How Middle School Students Construct and Critique Graphs to Explain Cancer Treatment

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Abstract: Using graphs in science is challenging as it requires both scientific and representational fluency. We examined how different graphing activities during science inquiry helped to develop these interrelated abilities in students. Grade 7 students (N=117) worked in pairs on a web-based cell biology unit to either generate or critique graphs of the effects of proposed cancer treatments on cell numbers. All students gained in their graph and science explanation abilities. While students who critiqued graphs gave better overall explanations within the unit, students who constructed graphs better applied their conceptual understanding of science to explain their graphs, both within the unit and later on the post test. We interpret these findings in terms of the relative affordances and constraints of critique and construction activities, and observe students' common misunderstandings of graphs. This study has implications for designing instruction that supports students' uses of graphs within science contexts.

Finding the synergy between graph and science understanding

The role of graphs in scientific practice is not often captured in typical K-12 curricula. Within scientific communities, graphs are used to predict, explain, and communicate complex concepts. In mainstream media, graphs persuade and inform citizens of important societal and environmental trends. The prevalence of graphs in both professional and everyday settings is such that people require a degree of graph literacy to make and critique arguments, and to interpret information for making decisions about personal and policy issues (e.g., Wiley et al. 2009).

For these reasons, there have been calls for curricula that develop students' abilities to use graphs to model, reason about, and communicate science ideas (e.g., Association for the Advancement of Science, 1993; National Research Council, 1996; Next Generation Science Standards, 2013). However, research continues to find that students struggle to understand and effectively use graphs in science contexts. This study explores the effects of different graphing activities incorporated into a collaborative web-based science inquiry unit on cancer and cell division.

Constructing and critiquing graphs as components of science literacy

Using graphs effectively involves coordinating an understanding of the relevant domain with an understanding of the representational language of graphs. That is, students must be able to encode and relate a graph's visual features to the concepts these represent (e.g., Friel et al., 2001; Shah & Hoeffner, 2002). As graphs are tools used to devise and evaluate solutions to complex science problems, the ability to both construct and critique them are critical components of scientific literacy. diSessa & Sherin (2000) refer to the abilities to critique and construct representations as components of meta-representational competence (MRC). To critique a graph is to determine the accuracy and effectiveness with which it conveys a message. To construct a graph, meanwhile, is a generative activity that is distinct from, yet just as important as critique (Leinhardt et al., 1990). By constructing graphs, students can visually demonstrate how they make sense of scientific information.

Reading and constructing graphs are challenging for students who are still developing their understanding of both science and of graphs. Indeed, prior research documents the many ways that student falter in their uses of graphs: They struggle to use graphs as evidence to support arguments (Lovett & Chang, 2007); they read graphs as literal pictures rather than acknowledge its axes (Clement 1985); they focus on individual points rather than on bigger trends; they fail to use content to explain axes and slope (Beichner, 1994); and they read graphs in terms of irrelevant other representational forms (see review by Leinhardt et al., 1990). Consistent with prior research, Lai et al. (2016) found that middle school students struggled to interpret graph features in terms of their related science concepts; and to recognize and interpret relationships depicted in visual features, such as trends, shapes, and noise. They moreover struggled to translate narratives of scientific phenomena into graphs, and instead provided superficial visual descriptions of graphs rather than descriptions grounded in science; and faltered in their efforts to interpret common graphical patterns, such as curve shapes and noise when making sense of global climate change and growth curves.

Constructing graphs is likewise difficult for students who are prone to create one-point graphs, generate a series of graphs to represent a single factor, and graph an increasing linear function regardless of the actual trend (Mevarech & Kramarsky, 1997). Moreover, graph construction activities can become easily mired in mundane tasks, such as plotting data points, which students are unlikely to connect to relevant scientific ideas. On the other hand, depicting relationships qualitatively may permit students to go beyond the data to make inferences based in their conceptual understanding, and to use graphs to engage in such scientific practices as predicting, arguing, and explaining. Interpreting qualitative features of graphs, however, has proven more difficult for middle school students than interpreting quantitative features of graphs (Hattikudur et al., 2012).

The need to emphasize graphs in science instruction

Studies find that students' understanding of graphs can be enriched through activities that involve explaining their reasoning and challenging the views of their peers (Kramarski, 2004). As well, curriculum designs that effectively integrate graphs into science contexts can enable students to successfully communicate scientific phenomena through graphs (e.g., Vitale et al., 2015). These findings suggest that instruction might go beyond guiding students in the technical tasks of constructing graphs and recognizing its features, to also supporting students in developing the metacognitive skill of critiquing graphs. The importance of graphs, along with students' struggles to use graphs, suggest a need for instruction that effectively incorporates graphs into realistic science inquiry activities (Lai et al., 2016).

In response, we integrated two graphing activities into a collaborative inquiry unit on cancer and cell division. We investigate the relative value added of students' qualitative construction and critique of graphs for supporting and revealing their abilities to explain and evaluate proposed cancer treatments.

Methods

The WISE *Mitosis* unit

We integrated a graphing activity into an existing middle school science unit on cancer and cell division. The unit, called *What makes a good cancer medicine?: Observing mitosis and cell processes* (aka, *Mitosis*) was authored in the Web-based Inquiry Science Environment (WISE, wise.berkeley.edu, Slotta & Linn, 2009). WISE is a free, open source learning environment with tools for authoring media-rich content, and for monitoring and guiding students' work. Units are designed according to Knowledge Integration (KI, Linn & Eylon, 2011), a framework that recognizes students' diverse ideas about science, and guides them in distinguishing, organizing, and integrating these into normative scientific understandings.

Mitosis introduces students to the process of cell division and the effects of cancer on the body. Central to the unit is an investigation of potential cancer treatments, in which students observe and compare animations of cells dividing normally, and when treated with different medicine options. Students work in pairs on shared computers, and use tools within the environment to develop, share, and refine their explanations for recommending one medicine over the others.

Next, the unit introduces surgery and chemotherapy as typical cancer treatments that each come with trade-offs: Surgery can quickly remove cancerous cells, but risks damaging healthy organs. As well, any remaining cancerous cells will continue to divide, which may lead to tumors to return. Meanwhile, chemotherapy avoids the risks of surgery, but because it targets all fast dividing cells—not just cancerous cells—it introduces side effects such as hair loss and nausea. Students analyze graphs of each treatment on a patient's number of cells over time. They read that because neither treatment is perfect, a goal in designing cancer treatment is to maximize the effects on cancerous cells while minimizing damage to healthy cells. A culminating graphing activity (further described below) has students use a graph to explain the effects of a possible cancer treatment on the number of cells in the body.

Participants and study design

Participants were 117 grade 7 students of a middle school in the west coast of the United States. They were taught by the same teacher, who had used previous versions of the same unit in the past several years. Students worked in pairs on a shared computer for approximately 10 consecutive days to complete the unit, including a pre and posttest that assessed their application of the science content. The teacher began each day with a whole class opener, in which she highlighted difficulties she noted in students' work from the previous day, and prepared students for the upcoming activities. Otherwise, the teacher circulated the classroom to assist groups as they worked through the unit at their own pace.

The teacher formed student pairs and randomly assigned half within each of her 4 class periods to complete one of two versions of the unit: *Construct* and *Critique.* These differed in the following activity

(Figure 1). *Construct* students were prompted to prescribe and explain a treatment plan for a cancer patient, and to complete a graph of the effects of their treatment on the numbers of cancerous cells over time. Meanwhile, *Critique* students were given a graph of the effects of a doctor's prescribed treatment on the numbers of cancerous cells over time, and prompted to annotate and explain how and why that treatment would or would not be effective. Afterward, students shared their graphs and explanations, and commented on the work of others in their class through an online discussion forum. They were then instructed to use their peers' ideas to revise their work.

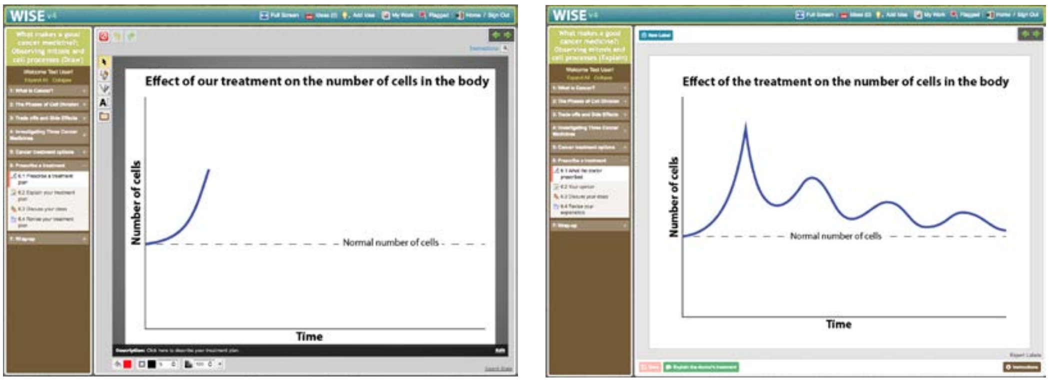


Figure 1. Screenshots of the *Construct* (left) and *Critique* (right) versions of the *Mitosis* unit.

Data and analysis

The data considered in this study include students' responses to the graphing activity embedded within the unit, which consisted of their graph artifacts (student-generated graphs from the *Construct* group and annotated graphs from the *Critique* group), and their accompanying written explanations of the cancer treatments. (Data on the ways that students shared and revised their ideas are reserved for future analyses.) We developed a rubric to rate students' abilities to integrate science content understanding with graphing abilities. This rubric identified the presence of several key concepts (Table 1), including: (1) an explanation based in science content learned in the unit (e.g., what cancer is, how cells divide, how chemotherapy works) as opposed to a literal description of the graph; (2) a sense of the imperfections or trade-offs of cancer treatment, as opposed to the belief that treatment is a straightforward and uncomplicated solution; (3) a recognition that to mitigate side-effects, the treatment must be given in multiple brief cycles rather than in a single dose; (4) a description of the graph that conveys the process of treatment by identifying sequences of events, as opposed to overlooking the nuanced changes in cell numbers over time.

The rubric also rated responses for their accuracy. One 4-point scale (0-3) rated the normativeness of students' written explanations, while another captured the accuracy of their graph artifacts (e.g., whether or not students indicated a decreasing number of cells, and whether the graph cohered with the written explanations). We summed the ratings on each aspect to obtain a single score with a possible total of 10 points. This score captures the overall quality of responses in terms of students' abilities to accurately apply relevant science content and graph features in their critiques or constructions of graphs.

The pre and post test consisted of five items that assessed students' abilities to apply concepts learned in the unit (e.g., explaining the importance of the phases of cell division, and describing the mechanism of cancer in terms of its effect on cell division.) For this study, we focused our analysis on one of these items, which had students generate and explain a graph of the number of cancer cells before, during, and after a proposed treatment. We used the rubric described above to code these responses. We also conducted a 30-minute long recorded phone interview with the teacher shortly after she had enacted the unit, and draw on this to help explain our findings.

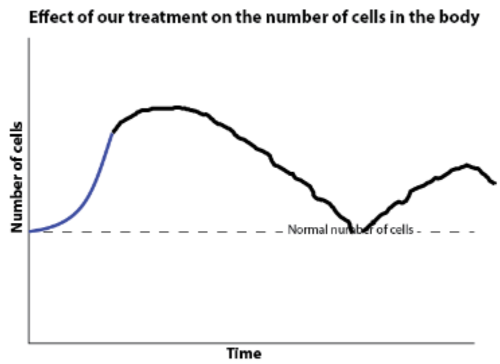
Table 1: Rubric for scoring students' responses, with examples (comparison groups indicated in italics).

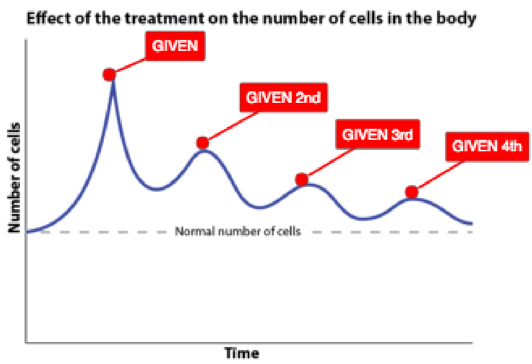
Category	Present
1.Content-based explanation	**Explanation: Uses relevant science content to interpret the graph.** Example

<table>
<tr><td></td><td>Critique: The chemotherapy keeps the cells from doing mitosis. When you have cancer your cells divide out of control you can get tumors from too many cells (...) The doctor's treatment plan worked by keeping her cell count near the normal amount but not harming the healthy cells but at the same time stop the cancer cells from dividing.</td></tr>
<tr><td>2. Sense of trade-off</td><td><u>Explanation</u>: Understands that cancer treatment involves a trade-off that can lead to side-effects.

<u>Example</u>
Construct: If you do chemotherapy for the just the right amount of time, you will get rid of the cancer cells and lose few normal cells.</td></tr>
<tr><td>3. Treatments cycles</td><td><u>Explanation</u>: Uses/recognizes an approach to treatment that mitigates risks and side-effects.

<u>Examples</u>

Critique: The doctors gave it to her multipul times to kill off the cancer cells...


Construct: When the number of cells reach the climax she takes not that much medicine. It'll go down but star rising again so she would take the medicine when it starts rising again.


</td></tr>
<tr><td>4. Narrative description</td><td><u>Explanation:</u> Conveys the process of treatment by identifying sequences of events, and recognizing the change in cell numbers over time.</td></tr>
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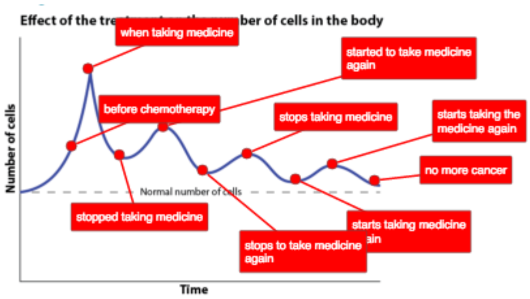
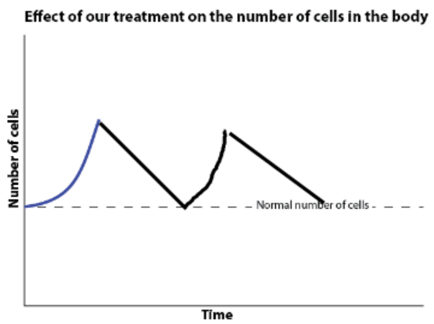
Examples

Critique



Construct: How the treatment would work is that we would apply it until it got back to normal, and then apply it again when the cells went above average. We think this will be effective because it will stop the cancer cells when they come back, but it won't go below normal.



Findings and discussion

Group differences on the embedded graphing activity

Students who critiqued the graph had significantly higher overall scores on the embedded graphing activity (N=29; M=9.59; SD=1.05) than students who constructed graphs of the effects of their own treatments (N = 32; M=8.63, SD=1.39), t(59) = 3.03, p<.005. A 2x4 chi-square test showed significant differences between groups in the occurrences of the specific aspects we coded, $x^2(2)=21.31$, p<.0001 (Figure 2).

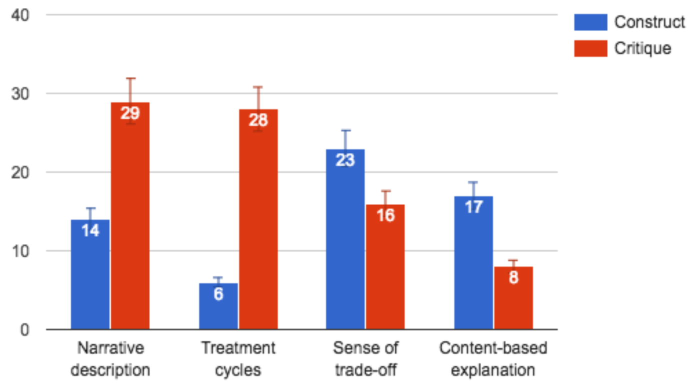


Figure 2. *Construct* and *Critique* students differed significantly in the frequencies of *Narrative description*, *Treatment cycles,* and *Content-based explanations* on the graphing item embedded in the unit.

Specifically, *Critique* students (N=29 M=.97, SD=0.19) were more likely than *Construct* students (N=32 M=.19, SD=0.40) to identify the importance of repeated doses of medicine, t(59)=9.64, p<.0001. This result might be explained by the fact that *Critique* students had only to identify these features from the given graph, while *Construct* students, who had to generate their own graphs, were left to discover this strategy on their own, which they did not always do successfully. *Critique* students (N=29 M=1.00, SD=0.00) were also more likely than *Construct* students (N=32 M=.44, SD=0.50) to describe the narrative process represented by the graph, t(59)=6.01, p<.0001. Being given an already constructed graph may have allowed *Critique* students to focus on developing narratives descriptions of it. Meanwhile, the extra effort of constructing a consensus graph may have led *Construct* students to put less effort into their written explanations. Notably, however, *Construct* students were more likely to use science content ideas to explain their graphs (N=32, M=0.53, SD=0.51) compared to *Critique* students (N=29, M=0.28, SD=0.45), t(59)=2.06, p<.05. It is possible that constructing a graph encouraged deeper thought into the graph's conceptual meaning.

Gains from pre to post

All students made significant gains on the graphing item from the pre (N=117, M=1.99, SD=2.79) to the posttest (N=117, M=7.42, SD=2.59), $t(232)=15.41$, $p<.0001$. *Construct* students gained slightly, but not significantly more (N=62, M=5.48, SD=3.43) than *Critique* students (N=55, M=5.36, SD=4.02). These findings suggest that in spite of differences in performance within the unit, both versions helped students improve their abilities to articulate key ideas, as well as to express these ideas normatively in both written and graphic forms.

Some of the group differences that were apparent within the unit persisted to the post test. Specifically, *Critique* students (M=0.24, SD=0.47) were more able than *Construct* students (M=0.08, SD=0.27) to identify the importance of cycling treatment, as shown by their greater pre to posttest gains on the graphing item, $t(115)=2.22$, $p<0.05$. It is likely that these students could easily reproduce features of the graph to which they were exposed during the unit. Likewise, the *Construct* students made significantly greater gains (N=62, M=0.45, SD=0.50) in applying content to their explanations compared to *Critique* students (N=55, M=0.22, SD=0.50), $t(115)=2.52$, $p<.05$. This finding suggests that *Construct* students were able to translate the abilities gained during the unit to their work beyond the unit.

Examples of students' challenges with using graphs to explain cancer treatment

In the better cases, students displayed a more nuanced understanding of the cancer treatment process by the end of the unit in both their written and graphed responses (e.g., Figure 3).

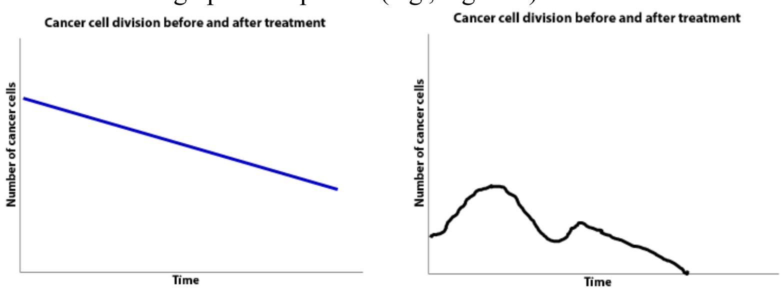


Figure 3. Left: One student's pretest response, which conveys a simplistic understanding of the effect of the medicine, along with the explanation: "The drug will stop the cells from multiplying…" Right: The same students' posttest response with the accompanying explanation: "My graph… is supposed to show that the cell count was rising before treatment, and after the start of treatment is went down, even past the normal cell count. In the middle of it, the cell count goes back up because there is a break in treatment to make sure there is no overdosage, but once the cell count starts to go back up, the treatment is restarted." (92037)

For the most part, however, we observed problematic features of students' responses that are consistent with other research (e.g., Lai et al., 2016). For example, with the exception of two student pairs, one in each comparison group, students failed to connect their ideas about science to their graphs, and instead restricted their explanations to describing their graph's visual features (e.g., "The treatment started, stopped, started again... This made the number of cells go up and down..."). In another example, one student pair in the *Critique* group mistook the y-axis to represent both the amount of medicine and the number of cells. As they wrote: "The doctor is giving Chemotherapy in smaller and smaller doses until the number of cells is at a normal amount." (218836)

While most students left their pretests blank or else scribbled nonsense and typed "I don't know," a few students created pictorial representations of the effects of cancer treatment (Figure 4); or graphed an increasing linear function (Figure 5). In each of these cases, the students improved their responses by the posttest. In some cases, however, students who displayed one misunderstanding of graphs at the pretest (using it as a pictorial representation of the phenomenon) ended with different misunderstandings by the posttest (drawing a series of graphs as opposed to a single one, and depicting rising linear functions in spite of the actual trend) (Figure 6).

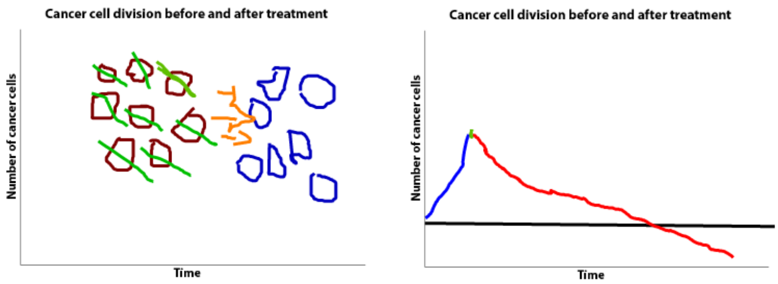


Figure 4. Left: One *Critique* student's pretest response showing a pictorial representation of the cancer treatment process. The graph is accompanied by the explanation: "The red circles are cancer cells. My drug is represented by the green lines crossing them out, then them turning them into regular cells." Right: The same student's posttest response is accompanied by the explanation: "The blue line represents when the person has cancer, and the number of there cells is growing rapidly. The green line represents when the drug is first taken. The red line, represents after the drug has been taken. The number of cells is going down, because the person is losing cells at a normal rate, but their body can't replace the cells." (89152)

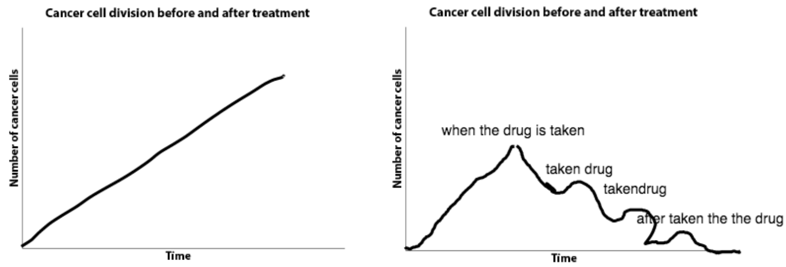


Figure 5. Left: One *Critique* student's pretest response, showing a rising linear function, and the same students' posttest response (right), demonstrating a more accurate narrative of the treatment process and the cycling of doses of medicine. (92399)

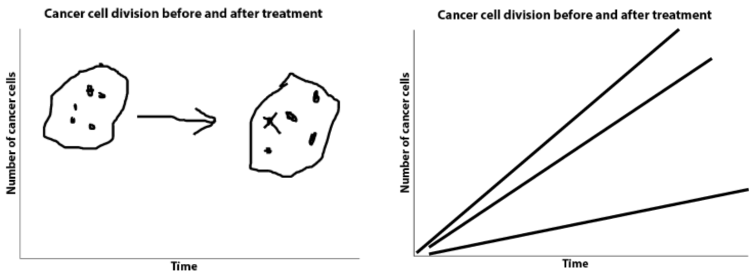


Figure 6. Left: One *Construct* students pretest response, showing a pictorial representation of cancer cells before and after treatment, and the same student's posttest response, which incorrectly uses a series of rising linear functions to represent the numbers of cancer cells before, during, and after treatment. (91962)

Conclusions and implications

We compared how students explained cancer treatment when constructing or critiquing qualitative graphs. Our findings suggest that critiquing graphs enabled students to generate better overall explanations, but that these explanations differed in particular ways. Specifically, the explanations of students who critiqued a given graph were more likely to convey a narrative of the underlying process, and to recognize the importance of cycling doses of medicine for mitigating side effects. Meanwhile, students who constructed graphs of their own treatment plans were more likely to use science concepts to explain their graph's meaning. These distinctions might be accounted for by differences in the practices that critique and construction either emphasize or minimize. That is, critique offers students with material upfront (a finished graph and a worked solution), which accomplishes some of the analytic work for students, and allows them to focus on elaborating other aspects of their explanations (e.g., coherent narrative descriptions). Meanwhile, construction requires students to generate material that is not provided. While doing so may prevent students from realizing nuanced solutions (e.g., cycling treatment as a way to mitigate side effects) and from spending as much effort in developing narratives of their explanations, the act of discussing and coming to consensus on a graph to generate may motivate students to think more deeply about the underlying conceptual meaning, and offer them a context in which to express that understanding.

This study offers an example and classroom trial of a graphing activity embedded within science inquiry instruction. Our interview with the teacher suggests that her opener activities, which modeled responses to other graphing items in the unit, may have prepared students to perform the graph critique and construction activity examined in this study. In spite of overall gains in their science and graphing abilities, the fact that certain students continued to display misunderstandings that are consistent with prior literature reveals an opportunity to investigate how students' graph construction reflects their scientific misunderstandings (cf. Vitale et al., 2015). It also suggests the need to further refine instructional materials that emphasize the synergy between graphing and scientific practices. In continuing our analysis of these data, we will investigate the ways that sharing and discussing graph artifacts with their peers impacted students' revisions, and the ways that technology can partner with teachers to support students' graphing practices in science contexts.

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