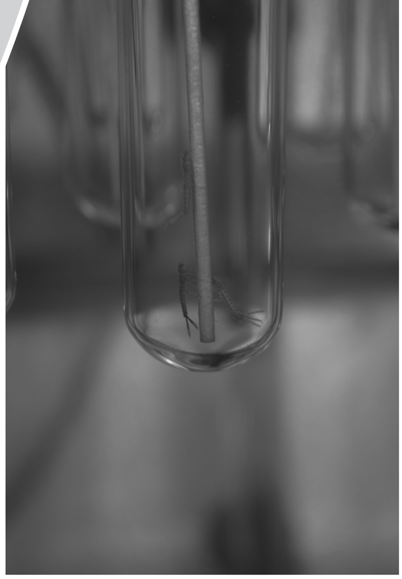
RESEARCH ON LEARNING

Authentic Scientific Research through an Undergraduate Ecology Course: Student Perspectives and Outcomes



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Abstract

Undergraduate science students who volunteer within a research laboratory group, or participate in funded research opportunities, in general are those who have the opportunity to engage in authentic research. In this article, we report the findings from two different iterations of a semester-long collaboration between a biology faculty member and a science education faculty member at a major research institution in the Southeastern United States. Specifically, the faculty members designed an ecology laboratory course for upper-level undergraduate students (primarily biology majors) where they would engage in an original and highly authentic ecological research project. The goal of this course was to have students explicitly learn about the nature of science (NOS), and authentic scientific practices such as inquiry and experimentation in the context of their own research. In the second year of the course, the global COVID-19 pandemic forced us to modify our approach to accomplish the same goals, but now in a remote and online format. Using questionnaires, concept inventories, and semi-structured interviews, the impact of the course on students' understandings of NOS, inquiry, and experimentation, in addition to their perspectives on the experience within the course compared to prior laboratory coursework, was investigated. We found that students showed modest gains in each of the aforementioned desirable outcomes. These gains were generally comparable in both face-to-face and remote course settings. Additionally, students shared with us their preference for authentic laboratory work as compared with the typical laboratory work with its given research question and step-by-step instructions. Our research demonstrates what is possible in both face-to-face and remote undergraduate laboratory courses in biology and the positive impact that was observed in our students. We hope it serves as a model for other scientists and science educators as they collaborate to design authentic research-based coursework for undergraduate biology students.

Key Words: *laboratory; authenticity; undergraduate; ecology.*

○ Introduction

Undergraduate students in science fields such as biology typically have limited opportunities to engage in authentic research on their university campuses (Burgin, 2020; Sadler et al., 2010). This is because a student's course load is often packed with required lectures and accompanying laboratory sections, so that there is little time for anything else. This makes volunteering in a faculty member's research group a practical impossibility for many students, particularly those from marginalized populations who may be working to put themselves through college. It often is not until a student reaches graduate-level studies within a scientific field that their university work begins to involve participation in authentic scientific research under the mentorship of a faculty member and/or the graduate students in their research group.

We also know that the traditional science learning experience involves laboratory work that is typically classified as less than authentic (Chinn & Malhotra, 2002; Hofstein & Lunetta, 2004; Holmes & Wieman, 2016; Martin et al., 1990). Moreover, if an undergraduate does not have the opportunity to participate in a Research Experience for Undergraduates or similar program, they are unlikely to have the time provided for them in the typical laboratory course to conduct an experiment of their own design from beginning to end (Holmes & Wieman, 2016). Additionally, upper level science undergraduate students tend to try to complete laboratory activities as quickly as possible and are often motivated by grades, rather than pursuit of a research question (DeKorver & Towns, 2016). Recommendations have been made to try to engage undergraduate students in more authentic involvement in the practices of science through research apprenticeships, undergraduate research experiences, or the reconceptualization of for-credit laboratory coursework (Charney et al., 2007; DeKorver & Towns, 2016). Such transformation of less than authentic biology coursework to experiences that involve students in the entirety of the research process is possible in undergraduate course settings (Goedhart & McLaughlin, 2016). However, even with such quality

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examples, these experiences are far from the norm. There are many reasons that undergraduate biology laboratory courses tend not to involve authentic work on the part of the students. These reasons, or barriers to implementation of authentic science work, include a lack of time, the large class size typical in many undergraduate biology laboratory sections, and a perceived lack of student readiness by the instructor to engage in such open-ended inquiry (Spell et al., 2014).

In response to these issues, a biology faculty member and a science education faculty member at a major university in the Southeastern United States (the authors of this article) developed a laboratory course in experimental ecology that was aimed at engaging student groups in original and authentic ecological research. The approach we took is very much like a standard course-based undergraduate research experience; however, the students had considerable flexibility in deciding on a research question and designing an experiment to address their question. At our institution, such an opportunity was not currently available in a way that would provide undergraduate biology course credit to interested students. The desired outcomes of the course were the development of more sophisticated student views of the nature of science (NOS), inquiry, and experimentation. In other words, we hoped that through participating in authentic scientific practices, undergraduate students would understand at a greater level of depth the ways in which knowledge is generated by the scientific community writ large. The course was made open to all upper level undergraduate biology majors and fulfilled a biology laboratory requirement. We hoped that this model would serve to provide an inclusive experience where most biology students would be eligible to enroll in the course so long as it fit in their schedule, and that the successful completion of the course would serve to advance their program of study.

○ Course Design and Modification

Year 1 (Fall 2019)

We designed the course in a way that would prepare students for and support them as they engaged in group ecological research. Students met once a week during a four-hour period, in addition to time spent outside the classroom period when students were conducting their work. For most students this amounted to roughly two to three hours of outside work. The time spent outside the classroom in conducting their research was comparable to other upper division courses at our institution. Student research projects were focused on freshwater lake ecosystems in general, and the use of damselflies (small insects, closely related to dragonflies) as a model empirical study system. As such, students took field trips to local lakes to observe their study system and collect damselfly larvae as well as food for damselflies – *Daphnia* (water fleas). They then developed their own research questions and set up experimental methodologies to answer those questions over the course of a semester-long course. Most students developed research questions that dealt with issues of predation (damselfly larvae consuming *Daphnia*) or cannibalization among the damselfly larvae, as well as the role of human activities (see Table 1).

Below is an excerpt from the syllabi that was provided to the students.

Table 1. Topical areas of student research projects, examples of student project titles, and what they did in their study.

Topics	Delivery	Number of Projects	Example Project Title	What They Did
Environmental effects	In person	2	Determining changes in mortality rate for *Enallagma* damselflies in relation to lake pH	Experimentally manipulated pH and determined how it affects damselfly mortality
Human influences	Both	3	Effects of light pollution on damselfly foraging success	Experimentally manipulated light levels to see how it affected damselfly foraging success
Cannibalism	In person	3	Cannibalism rates in damselfly nymphs as a result of food availability and timing	Experimentally manipulated the abundance and timing of damselfly prey to see how it affected cannibalism levels
Species diversity maintenance	Remote	1	Negative frequency-dependent selection in polymorphic damselflies by fish predators	Experimentally determined if fish predation was dependent on damselfly adult coloration and frequency
Sexual selection	Remote	1	Coloration of male and female damselflies. Color polymorphism and its effects on predation	Experimentally determined if bird predation was sex and color dependent

> We expect a lot from you. The glamorous view of everything working perfectly every time in research is an overblown and incorrect view of what research actually entails. Persistence, imagination, and a solid work ethic are among some of the most important attributes for gaining success in research. These are all things we can't teach you. You have to want to know. So, be curious. Don't be afraid to "fail." Try your best.
>
> Consequently, an important aspect of research is initiative. By this, we mean it is imperative to take ownership of your research. You have to be responsible for all aspects of the work. This course will require significant work outside of regular class time. All research groups (not the professors) will be responsible for conducting their research. Furthermore, you and your classmates may be required to come to the lab periodically, even during the weekend, to collect data as needed to test your hypotheses. You are welcome to split these duties with other group partners as long as everyone in the group shares the burden equally. We will of course help you out with acquiring supplies and logistics, but the implementation of the project is up to you. Projects that fail because you forgot to do something (feed bugs, etc.) can result in a less than desirable grade.

In addition to in-class discussions specifically related to conducting ecological research through experimentation, the science education faculty member was a regular visitor to the laboratory (in this case a greenhouse on campus), where they led students through discussions of the NOS and scientific inquiry. Specifically, students engaged in a philosophy of science card sort (Cobern & Loving, 1998), and an activity very similar to the e-mail lab described by Lederman et al. (2015).

Students conducted activities representative of practicing scientist. Specifically, they developed research proposals, conducted a literature review, kept an organized laboratory notebook, collected and graphically analyzed their data, prepared a research report, and gave a presentation of their research to the rest of the class at the end of the semester. Notably, these activities were largely designed entirely by the students, with minimal input from the research faculty. Figure 1 shows a picture of one laboratory group's experimental design. In the plastic cups are various water samples containing the species in question (damselfly larvae and *Daphnia*). Students then changed the conditions for each sample thereby setting up manipulated and responding variables. These variables could have been differences in exposure to sunlight, different numbers of larvae, more or less food (*Daphnia*), and so on. Thirteen students (all biology majors who were either juniors or seniors) enrolled in and completed the course.

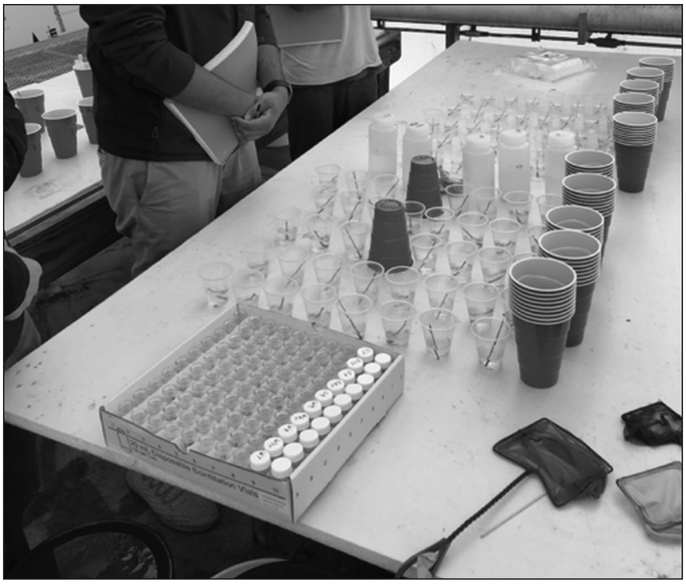

Figure 1. Student experimental design.

Year 2 (Fall 2020)

When we developed the course as described above, the plan was always to offer the experience to different classes of students over multiple semesters and multiple academic years. We did have the opportunity to implement the course as we planned during the Fall 2019 semester. The results of interview and survey data from that first implementation of the course indicated that the students were noticing that their experience was unique when compared to the typical undergraduate research experience and that they were indeed developing new insights about the NOS and the ways in which science is practiced. We were encouraged by these initial results and looked forward to adding an additional cohort of students to our data set the next time we offered the course in the Fall of 2020. However, the COVID-19 pandemic shut the university down and the university moved to a remote delivery format for most courses that were offered. Despite these circumstances, we were still able to offer the course albeit in a much-revised manner because of our opting to move the laboratory course from on campus to remote.

Of chief concern in the revision of the course was conceiving of a way for students to engage in authentic participation in experimental ecological research in a new remote setting. If engagement in authentic research is hard to come by even in face-to-face laboratory settings on campus, how much more so would it be when students were forced to remain in isolation? Our situation was far from unique, and just now publications are coming out that offer advice regarding how to conduct remote undergraduate science laboratories during a global pandemic (Fey et al., 2020; Morrison et al., 2021; Wang & Ren, 2020).

Despite these concerns, we were able to offer our class sessions synchronously online through Zoom. During these sessions, we were able to conduct the explicit NOS and Scientific activities in a revised way that worked through remote instruction. The laboratory experience itself was revised. Namely, rather than focusing on damselfly larval life stages (damselflies live in the water part of their life cycle and then emerge as flying adults), students used clay models of adult damselflies and then designed studies focused on various factors that could explain predation on damselflies (see Table 1). Scientific studies have often used clay models to study ecological phenomenon and we took inspiration from them (e.g., Rößler et al., 2018). For instance, some students compared urban and rural pond settings to see if predation rates on damselflies differed. The latter was obtained by observing the number of strikes made on those models by predator organisms (mostly birds). Figure 2 is an image of one of these clay models.

Students in groups of two or three were able to design and implement their own experiments with their models at various remote locations over the semester. Notably, in this experience students were able to set up projects in the field and they were able to do so safely under COVID-19 guidelines. As in previous offerings, students and faculty met weekly to discuss their projects. They were

Figure 2. Clay model used in remote experimentation.

still able to write up their laboratory report and present it virtually to their classmates at the end of the semester. Thirteen students (all biology majors who were either juniors or seniors) enrolled in and completed the course remotely during the Fall 2020 semester.

○ Research Methods

Our research questions were as follows:

1. What is the impact of authentic laboratory participation on student understandings of NOS, inquiry, and experimentation?
2. How do students perceive this laboratory section compared to other undergraduate laboratory coursework they have completed?

In order to answer the questions, students completed the VNOS-C questionnaire (Lederman et al., 2002) and the VOSI questionnaire (Lederman et al., 2014) both at the beginning of the course and again upon its conclusion. In year 1, all 13 students completed both pre and post VNOS and VOSI questionnaires. In year 2, 6 of 13 students completed both pre and post VNOS and VOSI questionnaires. The completion of these surveys was voluntary and was not a graded component of the course.

Six of the 13 students from year 1, and 10 of the 13 students from year 2 agreed to participate in semi-structured interviews where we asked them the following questions:

1. What have you learned about science as a result of this course?
2. What have you learned about conducting scientific research as a result of this course?
3. Have you ever designed a scientific investigation prior to this course? If so describe.

Additionally, all students took the biological experimental design concept inventory (BEDCI) both at the beginning and at the end of the course for both years (Deane et al., 2014). The BEDCI allowed us to quantitatively examine if student knowledge of experimental design increased. It is important to note that the course did not have an extensive lecture on experimental design. Any gains in knowledge were perceived to have occurred "organically." The only requirement was that the approach used by the students in asking their research questions was to use an experimental, not observational, approach. Thus, any potential increase in knowledge of experimental design occurred largely through students' efforts alone.

To statistically compare BEDCI scores pre- and post-course and between years, we used a linear model. To take into account the lack of independence by querying the same students pre and post completion of the course, we used a repeated measures design, treating student as a random effect. The model included the percent of the BEDCI questions that were correctly answered as the response variable and both year and pre–post testing time and their interaction as explanatory variables; Cohen's d is reported as a measure of effect size.

The questionnaires and concept inventories were analyzed according to the recommendations of the developers of those instruments. Each student was coded as either having an informed, a mixed, or a naive perspective regarding each aspect of NOS and scientific inquiry based on their written responses to the VNOS or the VOSI questionnaire accordingly. The two authors of this article independently analyzed a subset of the VNOS and VOSI questionnaires from year 1 that had been blinded (stripped of student identifiers as well as if the questionnaire was taken at the beginning or the end of the course) and recorded a 90% inter-rater consistency. The lead author then analyzed the remaining questionnaires from both years 1 and 2. The second author of the article performed statistical analysis of the BEDCI data sets for both years. Semi-structured interviews were analyzed through an application of inductive strategies for conducting qualitative research through constant comparisons between participants (Lincoln & Guba, 1985). Prior to collecting data, we received approval from our Institutional Review Board and our research was classified as Exempt.

○ Results

BEDCI Analysis

Across years, there were marginal increases in BEDCI correct responses (Type III Wald $\chi^2 = 5.51$, df = 1, $p = 0.018$), but there was a statistically significant interaction term (Type III Wald $\chi^2 = 3.86$, df = 1, $p = 0.049$), indicating that the pre–post difference depended on year the surveys were administered. We therefore subsequently conducted analyses separately by year (Figure 3)

During 2020 (pandemic year), students had a modest (27.45%; Cohen's $d = 0.74$, indicating a medium effect size strength) but significant increase in gains associated with an understanding experimental design (pre–post term: Type III Wald $\chi^2 = 13$, df = 1, $p = 0.0003$), but none in 2019 (pre–post term: Type III Wald $\chi^2 = 0.10$, df = 1, $p = 0.745$). While the gain in 2020 is notable, it is impossible to discern if this could be attributed to any pandemic-associated changes in pedagogy because we have no replication. That is, within years we did not replicate the two types of approaches used. Regardless, these results indicate that marginal increases in experimental design knowledge can occur, even if the course lacks a formal component associated with presenting detailed instruction on experimentation in the sciences. That said, if the goal is to gain significant knowledge increases in experimental design, we recommend that greater focus be placed on this specific learning objective.

VNOS and VOSI

The numbers of students who demonstrated gains in understandings of VNOS and VOSI are organized by year in Table 2.

Positively impacted NOS ideas included the differences between Theory and Law in science, the creativity involved in the entire scientific process, and that science is more than just a process of experimentation.

Positively impacted ideas of scientific inquiry included that the scientific method is not the only way to perform science, and that there are a variety of reasons why scientists might arrive at different conclusions from the same data set and that these reasons do not necessarily involve error on the part of the scientist. One of the students from year 2 couched their responses to the VOSI in the context of their own research involving the damselfly models that they had conducted over the semester. However, for another student from year 2, views about scientific inquiry seem to have regressed in that they thought there was no universal scientific method prior to the semester, whereas at the end they thought experimentation was the sole way to conduct science. Perhaps this is because in our course, the students were required to employ an experimental design in their research. We also did emphasize, through the use of the BEDCI, that sophisticated understandings of experimental design in biological sciences were a desirable outcome of the course. That being said, we did explicitly emphasize that experimentation was not the only way to practice science.

Student Perspectives

Analysis of the interviews conducted with the students from over both years revealed several common themes. One of these dealt with the very straightforward recipe-like way in which laboratory investigations are typically conducted in undergraduate coursework. This is represented in the following quote (see below) from one of the students. Multiple participants interviewed were able to clearly articulate these sorts of differences between their past laboratory work on campus and their remote participation in their research project through our course. Key differences identified were the ways that the typical undergraduate research experience is pre-designed with an outcome that is known in advance. One student told us that undergraduate laboratory experiments provide brief opportunities to engage in authentic practice, but that those opportunities fall well short of being representative of the entire scientific research process. Another student mentioned that the process of data analysis that occurred in our course was a new experience. It is interesting to note that three of the interviewed participants articulated that they understood their past laboratory experiences to be serving a different instructional purpose in preparing them with the skills and abilities that they would later need to engage in a complete experimental process like they did in our course. One student told us that they thought an authentic experience like the one they had in our course should be required of all science majors. The following interview excerpts from two different participants represent these viewpoints held by most of the students we interviewed.

> [Undergraduate laboratory investigations] are usually already all set up for you and everyone already knows the results. [It is designed for] you to get the experience so you don't really get to go in there and actually mess around with certain variables or have a say in how you want to design the experiment itself. This one [their experiment in this course], we've literally designed it from beginning to end. We even got to choose the topic and everything. It was really cool because it was definitely nothing like I had done before. I realized that the amount of detail and all the things we have to think about when actually designing an experiment.

> I just feel like for other [laboratory courses], they would give us, like the hypothesis, or maybe some of the results and then we answer questions about that, but in this one we actually had to do [the entire experiment]. I feel like this was the whole process, whereas the other one was kind of just snippets of it and then drawing conclusions from that.

Another student from the first year told us the following.

> This is I guess the first distinction … this is student led and my prior labs have just been – we're going to go through these labs, learn this procedure, get these results and then describe why you did or did not get these results. And those labs, especially the chemistry labs have been just repeated and repeated and there's a very solid baseline. These reactions and so on have been done thousands of times. This is what it should do. And this is what you should do to replicate that. Whereas this is really whatever you want to make it. It's very student driven.

Students also self-identified specific lessons, or novel ideas that they learned about how science is conducted over the course of the semester. They mentioned learning things such as, the scientific process is "more difficult," "rigorous," does not "always go as planned" as they conducted their ecological experiment. Three students discussed how the reality of multiple conclusions arising from the same data set was something that had not yet experienced prior to our course. Two students mentioned that engaging in scientific research involved much more creativity than they had previously thought. One student talked about how they had not realized that science was such a slow process, one mentioned that they learned

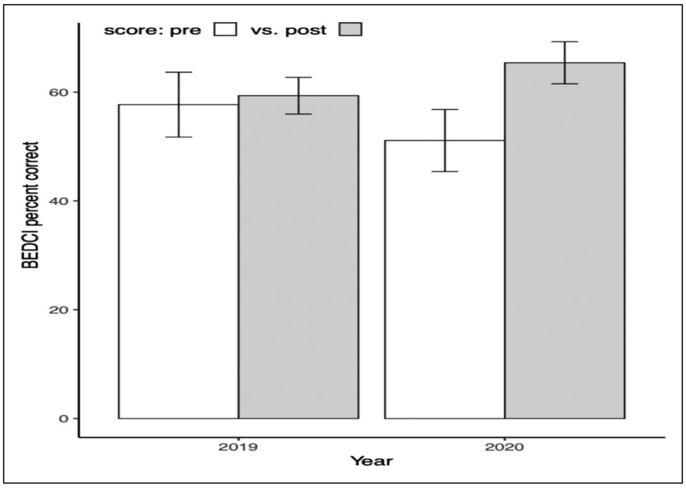

Figure 3. Changes in biological experimental design concept inventory (BEDCI) scores pre (*white*) vs. post (*blue*) course participation across years. Shown are the percent correct of 14 BEDCI questions asked (mean ± 1 SE).

Table 2. Number of students with gains in VNOS and VOSI scores (pre to post).

	N (with Full Data Sets)	Students with Gains in VNOS	Students with Gains in VOSI
Year 1	13	9	10
Year 2	6	4	3

just how interconnected science disciplines are and another articulated that science is broader and more inclusive than they had previously understood it to be. The following quotes from the students are representative of these perspectives.

> [The experiment is likely] not going to go your way and that's probably going to happen most of the time. You kind of have to overcome that and maybe use like creative solutions to get around it but still try to reach the best outcome that you can even if it's not like the perfect outcome that you were originally seeking for.

> [I] kind of assumed that, you know, everything had one specific answer, you know, stuff like that, so I never really took it – I guess I never really went with, well, this happens because of this, you know, but also you know, some other factors might influence like a different answer or something like that but … I mean, we really don't even know why our project ended the way it did.

Another student told us specifically about the importance of collaboration when doing scientific experimentation.

> Personally, I will never think of every aspect to, you know, a problem. No matter how hard I look at it, the answer could be simple, and it'll slap me in the face, like the temperature. So just that little bit of collaboration could save you hours … days or months at a time.

Somewhat surprisingly to us, two students discussed the benefits of conducting scientific experimental research remotely during a pandemic. One of these students mentioned that because students were conducting their research at many different sites because of students being in lockdown, the diversity of the collective data was much greater than it would have otherwise been. Another student talked about how they was forced to be even more creative in designing their procedures because of conducting their experiment remotely. The following quote illustrates this perspective.

> How in the world are we going to [do] this? In the midst of a pandemic where you, you can't really like go into the lab or do anything like that. And so, when he [the biology professor] told me we're going to be using clay models, I was like, "well how are we going to do an experiment with that?" Like, that doesn't make sense. And the more that we thought about it and tried to come up with ideas of doing that, it took a lot more creativity … with the circumstances that were given.

○ Conclusions

The contributions of this research to science education are twofold. First, it represents a model of unity between the science education community and the science community whereby a scientist and a science educator partnered to create and subsequently revise a laboratory course that would allow students to engage in authentic scientific research both before and during a global pandemic. Second, it offers a description of how undergraduate laboratory coursework can be revised to include even more students in opportunities to engage in authentic scientific research. In these regards, it contributes to a research base that generally talks about how undergraduate coursework tends to be less than authentic and ways in which that coursework could be revised (DeKorver & Towns, 2016; Holmes & Wieman, 2016). Additionally, we offer one more example of how remote learning during a pandemic can engage students in authentic research opportunities (Fey et al., 2020; Morrison et al., 2021; Wang & Ren, 2020). The ability to successfully achieve our course objectives in a remote setting shows that such a learning environment is still conducive to providing authentic research opportunities. This result therefore opens the possibility of bringing authentic research experience to larger groups, making research opportunities more accessible and inclusive. By creating a three-credit laboratory course focused on engaging students in authentic experimental design that satisfied a degree requirement for biology majors, we overcame what we see to be the main obstacle to undergraduate science research; that students have to do this on their own time as an extracurricular activity. Additionally, we believe that high-school biology teachers could implement aspects of this research particularly the remote experimentation we implemented as students could be encouraged to engage in research like this at home independently from class instructional time.

In conclusion, we noted that students demonstrated some moderate to limited gains in their understandings of NOS, inquiry, and experimentation. Of note is that increases in understanding experimental design are marginal – if that needs to be a key learning outcome, it needs to be addressed more directly in the class. That said, remote learning does not negatively impact understanding experimental design, although additional replication is necessary to better understand and remote learning effects. Additionally, the students were able to express in their own words some of the new understandings that they developed regarding authentic scientific research. We believe that this experience is worthwhile as it provided students with some gains in their understandings of science and the way that it operates and that students found the experience to be meaningful to them and their future goals as evidenced by the interviews we conducted with students.

We close with a summary of a notable conversation that took place during our interview with Andrew. Andrew was very involved as a high-school student in the science fair for multiple years and regularly advanced to the international science fair competition. He told us that this was the first time in his undergraduate career that he had conducted a similar authentic research project to those that he did as part of his high-school science fair experiences. Andrew was a senior biology major. We find it so unfortunate that it took the special creation of a new undergraduate laboratory course for Andrew to have an experience conducting authentic research. He was clearly ready for such participation upon arrival at the university, but it was never asked of him. We are left wondering how many other students like Andrew are out there among our undergraduate science students who are itching to participate in authentic scientific research. We encourage other faculty to develop laboratory work for college credit where undergraduate students can do just that.

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