AUTHENTIC RESEARCH INVESTIGATION

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AUTHENTIC RESEARCH INVESTIGATIONS OF A CONTROVERSIAL QUESTION: CAN PLANTS LEARN?

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ABSTRACT

Can plants learn? This question stirs up controversy and speculation in the classroom, as it is currently done in the scientific community at large. We leverage the controversy to ask students to contribute to the greater body of knowledge by using scientific principles in creative research projects. Ninth-grade honors biology students became familiar with original research and the surrounding controversy, and performed experiments testing two distinct forms of plant learning in Pisum sativum (pea) and Mimosa pudica (sensitive plant).

Key Words: research in biology education; nature of science; philosophy of biology; botany; history of science.

O Introduction

The scientific and engineering practices that are typically among the first subjects covered in high school biology are often taught using research questions whose answers are obvious to high school students. Having students investigate a current controversy in leading science can emphasize the significance and relevance of scientific and engineering practices and make the biology classroom a more authentic learning experience for students. Here, we describe a lesson plan using a modern controversial subject, which allows the students to hone their theoretical and experimental skills through an open-ended research experience.

O Plant Learning

Can we train plants to respond to bells, like Pavlov’s dogs? When this question was posed to a ninth-grade honors biology class, there was a brief puzzled silence — then, “But plants don’t have brains, right?” “What do you mean by ‘learn?’” “Don’t they grow better with classical music, is it like that?”

The question of plant learning is a modern controversy playing out in the scientific community. In 2016, Monica Gagliano, a senior research fellow at the University of Sydney, published a paper in Scientific Reports reporting that pea plants displayed a positive tropism toward a small CPU (central processing unit) cooling fan after being trained to associate it with a light source (Gagliano et al., 2016). One reviewer told Gagliano that “it’s very unlikely that plants are aware or conscious. So this entire project is meaningless” (Morris, 2018). A larger discussion of plant cognition — or of the especially controversial term plant neurobiology — is, as one Yale professor calls it, “the last serious confrontation between the scientific community and the nuthouse” (Pollan, 2019). Is the scientific community being closed-minded or is bad science being done (Pollan, 2013)? As recently as July 2019, eight scientists wrote an opinion letter in Trends in Plant Science strongly denouncing Gagliano’s conclusions and stating that her studies are biased in their philosophical foundations and implicate moral and ethical questions rather than focusing on the objectivity of data (Tazi et al., 2019).

Asking students, for their final biology project, to design and execute an experiment, write a paper, and design a poster addressing this controversial question immerses them in an authentic research experience from beginning to end (Brownell et al., 2012).

Traditionally, in high school biology, students perform a set of closed inquiries and submit artificial lab reports, which are often plagiarized (Rigano & Ritchie, 1995; Del Carlo & Bodner, 2004; Parameswaran & Devi, 2006; Ma et al., 2007; Sisti, 2007). Because of their prescriptive nature and limited scope, such activities are not effective for teaching the process of science (Bencze & Hodson, 1999; Rahm et al., 2003; National Research Council, 2006). On the other hand, some teachers may like closed inquiries, having little time to think about exploration as they juggle many responsibilities and having little training themselves in open inquiry (National Research Council, 2006; Zion & Mendelowici, 2012). However, the skill that is most important to gain from a science class is not necessarily knowledge, but the ability to critically evaluate information as being scientific or not (NGSS Lead States, 2013: Appendix H).

In addition, genuine assessment of students’ individual abilities to think critically in science is difficult. Answers to “cookbook” labs are easily found on the internet, and students often form group chats to share answers with each other. A different kind of
assignment—one that requires students to design their own study, collect and analyze their own data, and interpret the results in light of a yet-ambiguous research question—can force students to genuinely and critically think, taking away the crutches of the internet world and inviting them into scientific conversation (Gage, 2019). This article provides the details and results of a lesson plan designed to take advantage of the real-science potential of using an unsettled scientific question in the classroom, including our observations of student mastery of scientific and engineering practices and critical thinking.

**Objectives**

This long-term (five-week) project offers a formative and summative assessment of freshman students’ learnings of the nature of science. It teaches incoming freshman students who are taking their first science class in high school (1) scientific and engineering practices; (2) how to incorporate a STEM/engineering mindset; and (3) scientific literacy in reading a scientific paper, writing a scientific paper, and designing and presenting a science poster. This extended biology project meets the objectives for “Connections to the Nature of Science” in the Next Generation Science Standards (NGSS Lead States, 2013: Appendix H), which call for “learning science and engineering practices and developing knowledge of the concepts that are foundational to science disciplines. Further, students should develop an understanding of the enterprise of science as a whole—the wondering, investigating, questioning, data collecting, and analyzing.”

**Conceptual Preparation**

This assignment can be used to start and end a school year in high school biology (or it could be confined to a unit on plant physiology). In week 1 of the year, we started with a lecture on scientific and engineering practices (i.e., observations, hypothesis/question, procedure, data/results, and conclusion). The first example used was Pavlov’s dogs, introducing the terms unconditioned stimulus (food), unconditioned response (salivating), neutral stimulus (bell before training), conditioned stimulus (bell after training), and conditioned response (salivation in response to bell). The importance of replicating experiments was then explained, using the historical examples of Francesco Redi, John Needham, Lazzaro Spallanzani, and Louis Pasteur. The students were then presented with the question of whether plants can learn, and the last part of the introductory lecture was an overview of Monica Gagliano’s two studies, as follows.

**Pisum sativum (Pea Plant) Learning**

In the initial study, 45 pea seedlings grown in small individual pots were exposed to an 8:16 hour (light: dark) circadian cycle for five to eight days (Gagliano et al., 2016). They were then randomized to either the control group or the experimental group, upon which a bifurcated PVC pipe was placed on top of the plants (see Figure 1). During three days of training, a light and fan were presented on the same arm of the PVC pipe for 90 minutes at a time, three times a day. The plant was left in total darkness throughout. On test day, the control plants were left in the dark, without light or fan. They were expected to grow toward the light, where they had “seen” light last. The experimental plants were provided with fan stimulus on the right side. All of the control plants grew toward the left, and two-thirds of the experimental plants grew toward the right—a statistically significantly different outcome. Students should understand the reason for different aspects of the design and how this controls for different variables. For example:

- Exposing the seedlings to several days of eight hours light and 16 hours dark ensures that the circadian rhythm is set.
- Alternating sides randomly during training ensures there is no set pattern.
- Placing the fan on the opposite side of where light was last seen ensures a clear distinction between the control and experimental groups.
- Having the fan introduced before the light is a type of conditioning called “forward delay conditioning.”

**Mimosa pudica (Sensitive Plant) Learning**

*Mimosa pudica* closes its leaves rapidly when physically disturbed. In Gagliano et al. (2014), potted *M. pudica* plants were gently dropped from a height of 15 cm repeatedly (six spaced-out trains of 60 drops each); leaf width measurements were used to determine whether the plants habituated and stopped closing their leaves. The last test was to provide a dishabituating stimulus (shaking the plants at 250 r.p.m. for five seconds) to see if the original strong closing response was exhibited. The plants were tested six days later and again 28 days later to see if they “remembered” the dropping stimulus as nonharmful, as indicated by their closing up less when dropped again. Students should understand the following:

- Why the drops should be the same every time (it ensures training to the same stimulus)

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*Figure 1.* Monica Gagliano’s pea plant study design.
• That the data collected should include percentage of leaf closure, and the importance of marking the same leaves for measurement every time
• The timing of the dishabituation stimulus, and its intensity (another reviewer critiqued Gagliano’s study design for providing a dishabituation stimulus significantly stronger than the dropping; Biegler, 2018)

Scientific Literacy
As an exercise in scientific literacy, students read the original pea plant paper and answered basic questions to see how much they understood, having received an overview of the design in lecture. It was emphasized that they did not need to understand all the details. Reading the paper and answering questions on it was a scaffolding assignment to familiarize students with the layout of a scientific paper. Although the opposing viewpoints were not presented (in the interest of time), at least one response paper (e.g., Taiz et al., 2019) could also be assigned, to expose students to other scientists’ critiques in more detail. However, students were also directed to Gagliano et al. (2016), which includes comments and valid scientific concerns presented by other scientists. Because this was the students’ first time reading a scientific paper, we opted for depth instead of breadth in the time allotted to this project.

○ Details of the Assignment
Students were given five weeks at the end of the year for this project; a sample timeline and in-class time estimates are provided in Table 1. The project is largely student driven, but teachers should check in on students’ graphs and data analyses to make sure they project design can meaningfully answer the question of plant learning. Students were given the original papers again and were given the choice to work with the pea plant or the sensitive plant in groups of two or three. They could also decide to either exactly replicate the studies or come up with their own design. Their design and schedule of project execution had to be approved by the teacher before they could continue planning its execution. Meeting with every student group at least once a week was very important to check progress and for guidance.

Materials needed: This will differ depending on the students’ project designs. In general, the teacher should be ready to provide pea seeds, starter soil, and outlet timers. Pea seeds are available in bulk and easily obtainable. Students can obtain their own pots for their projects, depending on their design choices.

Germination: Soak Pisum sativum seeds in room-temperature water for 24 hours (or in warm water for a shorter period if time is short). Lay the soaked seeds in a single layer on damp paper towels. Wrap damp paper towels around the soaked seeds several times and place in a plastic bag to prevent moisture from escaping. Place in a dark place, and check after two to three days. The seeds should have radicles that are ≥5 mm long. Discard the seeds that have not germinated. Plant the germinated pea seeds ~1 cm below the surface of the potting soil (direction of radicle should not matter). See Table 2.

For M. pudica, the students used the setup shown in Figure 2 (estimated time to build: 30–45 minutes). This is made by taking two styrofoam blocks, cutting one (the plant-holder) to fit into the other (which will be the base), then taking four metal rods and piercing through both the plant-holder and the base. Check to make sure the plant-holder foam block rises and drops smoothly ~15 cm. The point is to make the dropping of the Mimosa consistent each time and prevent wobble as it goes down. You may have to hollow out the foam around the rods a little bit in order to make it drop smoothly. Make sure the plant-holder foam block fits firmly around the pot holding the Mimosa. If the impact is still too abrupt, add plastic bags to line the bottom of the base under the plant-holder. You might also have the students design this for an engineering class. Mimosa plants can easily be bought from hardware or gardening stores, as they are quite popular.

○ Results
Students came up with a variety of studies and designs, according to their creativity and bent. Summaries of students’ various studies and peer critiques are presented in Table 3.

Paper writing: This was the students’ first time writing a scientific paper based on their original research. Their previous science-writing experiences were lab reports. Guidelines, based on Nature’s Scitable “Scientific Communication” website (Doumont, 2010), summarized the contents of the website and provided examples. Students had only used MLA formatting previously, which is primarily used in the humanities, and so were asked to use a citation

Table 1. Sample timeline.

| Week | Monday | Tuesday | Wednesday | Thursday | Friday | Weekend |
|------|--------|---------|-----------|----------|--------|---------|
| 1    | Introduce project, rubric, and groups (~30 min. IC) | Groups brainstorm project idea (15 min. IC) | Brainstorm (15 min. IC) | Submit project design for approval | Receive feedback (teacher meets with groups one-on-one) | Start getting materials |
| 2    | Set up project materials: Germinate pea plant seeds (see schedule above), build a plant maze or build Mimosa dropper (IC² variable) | | | | |
| 3    | Collect data (IC variable, can be assigned as homework) T*: Check what kind of data students are collecting | | | | |
| 4    | Write paper and design poster (IC variable, can be assigned as homework) T: Check in on students’ graphs and data analyses | | | | |
| 5    | Continue writing | Presentations | Presentations | Discussion | |

IC = in-class time.
*T = note for teacher.
Table 2. Pea germinating schedule.

| Day 1        | Day 2                               | Day 3                      | Day 4                        | Day 5                       | Day 6                        | Day 7                        | Day 8                        |
|--------------|-------------------------------------|----------------------------|------------------------------|-----------------------------|------------------------------|------------------------------|------------------------------|
| Soak in water| Wrap seeds in damp paper towel      | Check for radicles, plant in damp soil | Train to 8:16 light:dark      |                             |                              |                              |                              |

Figure 2. *Mimosa pudica* setup.

Table 3. Samples of student work for *Pisum sativum* studies.

| Research Question | Study Design                                                                 | Results                                                                 | Conclusion                                                                 | Critiques from Peers          |
|-------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------|----------------------------------------------------------------------------|-------------------------------|
| Can plants learn to escape the last part of a maze by growing toward the direction of the fan? | Place two groups of pea plants in two mazes and train with light and fan; control is left to “escape” on its own, experimental plant is provided a fan to indicate direction of the escape hole | Two-thirds of the seeds of the experimental group grew toward the fan; only one-sixth of the plants in the control group grew toward the escape hole | Plants can be conditioned to grow toward fan | - Not controlled  
- Only one direction for plant to grow, following phototropism (not entirely testing ability to learn)  
- Light problems |
| Can plants learn to grow toward or away from a fan? | F+L: 71% Learning/Association Rate  
F vs L: 57% Learning/Association Rate | Some support for plant learning but can’t make any conclusions because of lack of control | - No control  
- Limited time  
- No real management |
| Can you get a video of plants displaying “fan-tropism”? | Every interval of training showed the plants angling toward the light and fan, displaying phototropism; when it came to the test day, the plants grew in the direction of the fan even though there was no light, exhibiting tropism toward the fan | Plants can be conditioned to grow toward fan | N/A |
Poster presentation guidelines: Students were instructed to use as little text as possible, and to focus on good figures and graphs (Figure 3).

Peer critiques: Students presented their papers to the class, while their peers gave qualitative feedback on strengths and weaknesses of the scientific design of the study being presented for extra credit (see Tables 3 and 4). This allowed teacher assessment of these students’ abilities to evaluate other scientific studies. Presenters also answered questions from classmates and teachers about their study designs, results, and conclusions.

Class discussion: Scientists read multiple papers reporting on different studies to come up with a stance on a particular question. At the end of everyone’s presentations, the students took an informal vote as to whether they thought plants could learn, based on their studies and their peers’ studies. The result: 100% of students, 18 out of 18, were convinced that pea plants could learn. Only six of 18, however, or 33% of the students, were convinced that Mimosa plants could learn. In order to be convinced, students said that they wanted to see more replication studies and a video of Monica Gagliano’s setup and results.

○ Conclusion

As an authentic research experience for students, this five-week project helped them see the entire scientific process that researchers undergo from hypothesis to conclusion. Students understood how to control for variables and how to interpret their results accurately. Peer feedback on other students’ studies also exhibited a mixture of self-awareness and acute (as well as some not-so-acute) data analysis, giving instructors insight into students’ critical-thinking abilities.

“I will not pretend that my experiment, completed in my brother’s bedroom with my mom, is going to have significant implications on the scientific community…. I will, however, entertain the idea that these findings make Gagliano’s case somewhat stronger.”

– Conclusion of one student’s project

Figure 3. Sample student poster.
### Table 4. Samples of student work for *Mimosa pudica* studies.

| Research Question                                      | Study Design                                        | Results                                                                 | Conclusion       | Critiques from Peers                                                                 |
|--------------------------------------------------------|-----------------------------------------------------|-------------------------------------------------------------------------|------------------|--------------------------------------------------------------------------------------|
| Training responsiveness in *M. pudica*                 | Control: Drop once on first day, and drop again on the fifth/test day  
Experimental: Drop once on first day; for three consecutive days, drop 60× with five-second intervals  
Rest fourth day, test fifth day by dropping once | Control plants (three) closed by the same percentage; experimental plants closed less by 0.35–0.8 cm | Plants learn     | • Did not take % of leaves  
• Time in between trainings was variable  
• Used different plants  
• Data not specific  
• Only done over three days |
| Can *Mimosa* plants learn from free falling?            | Used one plant; days 1 and 2 dropped 10× and waited in between each drop for plant to reopen | No difference                                                         | Plants did not learn | • N/A                                                                                 |
| Exploring the reactions of *M. pudica*                 | Control: dropped only once  
Experimental: dropped 40×, with 30 seconds in between each time; rest two days, then repeat; rest six days, then repeat; take 2.5-hour break and then repeat | No difference                                                         | Plants did not learn | • Experiment did not take place in constant number of days  
• Forgot control  
• Inconsistent procedure |
| A study of plants behaviors and botanical recognition  | Both plants dropped 10×/day for a total of 60 times  | Plants folded up more as more drops were applied                        | Plants did not learn | • No control  
• Too many variables  
• Diseased plants  
• Small sample, sketchy schedule |
| Can plants learn? Experimenting on *Mimosa* plant       | Dropped experimental plant 5× in 15 minutes for three days | Both control and experimental plants closed less                        | Due to fatigue, not learning | • Cherry-picking with ambiguous results  
• Only one day of testing?  
• Lack of dates  
• Too few breaks  
• Unclear explanation about steps |
| Learning experiment on *Mimosa* plant                   | Drop 10×/day with five minutes in between each drop | Went from being 70% closed to 20% closing                                | Plants learned   | N/A                                                                                  |

“We performed the experiment in the span of 8 days, each time was 1–2 days apart, which might have caused plants’ inability to learn because they weren’t constantly affected by the drops. The plants might have been able to learn if we had dropped them at least 30 times in one day…. The data does somewhat show a trend of them closing up the leaves less and less in respect to number of drops, although the correlation is extremely small and statistically insignificant, so it is most likely due to sampling variability. On the other hand, it could also be true that plants can’t really learn and Gagliano’s experiment was flawed in some ways.”

— *Sample of one group’s data analysis*

The project is enjoyable for students because (1) there is still drama in the scientific community about this – the question is not dead, irrelevant, or history – rather it’s hot, fresh, and spiced with “risible” (Taiz et al., 2019) name-calling; (2) the sensitive plants
fold their leaves upon contact and add life to a classroom; and (3) students had creative control over the design of their project (e.g., plant mazes or heart-shaped training) and had to come to their own decision about the question.

The project is useful for teachers because (1) it is student driven; (2) it is an authentic assessment, and instructors don’t have to wonder whether students copied the answers from the internet or from a previous year or bought a paper online; and (3) it allows assessment of students’ critical-thinking abilities in engineering design, in choosing to control for variables, and in the way they analyze the data and come to conclusions.

And it seems the drama continues (Taiz et al., 2019).

○ Supplemental Material

The following documents are available with the online version of this article:

- Appendix S1: Scientific Method Lecture
- Appendix S2: Gagliano et al. (2016) Article Questions
- Appendix S3: Project Brainstorming
- Appendix S4: Scientific Paper Instructions
- Appendix S5: Final Poster Guidelines
- Appendix S6: Grading Rubric

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