How-To-Do-It

The Graphing Detective: An Exercise in Critical Reading, Experimental Design & Data Analysis

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More than 300 policy studies concerning science education have been published since the appearance of *A Nation at Risk* in 1983 (Hurd 1989). Most of these studies indicate that science education—including biology—should "convey (to students) that the information presented (by textbooks) is the result of experimentation and that understanding is constantly being refined and is subject to change as new experiments are conducted" (National Research Council 1990, p. 29). Too often, students learn the "facts" of science without understanding how those facts are generated; that those "facts" are *interpretations* of data; and that those interpretations may well change in time. Too often, statements in textbooks and lectures are made without reference to the data on which those statements are based. Yet, students can become thoughtful consumers of scientific information only if they learn to evaluate data critically, along with the experimental designs that gave rise to those data. To be effective teachers, we must help students understand what a "scientific question" is how to gather appropriate evidence, how to analyze it and how to draw conclusions from that evidence.

Science education can be enlivened by encouraging discussions of experimental design and data interpretation. This paper suggests an inexpensive but powerful model through which this can be accomplished. The exercise further promotes "brain-on reading" (Pechenik 1992), in which students find themselves interacting with the material being read rather than simply going through the more typical and mechanical act of scanning from left to right and turning pages. Finally, the exercise provides a mechanism for using writing as a way of developing a student's ability to think critically (Zinsser 1988).

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An Example

The following exercise is readily adapted to a variety of classroom settings. We have used versions with students representing a broad range of grade and ability levels, with teachers in a graduate-level education course and as part of an in-service teacher training program. In all cases, we begin our discussion by showing students a table or graph from the scientific literature; we discuss how to locate such data summaries later in this article. For this example (Figure 1) we have chosen a figure from a paper by H. W. Harvey (Harvey 1933, as modified in Harvey 1969), although we emphasize that the exercise works well in any area of experimental biology. Note that the figure need not come from the recent scientific literature. In fact, choosing figures from the older literature can help establish the context in which present questions are being framed and help students appreciate that valid scientific inquiry is not a "modern" invention.

We have modified the original figure caption to suit our goals, but have not made substantive alterations to the figure itself. Before proceeding, we tell students only that the experimental organism is a diatom and that diatoms are unicellular algae (typically 50 to 500 μm in longest dimension) found in both fresh and salt water ecosystems. Like macroalgae and plants, diatoms photosynthesize in the light, "fixing" carbon from CO_2 into carbohydrates and releasing oxygen in the process.

The exercise has six steps, each in the form of a question (Table 1). Although the steps should be presented in the order shown, the exercise can be successful without going through all six steps; one can stop anywhere along the way in keeping with the instructor's current goals. Indeed, we suggest going through the exercise at frequent intervals during the year, emphasizing different aspects each time to keep things lively.

Step 1

If a figure is correctly executed, one can learn quite a bit about a study by examining the axes and figure caption. In the first step of the exercise, we ask students to tell us as much as they can about how this study was done, looking only at the graph itself (axes and data). In this case, we see that the study lasted for 60 hours, with the first samples being taken about five hours into the study. We also learn that Harvey measured oxygen production during this time (recorded as cubic centimeters of oxygen evolved per liter of seawater), presumably as an index of photosynthetic activity. The experiment included four treatments, each represented by a different line. We also know that oxygen concentrations were determined on seven occasions for three treatments, and on four occasions for one treatment, at intervals of about five to 15 hours.

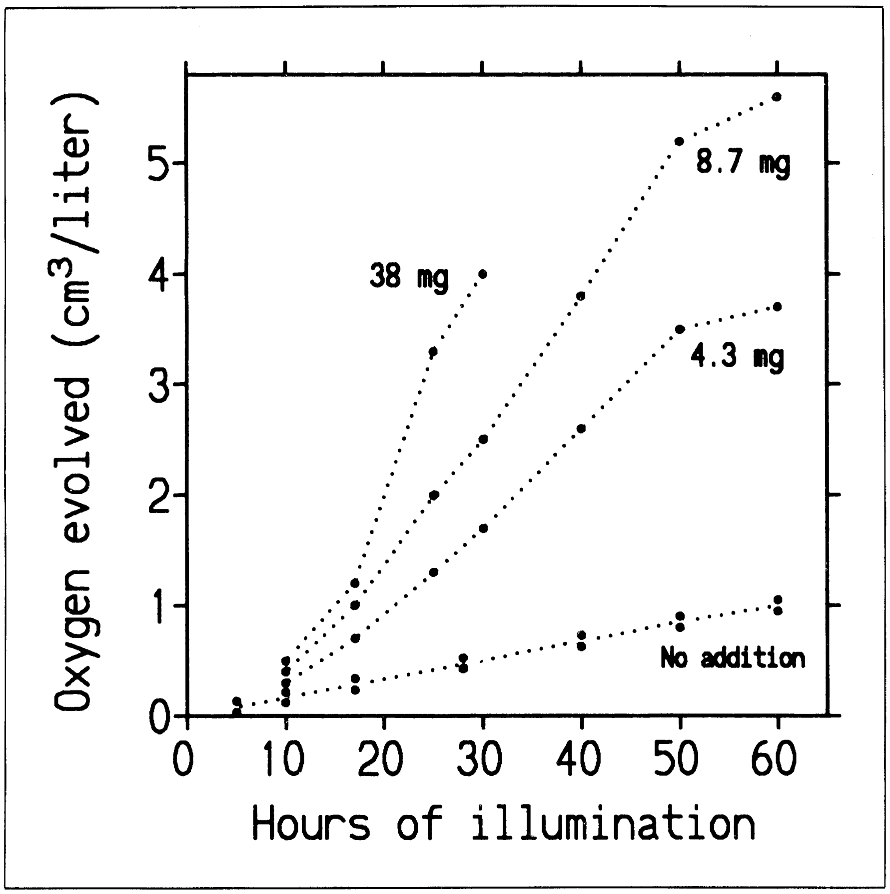

Figure 1. The influence of added phosphates on photosynthetic oxygen production by the marine diatom *Phaeodactylum tricornutum* (= *Nitschia closterium*). Flasks containing dense concentrations of the diatom were illuminated by two 500 watt lamps and incubated in a water bath at 15°C. Numbers on the graph indicate the amount of added phosphate, in mg added per m^3 of seawater.

Students may wonder whether each data point on the figure represents an average of several samples, but the use of two points for each control sampling suggests otherwise. Also, we might expect to see error bars extending vertically from each point, representing some measure of dispersion about the mean, if means were being plotted, and would expect the Y axis to be labeled "Mean oxygen evolved. . . ." So, each point *probably* represents a single measurement, and the control curve therefore *probably* passes through the means of the paired samples.

Before moving to Step 2, it is worth asking students to consider why "oxygen evolved" is plotted on the Y-axis rather than on the X-axis, thus introducing the concept of dependent and independent variables. The dependent variable is generally plotted on the Y-axis. In this case, the amount of oxygen produced *depends* on how much time has elapsed since the experiment began.

Table 1. Six steps that can be used with a figure to stimulate discussion of data interpretation and experimental design.

Steps	*Questions About the Graph*
1	Looking only at the axes and data, what do you know about how the study was done?
2	Looking now at the entire graph, including the figure caption, what else do you know about how the study was done?
3	What *can't* you tell about how this study was done?
4	What specific question is being addressed in the portion of the study represented by this graph?
5	Why would anyone want to ask the question referred to in Step 4?
6	What is the most important result shown by the graph?

Step 2

In the second step, we ask students to look at the figure caption and tell us what else they can learn about how the study was done. Clearly, Harvey began with cultures of a particular species of marine diatom, *Phaeodactylum tricornutum* (formerly *Nitzchia closterium*). But did he begin with five separate cultures or with one large culture that he then divided into five parts? This point can generate worthwhile and animated discussion. The best experimental design, of course, involves thoroughly mixing and then subdividing a single culture to maximize the likelihood of equal diatom concentrations in all flasks at the start of the experiment.

Harvey then elevated initial phosphate concentrations in some flasks by adding either 4.3, 8.7 or 38 mg of phosphate per cubic meter of seawater. Two samples served as controls and received no additional phosphate.

Or, did he use the same culture over and over again, adding different amounts of phosphate each time? Again, the best experimental design requires that the effects of the various phosphate additions be tested simultaneously. This ensures that all other factors, such as temperature and light intensity, are held constant so that different results in different treatments can be safely attributed to differences in the amount of phosphate added. Although we can't tell how Harvey actually did his experiment without additional information, we can probably agree on how he *should* have done it.

Step 3

Our third step is to ask students what they *can't* tell about how this study was done: "If you could interview Professor Harvey about his work, what would you ask him?" A variety of interesting questions may emerge in the course of discussion, as follows:

1. How did Harvey decide what concentrations of phosphate to use?
2. Why did he specifically look at the effect of phosphates?
3. What was the volume of water in each container?
4. What was the initial phosphate

concentration in the water before phosphates were added?
5. Does each data point represent a single sample, as suggested above, or is each the mean of several samples?
6. Why did Harvey first sample the control treatments about five hours before he first sampled the other treatments?
7. Why did he stop sampling one of the treatments (38 mg phosphate/m^3) after only about 20 hours?
8. How did he determine the oxygen concentration of the water samples?
9. What was the concentration of diatoms in each flask? And did this change during the experiment?

At this point, students can be asked (in class or as homework) to write a paragraph describing, in as much detail as possible, how the study was performed, as in the following example:

> *In 1933, Harvey apparently cultured the marine diatom* Phaeodactylum tricornutum *and divided the culture among five containers. Two of the containers served as controls. To the other three containers, he added either 4.3, 8.7 or 38 mg phosphate per cubic meter of seawater. Five hours after beginning the experiment he then determined the initial oxygen concentration in the two control bottles. He determined the oxygen concentration in all bottles five hours later and, for most of the treatments, five more times over the next 50 hours. He sampled oxygen concentrations in the bottle with the greatest amount of added phosphate only three more times and only over about 24 hours. All bottles were incubated at 15°C under constant illumination provided by two 500 watt light bulbs.*

Students can now work profitably in small groups to discuss each other's written work. They should pay particular attention to the accuracy and completeness of their descriptions.

Step 4

For the fourth step, we help students decide what specific question is being addressed in the portion of the study represented by the graph. In this example, the question is clearly contained in the figure caption. To what extent is photosynthetic oxygen production influenced by adding phosphates? A good figure caption is always constructed, in part, from the question driving the study (Pechenik 1992).

Steps 5 & 6

The last two steps get at the heart of doing science and interpreting data. For the fifth step, we ask students, "Why would anyone want to ask such a question?" Students will come up with a variety of answers here, which can provoke considerable discussion. Class time must be carefully allocated to allow for adequate treatment of the issue. Among the answers we have heard are the following:

1. Perhaps Harvey wanted to see if the diatoms were still alive.
2. Perhaps he wanted to see what effect pollution (e.g. fertilizers) might have on algal photosynthesis.
3. Perhaps he wanted to see how much total oxygen would be produced per unit of added phosphate.
4. Perhaps Harvey wanted to examine the potential production of food for herbivorous zooplankton, such as copepods and various larval stages.

Eventually the following answer may emerge: Ecologists have long been interested (and still are) in determining the chemical and physical factors that limit primary production (grams of carbon converted from CO_2 to carbohydrates per m^2 of ocean surface per year) in aquatic systems. By adding one nutrient to a water sample and measuring subsequent oxygen production, the effect of that nutrient on carbon fixation can be determined. If, for example, adding phosphates to a water sample does not increase photosynthesis, photosynthesis is probably not being limited by phosphate concentration. Perhaps the algae need more nitrates or silicates, or higher concentrations of certain trace metals such as copper, magnesium or iron, before they can photosynthesize at higher rates. The key issue here could be whether phosphate limits primary productivity in the sea. In other words, can we boost marine primary production rates by increasing phosphate concentrations in the water, and if so, by how much?

Even if the instructor finally has to provide a convincing rationale for the study, the preliminary discussion will have prepared students to receive this information.

The final step of the exercise is to get students discussing what they believe to be the most important result shown by the graph; essentially, we are asking "So what?" By the time students have discussed how the study was done, why it was done and why it was done the way it was done, they are well prepared to examine the data and are typically interested in doing so. In practice, we have students individually list three key results and then either present them for class discussion or work in groups of three to decide which is the single most important result.

When interpreting graphs, students at first tend to focus on the specific data points or comparisons of those data points. They should be encouraged to generalize their statements in light of the question driving the study, as determined in Step 4. For example, students may declare the key result to be that with the highest concentration of added phosphate, oxygen production at 18 hours was about six times higher than in control samples. But the more general statement would be that adding phosphates to the samples, up to the highest concentration tested, did indeed increase rates of photosynthesis. Once students get some practice in this line of reasoning, these discussions can become quite lively and students can end up teaching themselves quite a bit about data interpretation.

By the time students have completed Step 6, they are prepared to design studies of their own, to read original research papers on the subject or to learn more about the subject through lectures and assigned textbook readings. Instructors can also now give students some data and, after discussing how those data were obtained, ask students to prepare a suitable graph and accompanying figure legend.

Reading Tables

The exercise needs only minor modification for use with data tables. Indeed, only the first two steps require any changes: In Step 1, students examine only the column headings and numerical data; in Step 2, they consider the table caption and any accompanying notes.

Benefits

We see nine distinct benefits to leading students through this series of questions using different data throughout the year:

1. Students are exposed to different types of graphs and tables.
2. Students learn how to construct effective graphs and tables.
3. Students learn how to get

information from tabular and graphical material.

4. Students become interested and practiced in asking questions about data and how (and why) scientific research gets done.
5. Students often learn that the data of science are rarely as straightforward as textbook summaries often imply.
6. Students glimpse, and perhaps begin to understand, the true nature of scientific inquiry; they are exposed to key aspects of scientific research that make it interesting, exciting, controversial and even enjoyable to do, even when they are not yet able to conduct field or laboratory investigations themselves.
7. Students are prepared to hear more standard lecture material on the topic introduced by the graph—their appetites whetted for more information.
8. Students are prepared to design their own studies on the same or related topics.
9. Students learn how to read the formal scientific literature, particularly the Results and the Materials and Methods sections, which are the two most important components of any published research. When researchers read the literature in their field, they typically spend most of their time scrutinizing the tables and graphs, essentially going through Steps 1 through 6 as outlined above. By the end of Step 3, they can turn to the Materials and Methods section looking for the answers to particular questions about how the study was done. By the time they have completed Step 6, they have formed their own opinions about how the data should be interpreted and can safely read the Results and Discussion sections of the paper. The researcher may at times disagree with the paper's author (or authors), but it often turns out that the reader missed some important point elsewhere and quickly falls in line. But when disagreements remain, they can be a source of new research questions. Indeed, many significant research projects have their origins in such critical readings of prior research.

If one reads a research paper straight through without first examining the data as outlined here, it is more difficult to read that paper critically and many of these questions may never get asked.

Although the primary value of the exercise is its ability to provide students with a sense of how science is done while enhancing their critical and analytical skills, it also, we hope, enhances their enjoyment in learning biology.

Implementation

This exercise works especially well as a means of introducing a new topic. For instance, the graph discussed in our example could be used to introduce the topics of ecological limiting factors, plant or algal growth, food chains or a general discussion of photosynthesis. Similarly, graphs and tables can be used to introduce topics in animal behavior, developmental biology, physiology, biochemistry, invertebrate zoology, marine biology, limnology or population genetics. The written assignments associated with the proposed exercises should probably not be graded; it seems best to use formal examinations to test the students' growing ability to interpret data and discuss experimental design.

In seminar groups or small classes, advanced students can go on to read the paper from which the graph or table was excerpted, and then read other papers on the same or related topics. For example, discussing the Harvey (1933) graph could be followed by reading and discussing Perez et al. (1991), a recent paper concerning the role of phosphorus in limiting photosynthesis and growth of the sea grass *Cymodocea nodosa*.

Instructors can also incorporate relevant laboratory exercises or demonstrations into their lesson plans, allowing students to generate, present and interpret their own data. After studying the graph presented here, for example, students could measure rates of oxygen production by phytoplankton or *Elodea*, as a function of nutrient concentration.

Locating Suitable Graphs & Tables

Suitable data sets can be found in many advanced textbooks, in review papers (such as those in *Biological Reviews*, *BioScience*, *Quarterly Review of Biology* or *American Zoologist*), or in papers from the primary research literature. Some journals likely to bear fruit are *Biological Bulletin*, *Ecology*, *Animal Behavior*, *Behavioral Ecology and Sociobiology*, *Developmental Biology*, *Limnology and Oceanography* and *Marine Biology*. For lower level students, one can often find suitable graphs and tables in the science section of major newspapers. Whatever the source, it seems worthwhile to start students looking at data and representations of data as early as possible and as often as possible.

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