology firsthand, and experience virtually the raw data produced. While this approach provides procedural and content knowledge, it negatively affects the self-efficacy: an individual's belief in his or her capacity to execute behaviors necessary to produce successful experiments in the future (DeBoer et al., 2017). Figure 1 shows the positive change in self-efficacy when students watched experiments online (control group) versus actively participating in the laboratories from home using the SpikerBox, a low-cost lab tool (Price range: $150-250; Marzullo and Gage, 2012).

Even before COVID-19, distance learning had begun to attract an increasing portion of the world's learners, especially in higher education. Widely accessible Massive Open Online Courses (MOOCs) can even transcend economic concerns barring underrepresented and/or low-income students from enrolling in prestigious university programs. The global annual growth of distance learning was projected at over 10% between 2018 and 2023 (Wotto, 2020), with about a third of all university students in the United States being enrolled in at least one online course even in 2012 (Kentnor, 2015; Keebler & Huffman, 2020). Considering that the current decisions about prevalent or exclusive learning models largely depend on universities

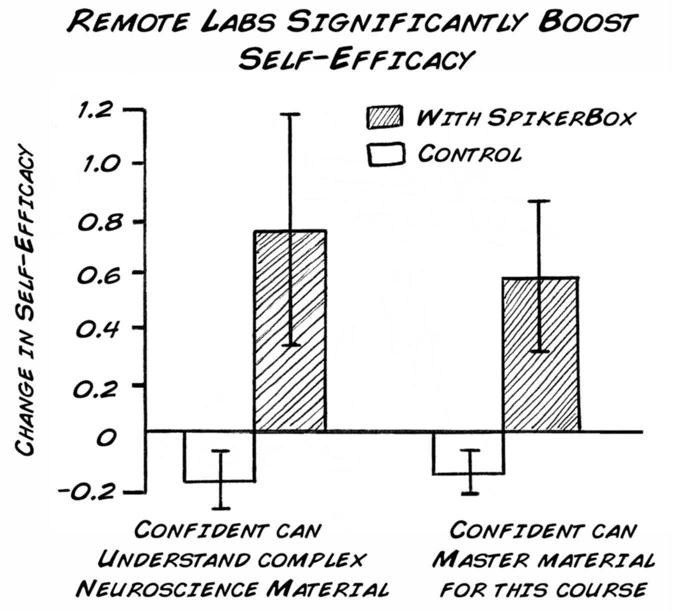


Figure 1. Remote Labs increase self-efficacy in mastering content in online neuroscience courses. Modified from (DeBoer et al., 2017).

and school districts themselves (Editorial Projects in Education, 2020), it is safe to assume that the 2020 turning point has increased the demand for distance learning multifold. Even if the pandemic does not usher in a full paradigm shift, we assert that the proposed value of remote labs like those described here and in the Supplement, albeit bolstered by the COVID crisis, will not remain in any way tied to it.

Whether remote labs will make a substantial impact on students' attitudinal and learning results in fully remote or hybrid environments remains to be seen. Based on the fact that online learning yields significantly better results when paired with hands-on activities (DeBoer et al., 2017; Koedinger et al., 2015), however, we have ample reason to believe that it will. In this paper, we will discuss our approach to developing remote labs for use in undergraduate laboratories; how to distribute technology, run demonstrations, and labs; and we share our work-in-progress experiences of performing fully remote laboratories with students at Bowdoin College.

MATERIALS AND METHODS

We have divided our remote lab planning into 4 stages:

Modify Labs for Remote

One of the core impediments educators are currently facing is the need to adapt their curricula to the idiosyncrasies of online or hybrid learning. This demand is especially taxing in STEM disciplines, which are heavily dependent on hands-on activities (Sandrone & Schneider, 2020). To address this need, we have modified our existing and extensively tested lesson plans to the remote learning environment. The labs include eight ECG, EMG, EEG, and EOG experiments that are fully aligned with the following standards: Next Generation Science Standards (NGSS), Human Anatomy and Physiology Society (HAPS), Advanced Placement Science (AP), and State Standards (e.g., Texas Essential Knowledge and Skills). These standards are suitable for K-12 and undergraduate science courses, specifically Anatomy & Physiology, Biology, Neuroscience, and Advanced Placement Biology courses. These standards were chosen as they emphasize science practices along with teaching concepts, which involve more active forms of instruction. The growing movement from mostly direct lecturing to active learning strategies in higher education (Freeman et al., 2014) aligns well with the framework of these standards (College Board, 2020; NGSS Lead States, 2013). We chose NGSS as the grounding set of standards for alignment because 20 states (and Washington D.C.) have adopted NGSS and 24 other states have developed their own science standards based on the Framework for NGSS which collectively represents over 71% of U.S. K-12 students. To align to these standards, the curriculum was then designed and arranged according to the Educators Evaluating the Quality of Instructional Products (EQuIP) Rubric for Science, which contains criteria used to measure the alignment and overall quality of lessons according to NGSS (Achieve and National Science Teachers Association, 2014). NGSS integrates three main dimensions of learning, often shortened to "3D Learning": which are Science and Engineering Practices (SEP), Crosscutting Concepts (CCC), and Disciplinary Core Ideas (DCI). These three dimensions are assessed together to provide both K-12 and undergraduate students a way to develop and apply scientific knowledge, skills, and concepts authentic to the practices of professional scientists.

Each lesson was evaluated using the EQuIP rubric's three categories: 3D Design, instructional supports, and monitoring student progress. For 3D design, we ensured each lesson allowed students to engage with and carry out investigations that required them to explain the phenomena. For instructional supports, we made sure lessons connected to authentic scenarios, built on student ideas, were scientifically accurate, and allowed for differentiation (such as by adding extension opportunities for exploring phenomena and concepts further. For monitoring student progress, we embedded opportunities into each lesson for formative assessment and practice of science skills.

To further adapt curricular materials to remote instruction, we ensured the student materials from the eight lessons could be used without direct teacher support. Relevant background content, procedures, figures, and "how-to" videos were added to student handouts. Technical guidance for hardware and apps are provided online. A teacher guide provides help to teachers to address necessary prerequisite knowledge, provide lesson-specific technical guidance, and provide instructional guidance as it relates to relevant standards. Technical guidance included which student devices were compatible with each investigation and relevant "how-to" videos for using all the different equipment. Additionally, guidance was given that all lectures and labs should be recorded and made available to students to allow them to review any class material and to repeat laboratory experiments. To support students who are not able to collect data, sample data sets were recorded and made available to teachers as well to provide for student analysis and comparison.

Design for Equity, Engagement and Accessibility

Some of the biggest challenges which can materialize while moving to remote labs can be summarized in three major themes: equity, engagement, and accessibility. Equity comes in the form of providing equal access to educational equipment/tools. The proposed labs can be performed on mobile devices that students likely already own, and the cost for the open-source equipment is less than $400 (Heart and Brain SpikerBox, Muscle Pro SpikerBox). The SpikeRecorder program that SpikerBoxes interface with also runs offline, allowing students to conduct investigations without a need for consistent internet access. Student protocols were made printable as well to be more accessible for home use or situations without internet. Engagement involves creating a remote learning experience that is not exhausting or one-dimensional, and thus not boring to students. Finally, accessibility implies taking into consideration students' special needs and different time zones. Care should be taken to ensure that all students have the minimal technology to carry out the remote labs. The latter includes scheduling meetings with students prior to the actual laboratory experiences to test the equipment and other devices (smartphones, tablets, laptop computers, etc.).

Distribution

All materials needed for remote labs (Figure 2), including equipment, cables and consumables should be individually boxed and assigned to students. Students on campus are able to pick up lab kits from the department, and those from home should be mailed kits in advance of the first lecture. A return label can be included for students working remotely.

To address any technical or practical concerns that may arise with students during the setup process, we suggest providing the first remote lab session as a support call to ensure that all students can connect kits, record signals, and perform analyses on the online meeting. Troubleshooting with particular students can be done in a break-out room, during breaks, or at a time reserved at the end of the meeting. Additionally, instructors should consider holding office hours at different times to provide flexible engagement to students in different time zones to address any other technical issues.

Evaluation

For evaluating students' achievement as well as attitudinal outcomes such as self-efficacy and self-concept, we suggest presenting students with an anonymous online survey before and after the semester. The survey will be optional and will collect demographics (age, gender, ethnicity, socioeconomic status, location), education and training, and familiarity with neuroscience and physiology research and concepts (DeBoer et al., 2017). The demographic data is needed because the program is being offered to a large and very diverse pool of students from various school districts, colleges and departments. These results (in addition to course grades and feedback) will help guide further refinements to remote labs each semester.

RESULTS

Eleven existing investigations from the Backyard Brains archives were sequenced by concept, creating a backwards-mapped storyline. This storyline approach means each lesson begins with phenomena that drive student curiosity and sensemaking throughout the subsequent investigations. Each of the eight lessons contains multiple investigations, all connected to the focal phenomena. Then, the three dimensions in the NGSS were integrated within each investigation based on the relevant phenomena, science content, skills, and concepts being addressed. Once these were determined, each investigation's student assessment questions were written and included at the bottom of student handouts. Associated background knowledge, procedures, tables, and discussion prompts were then included to help guide students through the formative practice of the assessed SEPs, DCIs, and CCCs. Once the core content of student handouts was created, remaining "interesting" questions, extension investigations, advanced techniques, and supplementary resources were included in the "Keep going!" section at the end of each student handout. Once copies of handouts were drafted, the reading level of the text was edited to be more accessible by students in secondary school settings, such as by defining unique terminology using simple words.

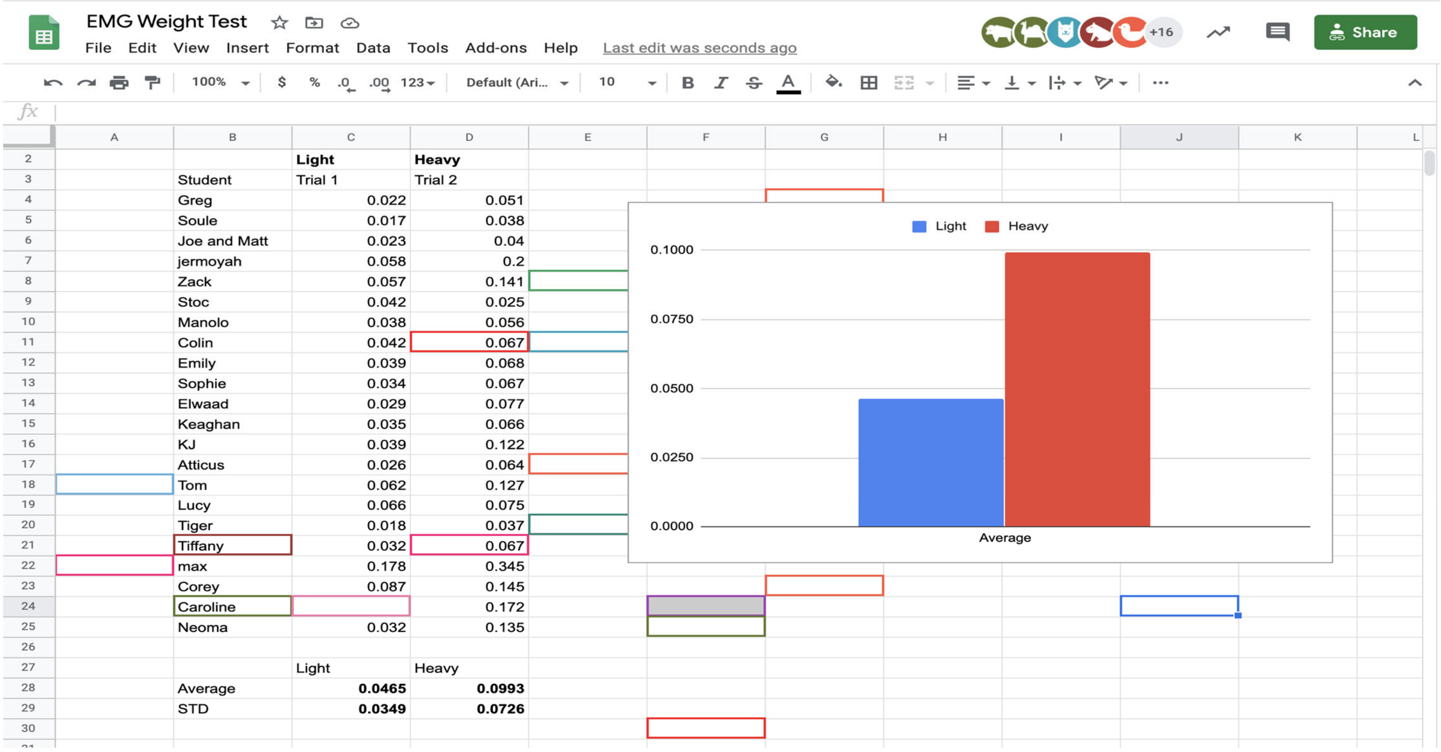
Outside of the core experience of each investigation in the student handouts, a teacher guide was developed to help educators know how to best facilitate these remote investigations when they cannot be physically with students. Sample 'spike' recordings were created and shared in the case that students could not get their equipment to work, needed comparison results, or a classroom did not have enough equipment for every student to have a SpikerBox.

Remote Lesson Plans

We developed eight lessons designed to contain 21 investigations in total but that are extendable to a number of potential directions of inquiry. Educators can choose to implement some or all of the proposed investigations.

1. *Introduction to the Heart* - Students capture ECG signals using Heart and Brain SpikerBox to determine their heart rate during rest, exercise, and the Valsalva maneuver.
2. *Reaction Time* - Students measure their reaction time using Muscle SpikerBox Pro while flexing their hands, dropping a ruler at random; they also design their own experiment.
3. *Reflexes and Reactions* - Students capture EMG signal in the rectus femoris muscle, eliciting a reflex with a tap to the patellar tendon; they also compare time difference between their reaction time and the reflex.
4. *Muscle Movement* - Students record EMG signal from bicep and tricep muscles in their arms as they act antagonistically and co-activate; they record the Root Mean Square (RMS) value to quantify muscle activity.
5. *Muscle Fatigue* - Students measure the EMG amplitude during isometric biceps contraction to learn about changes in muscle cells during fatigue.
6. *See Your Own Brain* - Students record the EEG from their occipital lobe as they hold still or open/close their eyes, capturing Alpha Rhythms of their visual cortex.
7. *Fight or Flight Response* - Students record ECG while using an 'ice water stimulus' to learn how their autonomic nervous system controls their heart rate.
8. *Measuring Eye Movements* - Students measure EOGs as they move their eyes left and right, up and down; they also quantify their results by recording their Saccade Calibration.

Figure 2. Left: Heart & Brain SpikerBox for recording EEG, EOG and EKG signals. Right: MusclePro SpikerBox for capturing EMG signals.



	Light	Heavy
Student	Trial 1	Trial 2
Greg	0.022	0.051
Soule	0.017	0.038
Joe and Matt	0.023	0.04
jermoyah	0.058	0.2
Zack	0.057	0.141
Stoc	0.042	0.025
Manolo	0.038	0.056
Colin	0.042	0.067
Emily	0.039	0.068
Sophie	0.034	0.067
Elwaad	0.029	0.077
Keaghan	0.035	0.066
KJ	0.039	0.122
Atticus	0.026	0.064
Tom	0.062	0.127
Lucy	0.066	0.075
Tiger	0.018	0.037
Tiffany	0.032	0.067
max	0.178	0.345
Corey	0.087	0.145
Caroline		0.172
Neoma	0.032	0.135
	Light	Heavy
Average	**0.0465**	**0.0993**
STD	**0.0349**	**0.0726**

Figure 3. Bowdoin students collaborating in realtime to test EMGs of light vs. heavy objects. This activity demonstrates that students can successfully collect data and use the analysis tools in software. Units are voltage root-mean-squared (Vrms).

These student lesson plans are attached in the Supplementary Materials and were derived from previous publications (Marzullo & Gage, 2012; Dagda et al., 2013; Shannon et al., 2014; Gage, 2019; Harris et al., 2020; Shin et al., 2020).

Bowdoin College Remote Labs

Twenty-three students were enrolled in the online neuroscience lab course for non-majors entitled, “Brains in Motion: Exploring the Interface between Mind and Body”. Each student was sent a new iPad Pro and a toolbox filled with Backyard Brains consumables and hardware required to do the experiments. The first lab session was a simple online experiment of recording EMG from the muscle while using two objects: a light and heavy object (no other details were provided about which objects to use). In 45 minutes, we were able to ensure that all students on the Zoom call were able to communicate their SpikerBox lab equipment with the iPad and were able to record and measure the data.

There were some common problems: some students had not received their iPads from the college by the time the semester had started which created problems with technological equity. Students were each able to measure the power of the EMG using the RMS calculation under the two conditions and populate an online Google Sheet in real time (Fig 3). This illustrated the collaborative nature of the remote labs while students were apart, allowing them to collect, interpret, and analyze data as they would in a physical lab space. The results were calculated as students added data, which allowed students to: 1) understand how measurements can be used to test hypotheses (heavier objects create larger EMGs); and 2) verify that each student could perform the steps of acquiring and analyzing biological signals.

DISCUSSION

Our distance learning solution has been devised so that it can: 1) tackle an acute issue of facilitating project-based remote learning of neuroscience, biology, and physiology; and 2) provide equal opportunity and exposure to hands-on scientific research to all students, underrepresented, low-income, and students of color included. We consider the first aim feasible because our curricula and methods are devised to empower, inspire, and equip students for independent scientific inquiry in any given set of conditions. At Bowdoin, students are being assessed by completing group lab reports, writing short essays related to the topics covered in class and will have to design and perform an end of semester group experiment project. To support that assessment, through alignment to the EQuIP rubric, each lesson in the curriculum gives students authentic practice of relevant science practices, content, and concepts. In the future, part of this experience will include a survey to assess the sense of accomplishment and overall level of learning. The second aim may often be overlooked, but contributes to student equity, and follows from the well-researched fact that active learning of STEM is especially beneficial for underrepresented students (Kanter & Konstantopoulos, 2010; Haak et al., 2011; Cervantes et al., 2015). The "Brains in Motion: Exploring the Interface between mind and body" course was designed as the first neuroscience course at Bowdoin College that does not require any science prerequisites and is available to non-majors, no matter their area of study. Through lectures, classroom experiments, and the design of their own experiments using the remote labs equipment; students receive a hands-on education in neuroscience on topics such as how electrochemical nerve signals control body movement, cardiovascular function, reflexes, and brain activity. Further, students engage in activities exploring potential technological applications of their projects, their societal/ethical impact, and implications.

The Neuroscience Learning Goals for this course include:

1. Understand and be able to use the scientific method to arrive at conclusions based upon appropriate evidence:
    a. Hypothesis development,
    b. Experimental design,
    c. Analytical reasoning and quantitative data analysis.
2. Know and understand fundamental concepts (e.g., in biology, psychology, chemistry) that are the underpinnings for the study of the brain and behavior.
3. Become familiar with fields related to neuroscience, in particular those that neuroscience seeks to explain and those that provide tools or principles that help explain neural functioning.
4. Demonstrate a broad intellectual foundation in neuroscience, including molecular, cellular, cognitive, and behavioral perspectives; understand how these perspectives are interrelated.
5. Become proficient in multiple techniques used in neuroscience research; be able to evaluate the strengths and weaknesses of each.
6. Apply the scientific method to questions relevant to neuroscience; design and conduct experiments to increase understanding of fundamental questions in neuroscience.
7. Be exposed to the ethical implications of neuroscience research and the use of neuroscience in society.

This course, including the implementation of remote laboratory equipment, could serve as a model for future academic offerings at other higher learning institutions.

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