Kinesthetic and visual scaffolding for understanding oxygen delivery and reading hemoglobin oxygen curves

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Abstract
I describe a kinesthetic activity about oxygen handling by hemoglobin with two specific goals: 1) to help students gain a better understanding of how hemoglobin properties affect oxygen delivery and 2) to improve the ability of the students to actually read the hemoglobin oxygen-binding curve. The activity makes understanding oxygen delivery more intuitive, provides a kinesthetic analog to delivery of oxygen, and provides data to plot for the hemoglobin-oxygen curve.

graphing data; hemoglobin; kinesthetic activity; oxygen

INTRODUCTION
Understanding oxygen delivery and reading hemoglobin oxygen-binding curves are difficult for many of my students. Here I describe a kinesthetic activity about oxygen handling by hemoglobin with two specific goals: 1) to help students gain a better understanding of how hemoglobin properties affect oxygen delivery and 2) to improve the ability of the students to actually read the hemoglobin oxygen-binding curve. The laboratory exercises also have two general objectives: 1) to help students appreciate that oxygen delivery is but another example of the basic physiological principle of mass conservation (1) and 2) to improve students’ general graph reading skills. To these ends, I developed a kinesthetic apparatus for determining oxygen handling by hemoglobin in different physiological conditions and I used unconventional plot axes for exercising student ability at graph interpretation.

Many studies that examine why students have a hard time reading graphs (2–5) classify the problem into two categories (3, 6). One category is that the students do not have adequate scientific knowledge in the domain of the graph, and the other category is that the students do not have adequate knowledge of how to read graphs. From the responses I get when I start talking about hemoglobin and oxygen delivery, it seems to me that many of my students have both problems. Since I think that the information on a graph actually helps me visualize the scientific concepts, I wanted to introduce a visual image early in the process. There remains a debate about whether to teach graph creation or graph interpretation first (3, 7).

To draw a graph, students need to have data. It has been suggested that when students generate their own data, it provides a sense of ownership (2) and therefore engages them more. To generate actual data for the oxygen-hemoglobin curve they would need an oxygen electrode, hemoglobin or blood samples, and methods for obtaining oxygen-depleted blood and then would need to change the oxygen concentration to known amounts. This is not practical in our laboratory. Furthermore, even if they were able to do the measurements, it would take them considerable time mastering the techniques in order to reduce the errors sufficiently to make the data useful for interpretation. Although I could supply them with data and have them plot those values, I decided to develop a laboratory apparatus that would provide “data” but would require no technical expertise. By using this apparatus, they can “discover” the application of mass conservation of oxygen delivery as being the amount of oxygen entering tissue capillaries minus the amount of oxygen leaving tissue capillaries, as well as have data to plot.

The literature suggests that different scaffolds can be used to help students read graphs (3, 8, 9). Two categories of scaffolds are those that reduce the cognitive load and those that provide visual and kinesthetic analogies for the graphs. In this activity, I reduce the cognitive load by initially overlooking the contribution of unbound oxygen to the blood oxygen content. In addition, the laboratory apparatus provides a visual as well as kinesthetic scaffold for understanding graphing.

Modell has suggested that there are approximately seven major principles in physiology, but most students have difficulty recognizing their use in different organ systems (1). In part, this is because different terminology is used (1), and in part this is because instructors are not explicitly mentioning the use of the principle. The analysis of how much oxygen is delivered to the tissue involves the basic principle of mass balance, so I wanted an apparatus that would make reflected students’ prior knowledge as another scaffold; for example,
they know how to use mass balance to determine how much liquid is spilled by comparing the amount of liquid in the bottle before and after the spill.

These ideas helped me formulate what I needed for the model. I wanted to generate data for the students to plot. I wanted it to relate to determining how much material is lost when spilling a bottle, and I wanted to reduce the cognitive load. I found that five data points provided a reasonable appreciation of the shape of the oxygen curve, so I wanted the apparatus to generate an analogy for how much oxygen is bound at 20, 40, 60, 80, and 100 Torr. In an actual experiment, one might have the oxygen at 20 Torr, measure the amount of oxygen bound, and then raise the oxygen to 40 Torr and measure the additional oxygen bound, so I wanted an apparatus that would allow students to measure how much additional oxygen was bound for a 20-Torr increase in oxygen pressure. I used a narrow rectangular box that the students could fill and then cut wooden blocks so the empty space generated the appropriate fraction of the total volume. If the height of each wooden block represented an increase of 20 Torr oxygen, students could then fill the apparatus with a measurable object to each level of the wooden block.

Table 1 provides an outline for the calculations to construct an apparatus with a P50 of 50 Torr. Rather than use the most accurate current equation for oxygen binding to hemoglobin, I used the Hill equation, as suggested by Leow (4). Figure 1 illustrates a way to visualize the process. In Fig. 1A, the diamonds are the data points for the traditional oxygen dissociation curve that plots the total amount of oxygen bound at each oxygen partial pressure. The squares represent the additional amount of oxygen bound for an increase of 20 Torr of oxygen versus the oxygen partial pressure. In Fig. 1B, I have merely turned the plot by 90°. I did this because then the students would be able to fill the apparatus from bottom to top. In Fig. 1C, I have added black rectangles to represent the pieces of wood. The open spaces are then available for the students to fill.

The laboratory apparatus consists of an Essentials Stackable Organizing Drawer (Dollar Tree) partially filled with six pieces of 1 in. × 2 in. wood. In the laboratory apparatus, the unpopped popcorn kernels represent oxygen. An increase in the vertical height of the kernels in the container represents an increase in partial pressure of oxygen. The total number of kernels in the container represents the amount of oxygen bound to hemoglobin. This laboratory apparatus allows the students to generate five data points on a hemoglobin-oxygen dissociation curve for each patient. With the apparatus, it is easy for students to visualize the amount of oxygen delivered to the patients' tissue as an example of the concept of mass conservation. Basically, the students calculate how much popcorn is delivered by determining the difference between the initial and final levels of popcorn, just as they might calculate the amount of fluid they have consumed from the initial and final levels of fluid in a drinking bottle. In addition, by analyzing the data obtained from their apparatus, they can construct the Hb-O2 dissociation curve, learn how to read the curve, and understand the implications for O2 delivery.

Understanding oxygen delivery to the tissue involves many concepts, even if we just focus on the role of blood in the delivery. To reduce the cognitive load (9, 10), the initial exercise concentrates on the delivery, and only later do I discuss unbound versus bound oxygen, accurate P50 values, saturation of hemoglobin, and the conversion of popcorn volume to the amount delivered.

I like to start this laboratory section by motivating the students so they understand why comprehending hemoglobin oxygen curves is important for clinical evaluation. To do this, I provide them with these two cases from the literature. Many other examples of hemoglobin mutations are available (11–13).

Table 1. Outline for the calculations to construct an apparatus with a P50 of 50 Torr

| P02 Torr | Total O2 Bound to the Hemoglobin at Each Pressure Calculated Using the Hill Equation | Additional O2 Bound for Each 20-Torr Increase in O2a | Container Width, in. | Width of Each Piece of Wood, in.b |
|---------|-------------------------------------------------------------------------------------|--------------------------------------------------|---------------------|----------------------------------|
| 0       | 0                                                                                   | 0                                                | 6                   | 6.0                              |
| 20      | 2                                                                                   | 2                                                | 6                   | 5.8                              |
| 40      | 29                                                                                  | 27                                               | 6                   | 3.9                              |
| 60      | 67                                                                                  | 38                                               | 6                   | 3.0                              |
| 80      | 87                                                                                  | 19                                               | 6                   | 4.5                              |
| 100     | 94                                                                                  | 7                                                | 6                   | 5.4                              |

a For example, 29 – 2 = 27 for the increase from 20 Torr to 40 Torr. For the width of each piece of wood, the largest value in column 3 is about half of the total width of the container. In this case, the largest value in column 3 is 38, so the width of each piece of wood (column 5) is calculated as value in column 4 minus (value in column 3 divided by 38 times 2.5). Each piece of wood is cut to the appropriate length and then placed in the container in the appropriate order.

Case 1: Baby A was born at term with an uncomplicated delivery (14). A quick test of five criteria as devised by Virginia Apgar (appearance, pulse rate, reflex irritability, activity, respiratory effort) gave a normal score, but the baby had blue nail beds, lips, and tongue. Despite the blue nail beds, she did not show any signs of difficulty in breathing (dyspnea). Her pulse oximeter oxygen saturation was 74%, well below the normal range of 95–100%. She was started on oxygen supplementation with a tube into her nose, and that greatly improved her oxygen saturation and the color of her nail beds. Her blood parameters appeared normal, her chest X-ray was normal, and an echocardiogram of her heart was normal. The health workers astutely thought that the “problem” might be due to a mutant hemoglobin, and indeed the baby was found to have Hemoglobin Kansas. This mutant hemoglobin has lower affinity for oxygen, so when breathing normal air the hemoglobin oxygen saturation is lower than normal. However, she was still able to deliver plenty of oxygen to her tissues. Why was that? Other than the effect on her nail bed, tongue, and lip color there were no other remarkable problems, and she was removed from the oxygen supplement and was ready to go.
discharged after 10 days to her home. [Note that in the original article the blue skin color is emphasized, but I now prefer to stress the nail bed color so the analysis applies to people of all colors.]

Case 2: Patient B, an 11-yr-old, was to have his gall bladder removed (15). The patient was known to have one copy of an abnormal hemoglobin gene (Hemoglobin Bryn Mawr). The protein product from the abnormal hemoglobin gene has extra high affinity for oxygen. The health care team was concerned that his oxygen delivery would not be optimal while under anesthesia. Therefore, they transfused blood with normal hemoglobin into the patient to ensure adequate oxygen delivery. Why would an extra high affinity for oxygen decrease oxygen delivery?

With this motivation, I tell the students that, in lieu of actually doing experiments with blood from these patients, we will use a laboratory apparatus to model the measurement. We have apparatuses, one each for the blood from baby A, patient B, and a patient with normal hemoglobin, as shown in Fig. 2. For the three different apparatuses, the P_{50} values are 25, 50, and 75 Torr, in contrast to the actual values of 20, 26, and 36 Torr for patient B (15), normal, and baby A (14), respectively. I have found that when I make apparatuses based on a P_{50} of 20, 26, and 36 Torr, between my errors in making the apparatus and the student errors in volume measurements, for some students the plots overlap for the different cases. After mastering the concepts of reading the graph, it is a simple matter for most students to understand the actual P_{50} values.

I start by having the students establish the 0 Torr partial pressure and the 0 oxygen bound to hemoglobin point on graph paper with the y-axis labeled “partial pressure of oxygen” and the x-axis labeled “blood oxygen content” (see Fig. 3, left). I use these unconventional axes so that the height of the popcorn in the apparatus corresponds to the “height” on the graph, i.e., the “vertical” axis.

The students are provided a graduated cylinder containing 150 mL of popcorn. The students then pour in enough popcorn to have the vertical height of the popcorn reach the top level of the first piece of wood. They record the volume of popcorn remaining in the graduated cylinder (R) and then...
calculate the amount in the apparatus as $150 - R$ (as mL of popcorn). Because the vertical height of each wood block represents an increase of 20 Torr, the amount of oxygen added to reach the top of the first block represents the amount of oxygen in blood at 20 Torr partial pressure of oxygen. I have the students plot the data point on the graph paper as milliliters of popcorn, as I think that lightens the cognitive load. For those who prefer to have the axes be

**Figure 2.** Laboratory apparatus for the 3 patients at different oxygen pressures. The height of the popcorn represents the partial pressure of oxygen ($PO_2$); the volume of popcorn represents amount of oxygen bound. Top row shows that hemoglobin has no oxygen bound at 0 oxygen pressure, since there is no popcorn present. In middle row, the popcorn is 2 wood blocks high; as the height of each block represents 20 Torr, this represents the situation in which the oxygen pressure is 40 Torr. At rest, the $PO_2$ in blood returning to the lungs is 40 Torr; thus, the volume of popcorn represents the amount of oxygen still bound to hemoglobin when the blood returns to the lungs. In bottom row, the popcorn is 5 wood blocks high, representing the situation in which the oxygen pressure is 100 Torr for blood leaving the lungs.

**Figure 3.** Example of data obtained from an apparatus for the normal patient. A: plotted with the partial pressure of oxygen on the vertical axis paralleling height in the laboratory apparatus. B: replotted with the partial pressure of oxygen on the horizontal axes as in the conventional plot.
blood oxygen content, the students can convert volume of popcorn to blood oxygen content. For all three patients the maximum amount of oxygen bound to hemoglobin (200 mL/L of blood) corresponds to 150 mL of popcorn per container (ignoring the complication of unbound oxygen).

The students then determine the volume of popcorn required to have the height of the popcorn reach the top level of the second piece of wood, representing the amount of oxygen in the blood at 40 Torr partial pressure of oxygen. Figure 2, middle, shows the popcorn kernels filled to 40 Torr. The total volume of kernels in the apparatus represents the amount of oxygen in blood at that pressure of oxygen. They continue until they have tested six oxygen pressures (0, 20, 40, 60, 80, and 100 Torr) and plotted them. They can then connect the data points and generate the curves for the three patients (2 abnormal and 1 normal). Figure 3, left shows the plot for the normal patient. I prefer to wait to have the students replot the data with the conventional axes for Hb-O2 dissociation curve as in Fig. 3, right to lighten their cognitive load.

I explain to the students that the apparatus (and the corresponding plots) can help them determine how much oxygen can be bound by each of these forms of hemoglobin and how much oxygen can be delivered at a specific tissue PO2 to the body by each form of hemoglobin in a person who is at rest. To do this, we need to know that when the blood leaves the lungs and heads to the tissue, the PO2 of blood leaving the lungs is 100 Torr if the lungs are normal and atmospheric PO2 is around sea level. When that blood returns to the lungs from the body, we assume that the partial pressure of oxygen is ~40 Torr.

The apparatus in Fig. 2, bottom, has the popcorn filled to level 5, representing a partial pressure of 100 Torr. The volume of popcorn represents the amount of oxygen bound to hemoglobin when the blood is leaving the lungs. The students can measure the volume of popcorn in Fig. 2, bottom (blood leaving the lungs) and compare that to the volume of popcorn in Fig. 2, middle (blood returning to the lungs). This visual representation helps them appreciate the amount of oxygen that has been delivered to the body by each of the forms of hemoglobin. From a purely visual observation, most students can appreciate that baby A (Fig. 2, left) delivers almost as much oxygen as the normal patient (Fig. 2, center) and that patient B (Fig. 2, right) delivers much less. I can then point out to them by comparing the amount of oxygen entering the tissue with the amount leaving and calculating the difference, they are using the principle of mass conservation (11).

As the students are expected to read the conventional Hb-O2 dissociation curve (Fig. 3, right), it is at this point that I introduce the conventional axes with height of popcorn on the x-axis and amount of popcorn on the y-axis. I then ask them to find the data points for 100 Torr and 40 Torr with these conventional axes. I then challenge them to explain: How do you calculate the amount of oxygen delivered, i.e., milliliters of popcorn, to the body with this plot?

I then ask them to explain why baby A has blue nail beds. To answer this question, they will need to be told that the nail bed color is due to the proportion of hemes that are deoxygenated. A pulse oximeter reads the percentage of hemes with oxygen bound, and I have previously had them read a brief summary of how a pulse oximeter works. It is at this point that I introduce the conversion from milliliters of popcorn to percent hemoglobin saturation by telling them that 150 mL of popcorn represents 100% of the hemoglobin bound with oxygen, which is 200 mL of oxygen per liter of blood at a hemoglobin concentration of 150 g/L. The students then can convert their blood oxygen content to percent saturation. If they are still not able to explain why baby A has blue nail beds, I ask them leading questions:

At 100 Torr, which patient(s) would have a pulse oximeter value of at least 90%? The answer is patient B and the normal patient.

At 100 Torr, which patient(s) has the lowest pulse oximeter reading? The answer is baby A. Thus, baby A will have blue nail beds.

I can then ask, How does the amount of oxygen delivered to the body in baby A compare to that in a normal person? By examining the apparatus and the volume of popcorn, they can probably see that baby A’s oxygen delivery is nearly equal to a normal person but is more than patient B.

I then remind them that normally a pulse oximeter reading of 80% is a poor condition. If the normal patient had a pulse oximeter reading of 80%, using the plots, what would their partial pressure of oxygen be? For this, they must look at the Hb-O2 dissociation curve to determine that it is ~70 Torr. One situation in which a patient with normal hemoglobin would be expected to have a pulse oximeter reading of 80% is at high altitude, because of the lower partial pressure of oxygen.

For students that have a thorough grasp at this point, I think they can be challenged by being asked to view the curves from the original paper for patient B (Ref. 15, Fig. 1) and explain to patient B (and his parents) why the patient would be expected to have lower oxygen delivery. In Fig. 3 of that paper (15), the students can observe the effect of transfusion with banked blood [which has low 2,3-diphosphoglyceric acid (2,3-DPG)] and then the shift over a couple of days as the red cells make 2,3-DPG.

When these patients grow up, how will the mutations affect their capacity for aerobic exercise? During aerobic exercise, skeletal muscle PO2 can decline to substantially below 40 Torr. This increases the PO2 gradient between capillary blood and muscle mitochondria. If the skeletal muscle PO2 during intense exercise were to fall from 40 Torr to 20 Torr, which patient delivers more additional oxygen? Patient B. Which has very little reserve? Baby A.

At this point, I often point out that oxygen delivery depends not only on the amount of oxygen bound to hemoglobin but also on the amount of hemoglobin. If they are puzzled, I give them an analogy by asking them, Does the number of calories I eat depend only upon the calorie content per serving? Of course not, it also depends on how many servings I have. I ask them to think about how their popcorn apparatus could be altered to create an analogy to explain changing hemoglobin concentrations. Some of them realize that the depth (that is the dimension into the page) of the apparatus would be analogous to hemoglobin concentration, with a less deep apparatus representing anemia and a deeper apparatus blood doping.

Before discussing the next part of the laboratory, using conventional graphs, I want to discuss possible points of...
confusion and possible improvements on the apparatus. One point of possible confusion regards the bound versus unbound oxygen. For me, understanding the basics of the oxygen hemoglobin curve is of primary importance and of less importance is understanding that there is some oxygen unbound in blood. Therefore, I do not discuss the amount of unbound oxygen in blood until later in the activity, but others may feel that appreciating that unbound oxygen should be addressed at the beginning. If so, this can be easily done with the apparatus in Fig. 4A, which represents blood with no hemoglobin. Alternatively, the amount of unbound oxygen is the amount of popcorn at the rightmost portion shown in gray in Fig. 4B.

A second area of concern is that the apparatus does exaggerate the differences in $P_{50}$ value as well as the fraction of oxygen that is unbound. However, in my experience once the students have mastered the concepts of reading the graphs, they have no problem thinking about other $P_{50}$ values.

In the future, there are two improvements I would like to make. The present popcorn apparatus also does not illustrate saturation well, and this could be corrected by making the apparatus taller to include oxygen pressures to 160 or 200 Torr. The second is to build a water-tight apparatus so that water can be used instead of popcorn. That might allow a more reasonable estimation of unbound oxygen and also could allow the collection of more data points and more accurate data.

Instructors with different styles or goals may differ on the order of presentation. I prefer the order presented, but others might prefer to have the students use the conventional curve first and then discuss the laboratory apparatus. One reason I prefer the order presented is that many students will implicitly apply the mass conservation principle to their finding from the laboratory apparatus to answer the question about oxygen delivery, and so pointing this fact out to them after completing the delivery calculation with the apparatus helps them appreciate both the basic, simple nature of mass conservation as well as its power in solving problems.

In the years before doing this activity I realized that many multiple-choice exam questions can be answered by memorizing what left and right shift mean without actually understanding how to read or understand the plot. Some “better” students had memorized a sequence: If given a partial pressure of oxygen and asked to find the percent saturation, find the percent saturation on the $x$-axis and draw a perpendicular line at that point. At the point where perpendicular line crosses the data curve, draw a horizontal line perpendicular to the $y$-axis. At the point where it crosses the $y$-axis is the answer. But they were not able to put the information into context, and their answers to more complicated questions revealed this problem. It is a bit like applying an equation. Some students may be able to solve $V = IR$, by memorizing that if they are given $I$ and $R$, they multiply to get $V$, but the ones who do not actually understand the full implications of the equation are stumped if given $V$ and $R$ and are asked to solve for $I$.

So, after completing the exercises with the laboratory apparatus, I then asked them to analyze hemoglobin oxygen curves with unconventional axes. There are precedents for the value of unconventional axes and graphs. Moore et al. (16) explicitly discuss the value of breaking conventions in order to support quantitative reasoning for preservice teachers, and they feel this helps students in general. Fox and Hollar (8) used unconventional axes to explore the strategies students use to read graphs and to try to determine what scaffolding an instructor can provide in order to teach students how to read graphs better.

For me, the unconventional axes serve two purposes.

One purpose was that I wanted to be sure students were actually reading plots and not picking up on a pattern (2, 5). I wanted to be sure they were actually able to look at axes,
determining which variable on which axis, and where the high or low value is located and then looking at particular values as well as understanding the implications of different curves.

The second purpose was to give them practice reading novel graphs, as students may encounter graphs that are novel to them in later courses or in their career. Certainly, when I try to interpret a plot with unconventional axes in class, or when double-checking my problem and exam graph answers, it takes me longer than usual and is definitely more work. This helps me to appreciate the difficulty students have in reading graphs and makes me realize the shortcuts I take when reading graphs with conventional axes. I find this to be an important step in applying Decoding the Discipline to my work (17). In the Decoding the Discipline approach, one needs to identify the bottlenecks for the students. For many of my students the bottlenecks are the first steps to reading a graph. When I look at a conventional graph, its familiarity allows me to be unaware of my initial steps. When I try to explain an unconventional graph to students, I have to pause and think about each step; I make a point of telling students what I am doing, so they can see the steps I take when I approach a novel graph. Since I think my students find thinking about conventional graphs a novel activity, I think this is important. In that sense, reading unconventional graphs is also about problem solving a novel situation, even for those students who are adept at reading conventional graphs.

I give them approximately four to six different axis combinations, saving at least two unusual axes for the exam questions. It has been suggested that developing fluency requires repetitive practice, though repetitive practice is not sufficient to develop sense, reading unconventional graphs is also about problem solving a novel situation. For many health science students, I find it satisfying when completing this activity helps them to understand the physiology behind another real case study. For example, patient C was an 11-yr-old with sickle cell disease (SCD) who was referred for evaluation of suspected sleep apnea (22). The clinicians monitored the patient’s oxygen saturation during sleep, and the value was low, 92%. However, the clinicians realized that they could not use the usual cutoff because the sickle hemoglobin has a different oxygen hemoglobin curve. The students are asked these questions:

1. For someone with normal hemoglobin (HbA), what is Po2 when the saturation is 90%? [They are expected to use the data shown in the Hb-O2 dissociation curve of Fig. 3B in the original paper (8) to postulate a value of ~60 Torr.]

It is important to note that some students may be misled by unconventional axes simply by what they are “used to” and also by the fact that these axes violate what they have learned about scientific conventions of graphing (3, 8). There is evidence that some choices of what type of graph to use are more intuitive than others (19, 20). For example, bar graphs seem more intuitive for comparing data but line graphs for displaying trends (20). However, which variable goes on the horizontal axis is subspecialty dependent. For example, pressure-volume curves have volume on the horizontal axis for the heart and on the vertical axis for the lungs. A similar confusion occurs in chemistry courses: in general chemistry the horizontal axis is time, whereas in biochemistry it is concentration (21). Nevertheless, because student graph reading depends upon their prior knowledge (6), it is important to realize that the unconventional plot in Fig. 3, left may give the impression to some students who are used to having the independent variable on the horizontal axis that the bound oxygen causes the increase in oxygen pressure.

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1. For someone with normal hemoglobin (HbA), what is Po2 when the saturation is 90%? [They are expected to use the data shown in the Hb-O2 dissociation curve of Fig. 3B in the original paper (8) to postulate a value of ~60 Torr.]
2. For patient C, with sickle hemoglobin (Hbs), what is PO2 when saturation is 90%? (They are expected to find an oxygen pressure of ~90 Torr when the oxygen saturation is 90%).

3. Does this patient’s PO2 (not pulse oximeter measurement) support a diagnosis of sleep apnea if a cutoff for apnea is set at a PO2 of 60 Torr?

In the first few laboratory discussions of the semester, I found that few students were able to answer questions that involved reading and interpreting graphs. The last laboratory exam of the semester had several oxygen-hemoglobin curves with novel axes that the students had not seen before. Only 5 of the 295 students scored less than 80% on the exam, and over 90% of the students scored 90% or above. On the end-of-semester, anonymous, course evaluation, I asked students to respond to the statement “The laboratory experience helped me learn how to read graphs better” on a Likert scale of strongly agree, agree, neutral, disagree, and strongly disagree. An overwhelming 90% of students scored 90% or above. On the end-of-semester examination, over 90% of the students scored 90% or above. On the end-of-semester examination, most of the students wrote about the graph reading part, the visuals, or the laboratory was especially good or most helpful, many students responded to an open-ended question about what aspect of the students’ ability to interpret external representations in biochemistry. Int J Sci Educ 31: 193–232, 2009. doi:10.1080/09500690701670535.

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